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Research article

Metabolic and Developmental Adaptations Conferring Salt Stress Tolerance in Tomato (*Solanum lycopersicum* L.) Varieties

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ABSTRACT

Tomato (*Solanum lycopersicum* L.) is an economically and nutritionally important vegetable crop in Bangladesh, but its productivity is severely constrained by soil salt stress in coastal regions. This study evaluated the physiological and biochemical responses of two tomato varieties, BARI Tomato 14 and BARI Tomato 21, under varying salt stress levels to identify potential salt-tolerant varieties. Seeds were subjected to five salt stress treatments (0, 3, 6, 9, and 12 dS m^{-1}) during germination, and three levels (0, 3, and 6 dS m^{-1}) at the vegetative stage under controlled condition following completely randomized design. Salinity markedly reduced germination percentage, root length, shoot length, biomass, moisture content, and vigor index. However, a mild stimulatory effect was observed at 3 dS m^{-1}, where BARI Tomato 21 achieved the highest germination (93.3%) and vigor index (1345.3), compared to BARI Tomato 14 (86.7% and 913.1, respectively). At the vegetative stage, salt stress induced a marked increase in proline (up to 51.4 mg 100 g^{-1} fresh leaf) and total soluble sugars (up to 2.92 g 100 g^{-1} fresh leaf), with BARI Tomato 21 accumulating greater levels than BARI Tomato 14, suggesting better osmotic adjustment capacity. In contrast, chlorophyll contents were decreased markedly with increasing salt stress, though BARI Tomato 14 maintained slightly greater chlorophyll retention. Overall, BARI Tomato 21 demonstrated superior tolerance to salt stress through enhanced osmoprotectant accumulation, improved vigor, and sustained biomass production, making it more suitable for cultivation in moderately salt-affected coastal soils. These findings provide valuable insights for breeding and management strategies aimed at improving tomato resilience in saline environments.

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Introduction

Soil salt stress is one of the most significant abiotic stresses that severely hamper crop development and productivity worldwide as well as in Bangladesh (Sikder et al., 2016; Kumar et al., 2018). With increasing climate change, salt stress has become a major agricultural challenge, especially in arid and semi-arid regions (Jodder et al., 2016; Haque and Hoque, 2023; Haque et al., 2025a). Globally, over 800 million hectares of land and about 1-million-hectare area in Bangladesh are affected by salt stress, posing a serious threat to food security and sustainable crop production (Munns & Tester, 2008). Salinity primarily hampers plant development through osmotic stress, nutrient imbalance, specific ion toxicity, and oxidative damage (Haque, 2018; Khanam et al., 2020). All those factors negatively impacted on plant development through hampering physiological and metabolic activities (Ashraf and Harris, 2004; Munns et al., 2003). Among many physiological and metabolic processes influenced by salt stress, changes in metabolic composition such as the accumulation of compatible metabolites is considered critical indicators of plant tolerance (Zhu, 2001; Jharna et al., 2001; Akter et al., 2020).

The tidal water inundation in Kharif (June-October) season and severe salt stress in Rabi (December-May) season are the common character of the coastal area of the

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Ganges delta in Bangladesh (Haque et al., 2023a). The reduction of upstream fresh water flow and concomitant soil salinization, along with underground water salinization are the major threat for crop production in the region (Haque et al., 2008). About 53% of the country's coastal areas are affected by salt stress. The combined effect of salt stress and excessive tidal water flooding is the main reason for lower crop coverage compare to other region of the country (Sume et al., 2023; Haque et al., 2023b, 2024a).

Tomatoes (*Solanum lycopersicum* L.), the scrambling high value vegetable crop, widely grown more than one hundred fifty countries over the world. Tomato is rich in vitamin C, carotenoids, vitamin E, proteins, and essential amino acids (Ibrahim et al., 2022). It is one of the most economically and nutritionally important vegetable crops, grown across diverse agro-climatic regions, moderately sensitive to salt stress, particularly in the germination and seedling stages. Exposure to salt stress can drastically reduce tomato yield by affecting physiological functions, including photosynthesis, water uptake, and nutrient assimilation (Cuartero and Fernández-Muñoz, 1999). One of the most noticeable effects of salt stress in tomato plants is the alteration of metabolic contents, such as soluble sugars, proline, chlorophyll, proteins, and antioxidant enzymes. These metabolic reactions are not only markers of salt stress but also act as protective mechanisms helping the plant to cope with adverse conditions (Jharna et al., 2013, 2014, 2017).

