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RESEARCH ARTICLE

Morphological and biochemical adaptations of finger millet (*Eleusine coracana*) to salinity stress: A principal component analysis

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Abstract

Salt stress is a major factor in decreasing the yield under challenging conditions. To overcome these issues, the current study investigates the impact of salinity stress on the growth and biochemical adaptation of finger millet (*Eleusine coracana*, variety TRY 1). Therefore, a pot experiment was conducted during 2023-2024, to assess the effects of salinity stress (EC levels ranging from <1 to 12 dS/m) on finger millet. The experiment followed a completely randomized design with three replications. Plant growth and yield improved under mild salinity (EC 2 dS/m). The highest grain yield of 12.3 g/plant and increased proline and chlorophyll content were observed at this salinity level. However, plant growth and yield significantly declined with increasing salinity (EC > 2 dS/m). Proline levels increased by 67% under EC 12 dS/m, highlighting its role in osmotic adjustment, while total sugars decreased by 16.2% at higher salinity. Chlorophyll content also increased slightly under moderate salinity but declined sharply at higher levels, indicating impaired photosynthesis. Overall, moderate salinity stress (EC 2 dS/m) promoted finger millet growth and physio-biochemical adaptations, whereas higher salinity levels led to marked reductions in productivity, growth and biochemical responses. The TRY 1 variety displayed notable salt tolerance, surviving up to EC 12 dS/m, with optimal growth at EC 2 dS/m.

Keywords

biochemical adaptation; morphological; osmotic adjustment; principal component analysis; salt tolerance

Introduction

The global population is projected to exceed 9 billion by 2050, yet food production has not increased at a corresponding rate (1). To meet future food demands, production must increase by 44 million tons annually over the next 40 years, representing a 38% rise beyond historical trends (2). However, arable land is rapidly decreasing due to land degradation, urbanization, salinity, drought and flooding. Climate change further exacerbates these challenges, particularly in arid, semi-arid and coastal regions, where rising sea levels lead to increased seawater intrusion into freshwater aquifers, making them saline. Additionally, changing precipitation patterns result in more erratic rainfall, leading to prolonged dry spells followed by heavy rainfall that can wash away freshwater

resources while also increasing evaporation rates due to higher temperatures, which reduces water availability and further concentrates salts in arable land. Together, these factors create a cycle that significantly impacts soil health and agricultural productivity, especially in coastal and low-lying areas (3). This issue is already affecting farmers, particularly in arid and semi-arid regions; reliance on saline water for irrigation is growing due to insufficient rainfall and a shortage of quality water (4). If poor irrigation practices persist, over 50% of the world's arable land could face severe salinity by 2050 (5). Consequently, agriculture is increasingly expanding into salt-affected regions due to irrigation with brackish water and seawater intrusion in coastal areas. Salinity negatively impacts crop production as high salt concentrations can lead to ion toxicity, with excess sodium and chloride ions hindering plant growth and disrupting the uptake of essential nutrients. This results in stunted growth and lower productivity, threatening food security (6). In India, significant salinity issues are evident in the Indo-Gangetic Plain, particularly in Punjab, Haryana, Uttar Pradesh and Bihar, where poor irrigation practices contribute to salinization. Coastal districts in Gujarat and Tamil Nadu suffer from seawater intrusion, while Rajasthan's Thar Desert faces rising salinity due to low rainfall and high evaporation, further exacerbating agricultural challenges (7).

Abiotic stress tolerance involves complex interactions at the plant and cellular levels. Increased Na^+ accumulation in plants under salinity stress affects morphology and biochemical adaptations and leads to chlorophyll breakdown (8). To address the challenges, finger millet has been chosen to study salinity stress due to its adaptability to harsh environments, high nutritional value and potential for stress tolerance. Millets, native to semi-arid tropics, are cultivated in regions like India, Sri Lanka and parts of Africa where salinity and drought are common. Finger millet (*Eleusine coracana*) is highly nutritious, rich in calcium, phosphorous, amino acids, dietary fibers and seed proteins, with anti-diabetic, antioxidant and antimicrobial properties (9).

Salinity stress often triggers various morphological and biochemical changes in plants, such as reductions in plant height, leaf area and root growth. Biochemically, it increases proline accumulation, a common response that helps plants cope with osmotic stress. Additionally, salinity can cause alterations in chlorophyll content, reducing photosynthetic efficiency and disrupting the balance of essential nutrients, impacting overall plant health and productivity. These changes are particularly relevant in studies of crops like finger millet, where salinity stress significantly affects both growth and biochemical composition (9). Morphological and yield traits such as plant height, leaf length and ear head weight are important indicators of a plant's overall health and response to stress. Plant height reflects the growth rate and leaf length is important as it is directly linked to photosynthetic capacity, which influences energy production and productivity. Ear head weight is directly related to yield. These traits offer valuable awareness of the plant's ability to withstand stress conditions like salinity (8). At the biochemical level, key compounds such as proline, chlorophyll and sugars play crucial role in osmotic adjustment, photosynthesis and energy metabolism under stress conditions.

The study aims to investigate the morphological and biochemical adaptations of finger millet under varying levels of salinity stress. This study employs Principal Component Analysis, to determine which traits most significantly contribute to salinity tolerance. These methods will help identify, key morphological and biochemical responses in finger millet and improve understanding of its adaptive strategies under salinity stress.

Materials and Methods

Experimental site and design

A pot experiment was carried out at the Department of Soil Science and Agricultural Chemistry, Anbil Dharmalingam Agricultural College and Research Institute, Tamil Nadu Agricultural University, Tiruchirappalli (10.75° N, 78.60° E), Tamil Nadu during 2023-2024. This location was selected because the saline irrigation water used in the experiment was prepared in the laboratory to simulate varying salinity levels, making the study relevant for understanding the effects of saline irrigation on crop growth. This experiment applied a completely randomized design (CRD) with three replications and seven levels of saline irrigation (less than 1, 2, 4, 6, 8, 10, 12 dS/m) for the millet crop, TRY 1, considered as salt tolerant variety.

Preparation of treatment

RO (Reverse osmosis) water was chosen as the control in this experiment because it has a very low electrical conductivity (EC) level, typically around 0.5 dS/m or lower, providing a baseline for comparing the effects of varying salinity levels on plant growth. The target salinity levels of irrigation water (ECw) required for the treatments were achieved by diluting seawater with RO water. Seawater was used in this experiment due to its typical ionic composition, which includes essential saline ions such as sodium (Na^+), chloride (Cl^-), magnesium (Mg^{2+}), calcium (Ca^{2+}) and sulfate (SO_4^{2-}). The average ionic concentrations in seawater are approximately 10500 mg/L for Na^+, 19000 mg/L for Cl^-, 1300 mg/L for Mg^{2+}, 400 mg/L for Ca^{2+} and 2700 mg/L for SO_4^{2-}. By utilizing seawater, we can effectively simulate real-world saline conditions that affect crops. This allows assessment of plant responses to salinity, reflecting the challenges faced in agricultural systems impacted by seawater intrusion and saline irrigation.

To prepare saline irrigation water with varying EC levels, seawater and RO water were mixed in specific proportions. Seawater, with a measured EC of 50 dS/m, was diluted with RO water to achieve the target EC values of 2, 4, 6, 8, 10 and 12 dS/m. The total volume of each solution was maintained at 20 liters.

The seawater volume was increased, and the RO water volume was decreased to maintain the total volume of 20 liters for each treatment. For 20 liters: T_2(2 dS/m) = 0.8 L seawater + 19.2 L RO water, T_3(4 dS/m) = 1.6 L seawater + 18.4 L RO water, T_4 (6 dS/m) = 2.4 L seawater +17.6 L RO water, T_5(EC 8 dS/m) = 3.2 L seawater + 16.8 L RO water, T_6 (10 dS/m) = 4.0 L seawater + 16.0 L RO water, T_7 (12 dS/m) = 4.8 L seawater + 15.2 L RO water. The prepared irrigation water was stored in 20 L plastic containers, and all treatments were irrigated manually every three days to maintain the desired moisture levels. The frequency of irrigation varied based on the salinity treatment, with more frequent irrigation for lower salinity levels to ensure consistent moisture. Water was applied directly to the soil surface of each pot,

allowing for even infiltration and minimizing surface runoff. Approximately 500 mL of water was applied per pot during each irrigation. Over the entire duration of the pot experiment for finger millet *(Eleusine coracana*), a total irrigation volume of approximately 17.5 L was utilized. This method ensured uniform water distribution, facilitating an accurate assessment of the plants' responses to varying saline conditions.

Morphological and yield assessment

The transplantation of finger millet (*Eleusine coracana*) seedlings typically occurs around the 15th day post-sowing, providing the seedlings with adequate time to establish growth and develop their root systems. Consequently, salinity treatments were applied 20 days after transplanting. Following this, various parameters were assessed at the time of harvest stage, including, plant height, leaf length, root length, shoot length, number of tillers per plant, number of fingers per ear head, finger length, ear head weight, grain yield and stover yield.

Physio-biochemical assay

In the experiment, leaf samples were collected at the tillering and flowering stages from each replication per treatment, resulting in a total of 42 samples. To preserve the integrity of biochemical compounds, the samples were immediately placed in a cooler at -4°C and stored prior to physio-biochemical analysis. The protocols for the assays included:

Chlorophyll content

The amount of chlorophyll was measured using Arnon's method (10). 0.5 g of leaf samples were homogenized in 80% ethanol after being centrifuged at 4000 rpm for 3 minutes. A UV spectrophotometer (PerkinElmer Lambda 365) was used to measure the absorbance at 663 and 645 nm. The following formulae were utilized to determine the amount of chlorophyll.

Chlorophyll a (mg/g FW) = [0.0127 × OD663 – 0.00269 × OD645] × (V/W)

Chlorophyll b (mg/g FW) = [0.0229 × OD645 – 0.00468 × OD663] × (V/W)

Total Chlorophyll (mg/g FW) = [(20.2 × OD645) + (8.02 × OD663)] × (V/ (1000 × W))

where OD- optical density at the appropriate wavelength, V - extract volume (mL), W - sample weight (g).

Proline content

The proline content was assessed using the method by Bates (11).0.2 g of fresh leaves were dissolved in 5 ml of 3% sulfosalicylic a cid. Glacial acetic acid and 2 mL of acidic ninhydrin solution were added to the homogenate after it had been filtered. The mixture was heated in a water bath at 100 °C for 60 min and then allowed to cool on ice for five minutes. After adding toluene, the absorbance at 520 nm was measured using a UV spectrophotometer (PerkinElmer Lambda 365). The proline content was given as µg/g of fresh sample weight.

Sugar content

To extract the sugars, 0.1 g of chopped leaf samples were agitat ed overnight in 10 mL of 80% ethanol. The reducing, non-reducing and total sugar concentrations were calculated using the Riazi method (12).

Statistical analysis

Analysis of variance (ANOVA) was used to analyze the data and find any significant mean differences with P ≤0.05, the least significant differences (LSD) were used to compare treatments for significance. A statistical software tool called OPSTAT was utilized for the analyses (13). Additionally, principal component analysis was performed using the STAR 2.0.1 statistical program (14).