Different tomato varieties exhibit varying degrees of salt tolerance, largely due to their differential ability to accumulate and regulate metabolic constituents under stress. The accumulation of osmoprotectants like proline and soluble sugars under salt stress helps maintain cell turgor and protects cellular structures (Billah et al., 2017; Dutta et al., 2025). In recent years, the study of salt-induced metabolic changes in crops have gained increasing attraction, due to their important role on stress tolerance mechanism and aids in the screening and develop salt resilient cultivars. In Bangladesh context, where coastal regions like Patuakhali are frequently affected by soil salt stress, it becomes imperative to understand how different tomato varieties respond to the metabolic level. Identifying tolerant varieties based on their metabolic reactions could contribute markedly to the development of salt-resilient tomato varieties (Rahman et al., 2016). The varietal performance under saline conditions particularly in the southern coastal regions of Bangladesh remains inadequately studied. This gap in the existing body of research underlines the significance of the present study, which seeks to evaluate the salt stress tolerance of the varieties in such environments.

Therefore, the study aimed to evaluate physiological and biochemical responses to salt stress in two tomato varieties to identify potential tolerance mechanisms. The research seeks to identify potential markers of salt stress tolerance by analyzing changes in key metabolic constituents under controlled salt stress treatments. This study will not only enhance our understanding of the metabolic basis of salt stress tolerance in tomatoes but also support future breeding programs aimed at improving salt stress resilience in the coastal ecosystem.

Materials and Methods

Salinity induced changes in tomato plant with respect to agronomical and metabolic parameters were monitored at the germination, and vegetative stages. The experiment on germination was conducted at the laboratory of the Department of Biochemistry and Molecular Biology of Patuakhali Science and Technology University (PSTU), Patuakhali, Bangladesh. The vegetative stage experiment was done in the net house of PSTU, Patuakhali. The chemical analysis of plant samples was performed in the same department of PSTU. Seeds of 2 tomato varieties was collected from Regional Horticulture Research Centre, Patuakhali and used in the experiments.

Salt Stress Induced Changes in Tomato Varieties at Germination Stage

Two tomato varieties namely BARI Tomato 14 and BARI Tomato 21 were tested in the study. Both the varieties are high-yielding hybrid variety developed by the Bangladesh Agricultural Research Institute (BARI) as part of its initiative to enhance tomato production through varietal improvement.

The experiment had five salt stress levels viz. 0, 3, 6, 9 and 12 dS m^{-1}. The 8-12 dS m^{-1} salinity level was considered as moderately saline soil (FRG 2024). All the salt stress levels were applied in two tomato varieties with three replications following completely randomized design. The germination experiment was done in 15 cm diameter petri dishes. Two filter papers were placed in the bottom of each petri dish. Total twenty-five healthy seeds were sown on each petri dish. Ten milliliter of each salt solution was poured into each petri dish so that all the seeds were immersed partially. Proper lighting was maintained. The day temperature was 25±2°C while night temperature was 18±2°C. Upon drying of the filter papers distilled water was sprayed on it to keep them moist like initial.

Data on germination percentage was determined through counting the number of germinated seeds after 5 days of sowing and the results was converted into percentage as follows:

$$Germination\ (\%) = \frac{Number\ of\ seeds\ germinate}{\text{Total number of seeds set for test}} \times 100$$

The development data were recorded ten days after seed placement in the petri dishes. Shoot and root length data were recorded from randomly selected five seedlings using centimeter scale. Biomass fresh weight was noted by weighing the mass of roots and shoots in grams taking ten randomly selected seedlings from each Petri dish. For determining moisture content ten randomly selected seedlings were oven dried at 65°C for 48 hours and weighing those using sensitive balance and the average data was recorded from three replicates. The biomass weight data were reported on dry weight basis. Moisture content was calculated using following equation:

$$Moisture\ (\%) = \frac{Weight\ of\ original\ sample - Weight\ of\ dried\ sample}{Weight\ of\ original\ sample} \times 100$$

The vigor index was computed using the following formula (Abdul-Baki and Anderson (1973):

VI= Germination% × (Root length in cm + Shoot length in cm).