Results and Discussion

This study examined the effect of salinity stress on growth, yield, proline content, chlorophyll (a, b, total) and sugar levels in finger millet varieties. The parameters were analyzed with the use of PCA to determine which traits most significantly contribute to salinity tolerance.

Morphological performances

The results demonstrated that the finger millet variety exhibited significant changes in growth metrics under varying salt stress conditions (Table 1). Plant height decreased with increasing salinity. The maximum height recorded was 94.7 cm at an EC of 2 dS/m, about 30% greater than the control (72.8 cm). When salinity increased, plant height consistently dropped by 8% at EC 4 dS/m from 94.7 cm to 89.2 cm, 11% at EC 6 dS/m from 94.7 cm to 86.7 cm and 22% at EC 8 dS/m from 94.7 cm to 76.5 cm in comparison to EC 2 dS/m. The lowest height, 68.7 cm was measured at EC 12 dS/m, which was 27% less than the maximum height noted.

At EC 2 dS/m (T_2), the longest roots and shoots were measured at 18.9 cm and 86.9 cm, respectively. As salinity increased, root and shoot lengths decreased; the minimum measurements were found at EC 12 dS/m (T_7) with roots at 9.3 cm and shoots at 63.7 cm. At EC 2 dS/m (T_2) plant had the greatest leaf length of 42.5 cm. However, at EC 12 dS/m, leaf length sharply decreased by 19.1 cm, a drop of more than 55%. (Table 1).

The results show that high salinity has negative effects on plant development overall, with significant decreases observed across all assessed parameters in response to increased salt. Conversely, at lower salinity levels (EC 2 dS/m) plant development was optimal, with increases in plant height, root length and leaf length compared to the control. Salt-tolerant plants may utilize Na^+ ions to maintain turgor pressure,

Table 1. Effect of salinity stress on growth performances in finger millet

Treatment Details	Plant Height (cm)	Leaf Length (cm)	Root Length (cm)	Shoot Length (cm)
T_1 Control (EC <1 ds/m)	72.8	31.6	16.8	65.6
T_2 EC@ 2 ds/m	94.7	42.5	18.9	86.9
T_3 EC@ 4 ds/m	89.2	35.4	15.9	81.7
T_4 EC@ 6 ds/m	86.7	33.2	13.6	79.8
T_5 EC@ 8 ds/m	76.5	29.4	12.4	70.4
T_6 EC@ 10 ds/m	71.5	22.9	10.5	66.1
T_7 EC@ 12 ds/m	68.7	19.1	9.3	63.7
SE(d)	1.511	0.286	0.212	1.635
CD (P=0.05)	3.24	0.613	0.455	3.507

but as salinity exceeds this level, growth declines likely due to toxic effects from elevated sodium levels, disrupting nutrient uptake and causing cell damage (15). A slight increase in salinity could trigger adaptation processes that reduce the plant's ability to absorb water, which would impact cell division and growth (16, 17).

Yield performances

Under control conditions (EC <1 dS/m), the plants exhibited an average of 5.33 tillers per plant, which increased by approximately 50% at EC 2 dS/m. However, with increasing salinity, the number of tillers decreased, showing a 46% reduction at EC 12 dS/m compared to the control. A similar trend was followed by other parameters, viz., number of fingers per ear head, length of fingers and ear head weight (Table 2).

Grain yield showed a substantial increase of 46% at EC 2 dS/m (12.3 g/plant) compared to the control, but subsequently decreased by 19% at EC 4 dS/m, 28% at EC 6 dS/m, 36% at EC 8 dS/m and 57% at EC 12 dS/m. Stover yield increased by 16% at EC 2 dS/m (258.40 g/plant) compared to the control but showed a downward trend at higher salinity levels (Table 2).

In this range, irrigating with diluted seawater provides ions that serve a dual role, contributing to osmotic adjustment and nutrient uptake without reaching toxic levels (18). The results indicate that moderate salinity enhances yield parameters specifically, the number of fingers per ear head, finger length, ear head weight, grain yield and stover yield. But higher salinity disrupts nutrient absorption and leads to ion toxicity, significantly reducing finger millet growth and productivity. These findings align with previous studies, showing that the highest yield occurs under low salinity irrigation, while the lowest yield is observed under high salinity conditions (19).

Physio-biochemical attributes

The accumulation of compatible solutes, including proline and sugars plays a crucial role in osmotic adjustment in plants. Furthermore, chlorophyll content is essential for photosynthesis and serves as an indicator of the plant's health (20). In this study, variations in chlorophyll content under salinity stress offer valuable insights into the health and photosynthetic capacity of the plants.

Proline content under salinity stress

Proline content in finger millet increased progressively with higher salinity levels, reaching 47.12 µg/g at EC 12 dS/m. Under control conditions (EC <1 dS/m), proline levels were 28.22 µg/g during tillering and 33.48 µg/g during flowering. At the highest salinity level (EC 12 dS/m), proline content increased to 47.12 µg/g during tillering (a 67% increase) and 55.24 µg/g during flowering (a 65% increase) (Table 3). This significant rise in proline content highlights its role as a key osmoprotectant, helping finger millet to adjust osmotically and mitigate the effects of salinity stress.

At moderate salinity (EC 2 dS/m), proline content increased by 15% contributing to better osmotic adjustment and supporting a higher grain yield of 12.3 g / plant. This suggests that moderate salinity stress allows the plant to utilize proline efficiently, enhancing stress tolerance and sustaining productivity (21).

At EC 12 dS/m, grain yield drops to 5.3 g per plant, indicating that excessive salinity overwhelms the protective effects of proline, leading to metabolic disruptions and reduced productivity. Thus, while proline plays a key role in stress tolerance, its effectiveness diminishes under extreme salinity conditions, causing a yield decline in finger millet.

Sugar accumulation under salinity stress

The analysis of sugar content in salt-tolerant finger millet revealed notable variations across salinity treatments. At EC 2 dS/m, reducing sugars were lowest with concentrations of 2.1 mg/g during tillering and 3.7 mg/g during flowering. At 12 dS/m, reducing sugars increased to 5.2 mg/g during tillering and 6.4 mg/g during flowering, reflecting an increase of approximately 116.67% and 64.10%, respectively (Table 4). In contrast, non-reducing sugars decreased significantly, showing a decline of 62.3% during flowering at 12 dS/m (4.2 mg/g). This reduction can be attributed to the metabolic stress induced by higher salinity, which impairs sugar synthesis pathways and disrupts normal

Table 2. Effect of salinity stress on yield parameters of finger millet

Treatment Details	No. of tiller/ plant	No. of fingers/ ear head	Length of fingers (cm)	Ear head weight (g)	Grain yield (g/ Plant)	Stover yield (g/plant)
T_1 Control (EC <1 ds/m)	5.33	4.7	7.2	10.4	8.4	222.97
T_2 EC@ 2 ds/m	8.00	6.7	7.8	11.2	12.3	258.40
T_3 EC@ 4 ds/m	6.67	5.7	7.5	10.7	9.8	232.50
T_4 EC@ 6 ds/m	5.33	5.0	6.9	10.1	8.9	228.03
T_5 EC@ 8 ds/m	5.00	4.3	6.1	9.3	7.9	217.91
T_6 EC@ 10 ds/m	4.67	3.7	5.4	8.6	6.8	202.80
T_7 EC@ 12 ds/m	4.33	3.3	5.0	7.7	5.3	191.70
SE(d)	0.504	0.436	0.105	0.208	0.157	3.172
CD (P=0.05)	1.08	0.935	0.225	0.446	0.337	6.80

Table 3. Effect of salinity stress on proline content (µg/g) at tillering and flowering stages of finger millet

Treatment Details	Reducing sugars (mg/g)		Non reducing sugars (mg/g)		Total sugars (mg/g)	
	Tillering	Flowering	Tillering	Flowering	Tillering	Flowering
T_1 Control (EC <1 ds/m)	2.4	3.9	6.9	8.2	9.3	12.1
T_2 EC@ 2 ds/m	2.1	3.7	7.4	8.7	9.5	12.4
T_3 EC@ 4 ds/m	2.5	4.2	6.6	7.9	9.1	12.1
T_4 EC@ 6 ds/m	3.4	4.9	5.4	7	8.8	11.9
T_5 EC@ 8 ds/m	3.9	5.3	4.9	6.3	8.8	11.6
T_6 EC@ 10 ds/m	4.4	5.8	3.8	5.5	8.2	11.3
T_7 EC@ 12 ds/m	5.2	6.4	2.6	4.2	7.8	10.6
SE(d)	0.087	0.108	0.082	0.152	0.173	0.254
CD (P=0.05)	0.187	0.232	0.176	0.326	0.371	0.545

Table 4. Effect of salinity stress on reducing sugar, non-reducing sugar and total sugar content (mg/g) at tillering and flowering stages of finger millet

Treatment Details	Proline (µg/g)	
	Tillering	Flowering
T_1 Control (EC <1 ds/m)	28.22	33.48
T_2 EC@ 2 ds/m	32.56	38.92
T_3 EC@ 4 ds/m	36.87	40.83
T_4 EC@ 6 ds/m	38.74	44.87
T_5 EC@ 8 ds/m	41.29	48.75
T_6 EC@ 10 ds/m	43.56	51.2
T_7 EC@ 12 ds/m	47.12	55.24
SE(d)	0.877	1.109
CD (P=0.05)	1.88	2.38

metabolic functions. Under saline conditions, plants may divert energy resources towards osmoregulation and stress response rather than synthesizing non-reducing sugars. This shift can lead to lower non-reducing sugar accumulation, ultimately affecting plant health and productivity (22). Overall, total sugars decreased by 16.2% during flowering at the highest salinity level. The standard error of difference SE(d) and critical difference (CD) values at P=0.05 indicate statistically significant differences among treatments, underscoring the impact of increasing salinity on sugar accumulation in finger millet.

Moderate salinity stress in finger millet helped avoid excessive stress on the plants, leading to increased total sugar concentrations without significantly reducing yield. In moderate salinity conditions (EC 2 dS/m), the sugar content increased, where increased electrical conductivity led to finger millet with higher reducing sugar content (23). In contrast, under higher salinity levels (e.g., EC 8 dS/m and beyond), there was a decline in yield and sugar content.

Salinity effects on chlorophyll content

At a salinity level of EC 2 dS/m, chlorophyll content in finger millet showed a slight increase, by approximately 2.86% compared to the control (3.6 mg/g FW). Chlorophyll *a* content during tillering increased by 2.6% and flowering by 1.99% over the control. Chlorophyll *b* content increased by 3.4% during tillering and 2.3% during flowering. Total chlorophyll content also exhibited an increase of 2.86% during tillering and 2.1% in flowering (Table 5). However, salinity levels beyond EC 2 dS/m led to a reduction in chlorophyll content. This reduction highlights the detrimental effects of high salinity on chlorophyll synthesis and photosynthetic capacity.

This indicates that moderate salinity enhances chlorophyll production, potentially supporting better photosynthetic activity and overall plant health at EC 2 dS/m. Mild saline water enhances growth due to Na^+ acting as an osmotic regulator. Beyond moderate salinity levels, the growth-promoting effects of Na^+ diminish, leading to a decline in both chlorophyll content and yield. This reflects the balance between beneficial and harmful effects of Na^+ depending on its concentration (24).