Effects of salt stress on tomato varieties at vegetative stage

Same tomato varieties were also used for vegetative experiment, conducted in the net-house with ambient air temperature and light conditions. The soil (3kg) was placed into pots and salinized with NaCl solution treatments at the rates of 0, 3 and 6 dS m^{-1}. The treatments were replicated three times using completely randomized design. Salt solutions were prepared earlier and applied to the pots as irrigation water to saturate the soils. The control was maintained by applying fresh water for irrigation. For every treatment same amount of respective saline water was added. For basal fertilizers 100mg N kg^{-1} as urea and 80mg P kg^{-1} as triple super phosphate and 100 mg K kg^{-1} soil as muriate of potash was added in the pots. Six tomato seeds were sown into each pot, and were thinned out to four after complete emergence. Forty days after seed sowing the plant height data were recorded. The leaves were sampled separately for metabolic analysis.

The total sugar content in the fresh leaf sample was determined following anthrone method (Dubois et al., 1956); while proline content was detected following sulfosalicylic acid extraction method (Bates et al., 1973). The chlorophyll content in leaves was determined using acetone (Coombs et al., 1985).

The percent decrease of any specific agronomic parameter due to salt stress was calculated using below formula:

$$\%Decrease = \frac{Traits\ of\ control\ treatment - Traits\ of\ salinized\ treatment}{Traits\ of\ control\ treatment} \times 100$$

The percent increase of some metabolic parameters like total sugar and proline was calculated using the below formula.

$$\%Increase = \frac{Traits of\ salinized treatment - Traits of\ control treatment}{Traits of\ control treatment} \times 100$$

Statistical analysis

Data analysis of different parameters was done following ‘Statistical Tool for Agricultural Research, STAR’ software using the principle of completely randomized design. The ANOVA was constructed using three replicated data. The significance level of varieties and salinity levels and their interactions have been given in different tables. The mean separation test was done at 5% significance level by Duncan’s Multiple Range Test (DMRT).

Results

Salinity induced changes in tomato varieties at germination stage

Effect on germination percentage

Considering single effect of salt stress, the germination percentage ranged from 32.5 – 90.2% over the salt stress levels; the highest germination percentage was found in 3 dS m^{-1} and lowest was in 9 dS m^{-1} saline water irrigation treatments (Table 1). Regarding single effect of variety, highest (78.3%) germination was found in BARI Tomato 21 genotype, and 55.9% was found in BARI Tomato 14. Regarding interaction effect the highest (93.3%) germination percentage was noted in the BARI Tomato 21 variety with 3 dS m^{-1} salt stress, and the lowest (8.00%) was recorded in treatment combination of BARI Tomato 14 with 9 dS m^{-1} salt stress. At 12 dSm^{-1} salt stress none of the varieties were germinated.

In case of percent decrease over control, the germination percentage of the treatment combination of BARI Tomato 14 variety and BARI Tomato 21 at 3 dS m^{-1} salt stress had the best performance. In this study, 9 dS m^{-1} salt stress recorded the lowest (34.2%) decrease in germination over control in variety BARI Tomato 21, whereas highest (89.8%) decrease was in BARI Tomato 14 (Fig. 1). At 12 dS m^{-1} salt stress, both the variety fail to germinate, suggesting that tomato varieties cannot tolerate this level of salt stress. So, based on germination percentage the variety BARI Tomato 21 was markedly better salt tolerant than BARI Tomato 14. Increased salt stress levels markedly reduce the germination percentage, however, greater germination in 3 dSm^{-1} salt stress compared to salt stress control (0 dS m^{-1}) was happened because sodium in reduced concentration act as a plant nutrient.

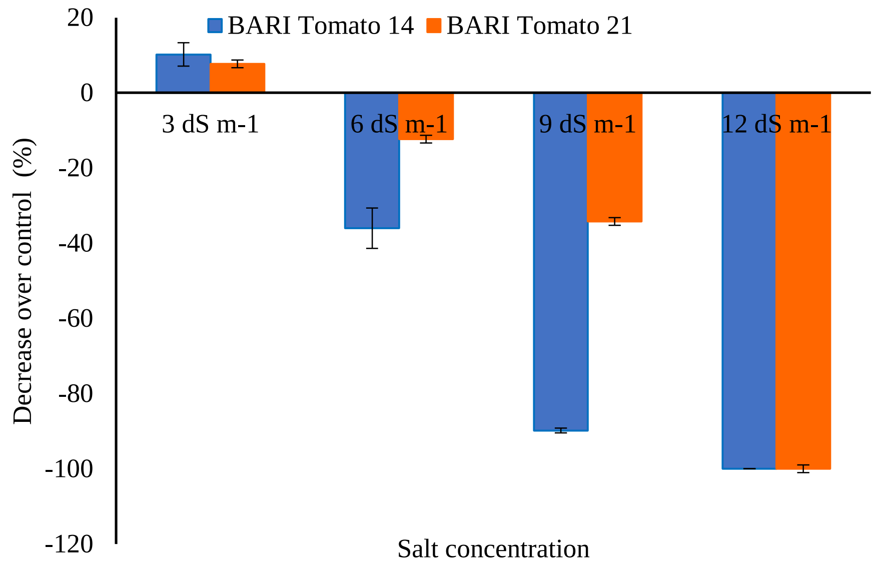

Figure 1: Germination percentage decrease over control (%).Vertical bar indicates standard error of means