Genetic diversity

Principal component analysis

PCA was employed to simplify the dataset and identify key traits contributing to genetic diversity within the population. PCA helps identify which plant traits contribute most to the variation in response to salinity stress within the population. PCA was applied to reduce the dimensionality of the dataset and uncover new underlying variables (25).

Mean morphological and yield performance of finger millet under salinity stress

Eigenvalues greater than 1 were observed in the first principal component (PC1), with a value of 9.24, contributing over 92.35% of the total variation in this study (Table 6). A scree plot (Fig. 1) shows how much variation is explained by each principal component. PC1, with an eigenvalue of 9.24, accounted for 92.4% of the total variation. The eigenvalues gradually decreased with increasing principal components, indicating a diminishing contribution to the variance. This suggests that most of the variation is explained by PC1, with subsequent components contributing less. PC1 contributed the most to the variance (92.35%), followed by PC2 (5.39%) and PC3 (1.56%). PC1 had the greatest influence on the principal component associated with the traits such as plant height, leaf length, root length, shoot length, number of tillers per plant, number of fingers per ear head, finger length, ear head weight, grain yield and stover yield (Table 7, Fig. 2). These findings align with previous principal component analyses of growth and yield traits in finger millet (26).

Table 5. Effect of salinity stress on chlorophyll a, b, total chlorophyll content at tillering and flowering stages of finger millet

Treatment Details	Chlorophyll a (mg/g FW)		Chlorophyll b (mg/g FW)		Total Chlorophyll (mg/g FW)	
	Tillering	Flowering	Tillering	Flowering	Tillering	Flowering
T_1 Control (EC <1 ds/m)	2.33	2.51	1.17	1.29	3.5	3.8
T_2 EC@ 2 ds/m	2.39	2.56	1.21	1.32	3.6	3.88
T_3 EC@ 4 ds/m	2.35	2.49	1.18	1.27	3.53	3.76
T_4 EC@ 6 ds/m	2.26	2.47	1.15	1.21	3.41	3.68
T_5 EC@ 8 ds/m	2.11	2.29	1.05	1.15	3.16	3.44
T_6 EC@ 10 ds/m	1.58	2.18	0.79	1.09	2.37	3.27
T_7 EC@ 12 ds/m	1.05	1.97	0.56	0.99	1.61	2.96
SE(d)	0.028	0.053	0.022	0.029	0.070	0.097
CD (P=0.05)	0.06	0.114	0.047	0.062	0.150	0.208

Table 6. Eigen values of mean morphological and yield performance of finger millet under salinity stress

Principal component	Eigen value	Percentage of variance	Cumulative percentage of variance
PC1	9.24	92.35	92.35
PC2	0.54	5.39	97.74
PC3	0.16	1.56	99.30
PC4	0.06	0.57	99.87
PC5	0.011	0.11	99.98
PC6	0.002	0.024	100

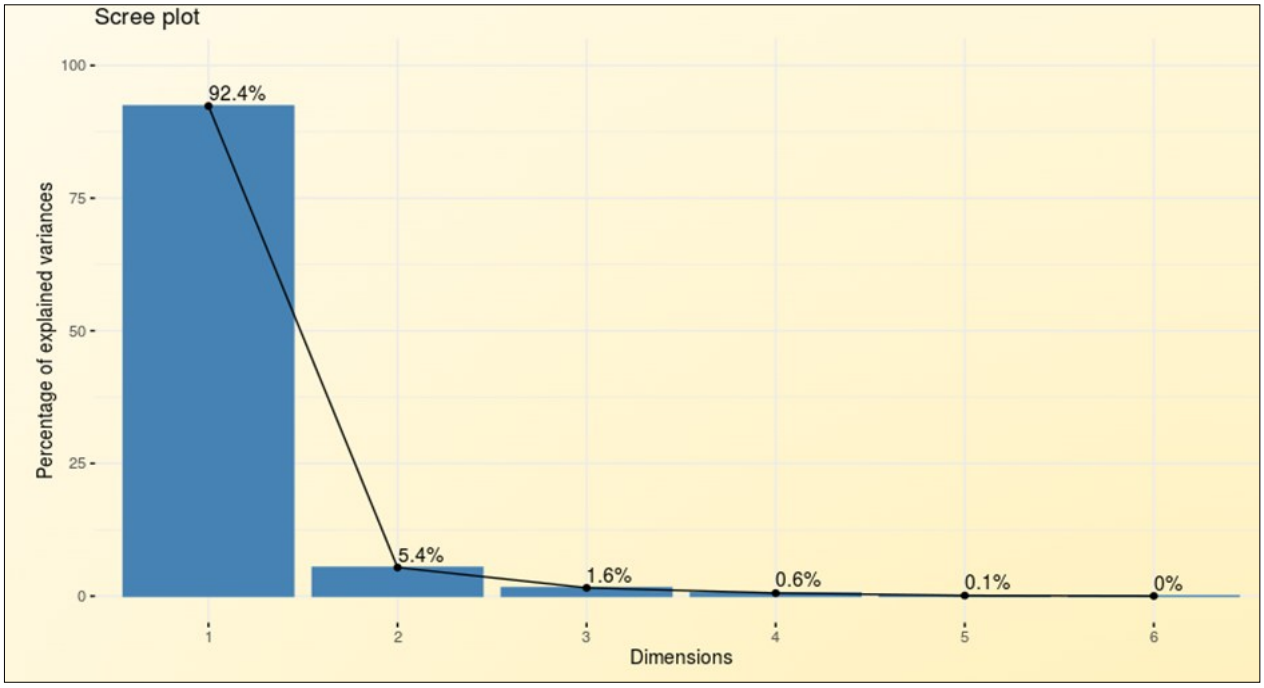

Fig. 1. Scree plot of variables of mean morphological and yield performance of finger millet under salinity stress

Table 7. Percent contribution of variables on principal components of mean morphological and yield performance of finger millet under salinity stress

Variables	PC1	PC2	PC3	PC4	PC5	PC6
Plant Height	9.412	21.992	7.002	2.103	1.044	1.507
No. of Tillers /Plant	9.758	2.163	50.01	15.039	5.441	9.147
No. of Fingers /Ear head	10.762	0.329	1.942	1.785	2.638	0.105
Length of Fingers	9.859	10.869	13.65	16.548	1.904	2.76
Ear Head Weight	9.976	10.244	11.839	0.557	44.062	0.351
Leaf Length	10.666	0.504	1.315	15.27	2.176	54.337
Root Length	9.359	23.383	3.868	1.763	20.33	16.133
Shoot Length	8.94	30.422	6.071	1.236	0.915	2.363
Grain Yield	10.65	0.062	3.505	15.049	16.533	11.851
Stover Yield	10.618	0.033	0.797	30.65	4.957	1.447

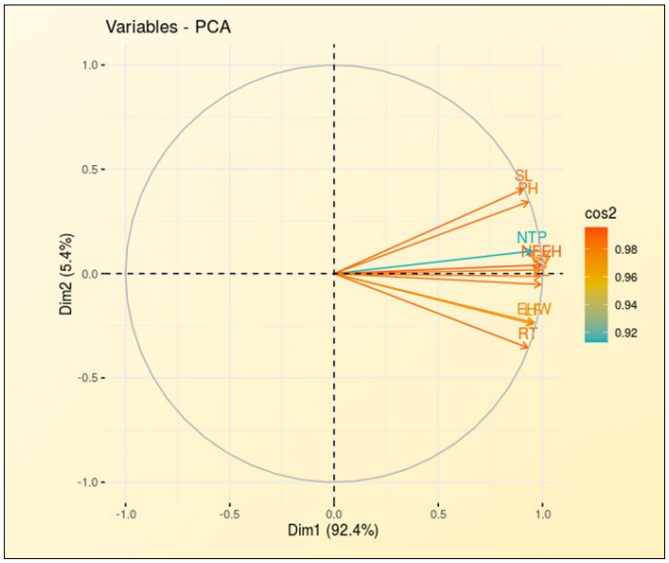

Fig. 2. Contribution of variables on principal component of mean morphological and yield performance of finger millet under salinity stress

Note: PH (Plant Height), NTP (No. of Tillers /Plant), NFEH (No. of Fingers /Ear head), LF (Length of Fingers), EHW (Ear Head Weight), LL (Leaf Length), RL (Root Length), SL (Shoot Length), GY (Grain Yield), SY (Stover Yield)

Mean biochemical performance of finger millet under salinity stress

Only one principal component (PC1) had an eigenvalue greater than 1, at 6.73, contributing 96.08% of the total variation (Table 8). A scree plot (Fig. 3) illustrates the percentage of variation explained by each principal component based on eigenvalues. The graph gradually decreased with decreasing eigenvalue with increasing principal components. The maximum contribution to the variance was due to PC1 (96.08%) followed by PC2 (3.09%). The PC1 showed the maximum contribution of variables on principal components with traits such as proline content, Chlorophyll a, b, total chlorophyll content, reducing sugar, non-reducing sugar and total sugar (Table 9) (Fig. 4). These results were in accordance with the PCA for biochemical attributes in mungbean (27).

Table 8. Eigen values of mean biochemical performance of finger millet under salinity stress

Principal component	Eigen value	Percentage of variance	Cumulative percentage of variance
PC1	6.73	96.08	96.08
PC2	0.22	3.09	99.17
PC3	0.051	0.73	99.90
PC4	0.007	0.098	99.996
PC5	0	0.004	100
PC6	0	0	100

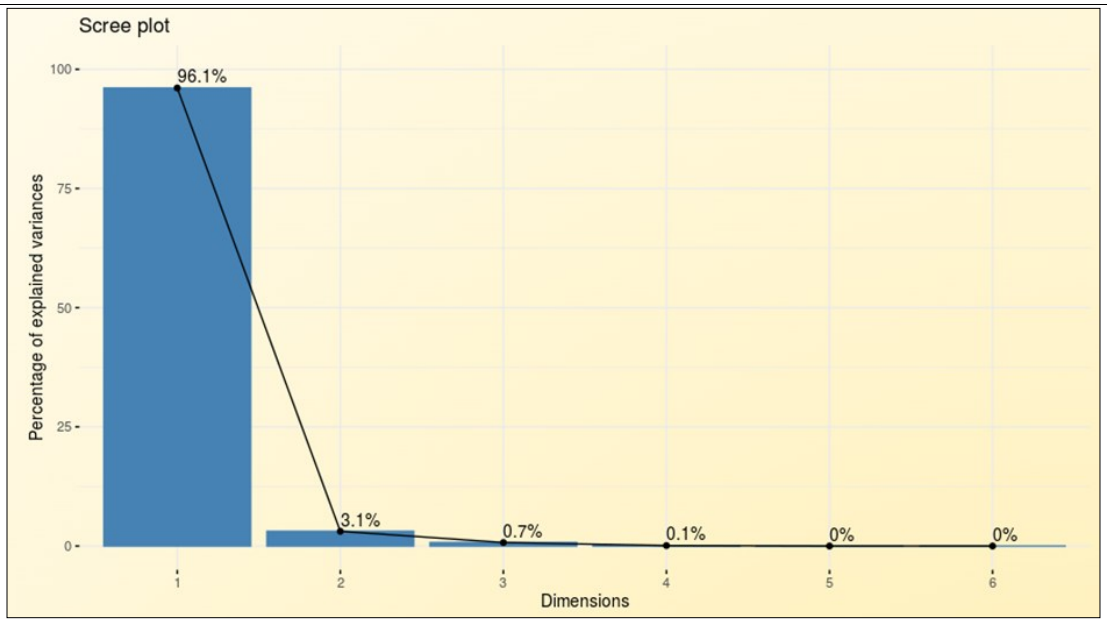

Fig. 3. Scree plot of variables of mean biochemical performance of finger millet under salinity stress

Table 9. Percent contribution of variables on principal components of mean biochemical performance of finger millet under salinity stress

Variables	PC1	PC2	PC3	PC4	PC5	PC6
Proline	12.941	51.972	33.703	1.373	0.012	0
Chlorophyll a	14.294	15.828	8.435	0.993	32.004	27.438
Chlorophyll b	14.582	8.318	1.897	2.407	65.559	6.98
Total chlorophyll	14.404	13.056	5.729	1.4	1.095	62.034
Reducing Sugar	14.414	7.891	22.79	27.011	0.948	0.956
Non Reducing Sugar	14.657	2.411	17.675	0.177	0.382	2.296
Total Sugar	14.709	0.524	9.771	66.64	0.001	0.296

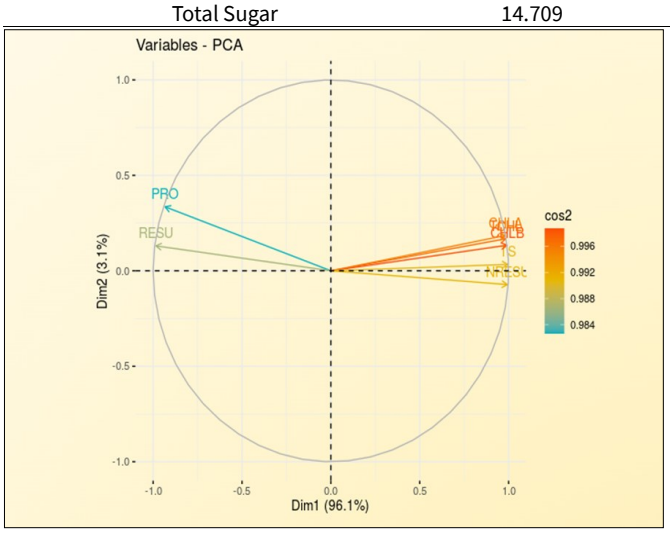

Fig. 4. Contribution of variables on principal component of mean biochemical performance of finger millet under salinity stress

Note: PRO (Proline), CHLA (Chlorophyll a), CHLB (Chlorophyll b), TC (Total chlorophyll), RESU (Reducing Sugar), NRESU (Non Reducing Sugar), TS (Total Sugar)

Conclusion

The findings indicated that the finger millet variety- TRY 1 is salt -tolerant, surviving salinity levels up to EC 12 dS/m, with growth promotion observed at mild salinity (EC 2 dS/m). Plant growth gradually decreased with increasing salinity levels beyond 6 dS/m, indicating the threshold at which salinity stress becomes detrimental. Similar growth patterns were observed in leaf, shoots and root length, along with a significant increase in grain and stover yield at moderate salinity levels. The plant exhibited increases in proline, chlorophyll and sugar content, indicating its physiological and biochemical adaptations to salt stress. As salinity increased beyond EC 2 dS/m, a decline in growth, yield and physiological parameters was observed, highlighting the detrimental effects of high salinity on biochemical and metabolic functions. Moderate salinity conditions enhance finger millet tolerance and yield, while higher salinity levels cause stress that significantly hampers growth and productivity.

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Authors' contributions

NM carried out the experiment, work plan, and methodology, took observations, analyzed the data and wrote the draft manuscript. MB carried out the work plan, conceptualization, providing funding acquisition, methodology and supervision and coordinated the work. SM contributed by imposing the experiment, laboratory analysis, reviewing and editing. SR helped in summarizing and revising the manuscript. VD Coordinated the work, methodology and editing. MN helped in editing, summarizing and revising the manuscript. RLM carried out the work plan and conceptualisation.

Compliance with ethical standards

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

Ethical issues: None

References

1. Desa UN. World population prospects, the 2017 Revision, Volume I: comprehensive tables. New York United Nations Department of Economic and Social Affairs; 2017.
2. Tester M, Langridge P. Breeding technologies to increase crop production in a changing world. Science. 2010;327(5967):818-22. https://doi.org/10.1126/science.1183700
3. Hussain MI, Al-Dakheel AJ. Using alternate water resources for cultivation of salt tolerant perennial grasses under marginal environment. TROPENTAG, Management of Land Use Systems for Enhanced Food Security-Conflicts, Controversies and Resolutions: Berlin, Germany. 2015;16:16-18.
4. Neocleous D, Ntatsi G, Savvas D. Physiological, nutritional and growth responses of melon (*Cucumis melo* L.) to a gradual salinity built-up in recirculating nutrient solution. J Plant Nutr. 2017;40 (15):2168-80. https://doi.org/10.1080/01904167.2017.1346673
5. Machado RMA, Serralheiro RP. Soil salinity: effect on vegetable crop growth. Management practices to prevent and mitigate soil salinization. Horticulturae. 2017;3(30):2-13. https://doi.org/10.3390/horticulturae3020030
6. Munns R, Passioura JB, Colmer TD, Byrt CS. Osmotic adjustment and energy limitations to plant growth in saline soil. New Phytol. 2020;225(3):1091-96. https://doi.org/10.1111/nph.15862
7. Kumar P, Sharma PK. Soil salinity and food security in India. Front Sustain Food syst. 2020;4:533781. https://doi.org/10.3389/fsufs.2020.533781
8. Krishnamurthy R, Bhagwat KA. Effect of NaCl on enzymes in salt-tolerant and salt-sensitive rice cultivars. Acta Agron Hung. 1995;43:51-57.
9. Mundada PS, Nikam TD, Kumar SA, Umdale SD, Ahire ML. Morpho-physiological and biochemical responses of finger millet (*Eleusine coracana* (L.) Gaertn.) genotypes to PEG-induced osmotic stress. Biocatal Agric Biotechnol. 2020;23:101488. https://doi.org/10.1016/j.bcab.2019.101488
10. Arnon D. Copper enzyme in isolated chloroplast and chlorophyll expressed in terms of mg per gram. Plant Physiol. 1949;24:1-15. https://doi.org/10.1104/pp.24.1.1
11. Bates LS, Waldren RP, Teare ID. Rapid determination of free proline for water-stress studies. Plant Soil. 1973;39:205-07. https://doi.org/10.1007/BF00018060
12. Riazi A, Matsuda K, Arslan A. Water-stress induced changes in concentrations of proline and other solutes in growing regions of young barley leaves. J Exp Bot. 1985;36(11):1716-25. https://doi.org/10.1093/jxb/36.11.1716
13. Sheoran OP, Tonk DS, Kaushik LS, Hasija RC, Pannu RS. Statistical software package for agricultural research workers. Recent Advances in Information Theory, Statistics and Computer Applications by DS Hooda and RC Hasija Department of Mathematics Statistics, CCS HAU, Hisar. 1998;8(12):139-43.
14. Priyanka B, Singh DP, Khulbe RK. Genetic variability and association analysis of advanced lines and cultivars following intervarietal and interspecific crosses in blackgram. Crop Improv. 2011;38(1):67-70.
15. Atzori G, Nissim WG, Caparrotta S, Masi E, Azzarello E, Pandolfi C, et al. Potential and constraints of different seawater and freshwater blends as growing media for three vegetable crops. Agric Water Manag. 2016;176:255-62. https://doi.org/10.1016/j.agwat.2016.06.016
16. Hegazi A. Effect of diluted seawater irrigation and exogenous proline treatments on growth, chemical composition and anatomical characteristics of *Conocarpus erectus* L. J Agric Res. 2010;36(4):420-46.
17. Javeed HM, Wang X, Ali M, Nawaz F, Qamar R, Rehman AU, et al. Potential utilization of diluted seawater for the cultivation of some summer vegetable crops: Physiological and nutritional implications. Agronomy. 2021;11(9):1826. https://doi.org/10.3390/agronomy11091826
18. Hegazi MA. Influence of soil type, sowing date and diluted seawater irrigation on seed germination, vegetation and chemical constituents of *Moringa oleifera* Lam. J Agric Sci. 2015;7(3):138. https://doi.org/10.5539/jas.v7n3p138
19. Turhan A, Kuscu H, Ozmen N, Sitki Serbeci M, Osman Demir A. Effect of different concentrations of diluted seawater on yield and quality of lettuce. Chil J Agr Res. 2014;74(1):111-16. https://doi.org/10.4067/S0718-58392014000100017
20. Makarana G, Kumar AS, Yadav RK, Kumar RA, Soni PG, Lata CH, Sheoran P. Effect of saline water irrigations on physiological, biochemical and yield attributes of dual purpose pearl millet (*Pennisetum glaucum*) varieties. Indian J Agric Sci. 2019; 89(4):624-33. https://doi.org/10.56093/ijas.v89i4.88847
21. Wani AS, Ahmad A, Hayat S, Tahir I. Is foliar spray of proline sufficient for mitigation of salt stress in *Brassica juncea* cultivars?. Environ Sci Pollute Res Int. 2016;23:13413-23. https://doi.org/10.1007/s11356-016-6533-4
22. Gao Z, Sagi M, Lips SH. Carbohydrate metabolism in leaves and assimilate partitioning in fruits of tomato (*Lycopersicon esculentum* L.) as affected by salinity. Plant Sci. 1998;135(2):149-59. https://doi.org/10.1016/S0168-9452(98)00085-5
23. Mukami A, Ng'etich A, Syombua E, Oduor R, Mbinda W. Varietal differences in physiological and biochemical responses to salinity stress in six finger millet plants. Physiol Mol Biol Plants. 2020;26:1569-82. https://doi.org/10.1007/s12298-020-00853-8
24. Tahjib-UI-Arif M, Sohag AA, Afrin S, Bashar KK, Afrin T, Mahamud AS, et al. Differential response of sugar beet to long-term mild to severe salinity in a soil-pot culture. Agriculture. 2019;9(10):223. https://doi.org/10.3390/agriculture9100223
25. Mirunalini SP, Ganga M, Rajamani K, Meenakumari B, Suganthy M, Boopathi NM. Phenotypic characterization and genetic variability, genetic diversity of elite mutants of *Jasminum auriculatum* Vahl and induction of homeotic mutants. Plant Sci Today. 2024; 11(3):142-51. https://doi.org/10.14719/pst.3523
26. Mahadik S, Belur Satyan K. Morpho-physiological and biochemical variations in finger millet genotypes under induced salinity stress at seedling stage. Cereal Res Commun. 2023;21:1-9. https://doi.org/10.1007/s42976-023-00441-y
27. Ogunsiji E, Umebese C, Stabentheiner E, Iwuala E, Odjegba V, Oluwajobi A. Salicylic acid enhances growth, photosynthetic performance and antioxidant defense activity under salt stress in two mungbean [*Vigna radiata* (L.) R. Wilczek] variety. Plant Signal Behav. 2023;18(1):2217605. https://doi.org/10.1080/15592324.2023.2217605