Effect on shoot length

The shoot length of tomato varieties markedly ($P<0.001$) influenced due to different level of salt stress and variety, and the interaction between salt stress and variety (Table 1). Considering single effect of salt stress, the shoot length ranged from 2.59 cm to 3.83 cm, and single effect of variety varied from 2.44 cm to 3.97 cm. In the present study the highest shoot length was observed in 3 dS m^{-1} salt stress. Shoot length decreased gradually due to increased salt concentration. Therefore, the lowest shoot length was found in 9 dS m^{-1} salt stress. Regarding single effect of variety highest shoot length of 3.97 cm was found in BARI Tomato 21 variety, and the lowest of 2.44 cm was found in BARI Tomato 14. Regarding interaction effect it was found that BARI Tomato 21 increased shoot length even increasing salt concentration up to 9 dS m^{-1}; unfortunately BARI Tomato 14 was found highly sensitive to salt stress as this parameter drastically.

Effect on root length

Over the salt concentrations the root length ranged from 4.01 cm to 8.61 cm. The highest root length was noted in 3 dS m^{-1} salt stress and lowest in 6 dS m^{-1} salt stress (Table 1). Considering single effect of variety, BARI Tomato 21 recorded the highest root length of 8.17 cm, and BARI Tomato 14 had the least of 3.96 cm. Based on interaction effect BARI Tomato 14 showed the highest root length at 3 dS m^{-1} (7.00 cm), followed by 0 dS m^{-1} (5.29 cm), with a sharp decline at greater salt stress levels (1.90 cm at 6 dS m^{-1}, 1.67 cm at 9 dS m^{-1}). BARI Tomato 21 exhibited greater salt tolerance, maintaining high root length at 3 dSm^{-1} (10.23 cm) and 0 dS m^{-1} (9.18 cm), with slight reductions at 6 dS m^{-1} (6.12 cm) and 9 dSm^{-1} (7.15 cm).

Table 1: Single and interaction effect of salt stress and variety on germination percentage, and root and shoot length of tomato at germination stage

Salt concentration	Tomato varieties: BARI Tomato 14	Tomato varieties: BARI Tomato 21	Salt concentration mean
Germination percentage (%)			
0 dSm^{-1}	78.7 B b	86.7 A a	82.7
3 dSm^{-1}	86.7A a	93.3 A a	90.2
6 dSm^{-1}	50.3 B c	76.0 A b	63,2
9 dSm^{-1}	8.00 B d	57.0 A c	32.5
12 dSm^{-1}	0	0	
Variety mean	55.9	78.3	
*Significance level: Variety-***, Salinity-*** and interaction-***; Standard error (±): Variety-1.77, Salinity-2.50 and interaction-3.53, %CV- 6.45; LSD- 7.48*			
Shoot length (cm)			
0 dSm^{-1}	3.37 A a	3.69 A b	3.53
3 dSm^{-1}	3.53 B a	4.14 A ab	3.83
6 dSm^{-1}	1.92 B b	3.83 A ab	2.87
9 dSm^{-1}	0.95 B c	4.24 A a	2.59
12 dSm^{-1}	0	0	
Variety mean	2.44	3.97	
*Significance level: Variety-***, Salinity-*** and interaction-***; Standard error (±): Variety-0.12, Salinity-0.17 and interaction-0.24; %CV- 9.39 ; LSD- 0.5217*			
Root length (cm)			
0 dSm^{-1}	5.29 B b	9.18 A b	7.23
3 dSm^{-1}	7.00 B a	10.23 A a	8.61
6 dSm^{-1}	1.90 B c	6.12 A c	4.01
9 dSm^{-1}	1.67 B c	7.15 A c	4.41
12 dSm^{-1}	0	0	
Variety mean	3.96	8.17	
*Significance level: Variety-***, Salinity-*** and interaction-*; Standard error (±): Variety-0.24, Salinity-0.34 and interaction-0.48; %CV- 9.83; LSD- 1.03*			

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*CV= Co-efficient of variation, *=Significant at 5.0% level, ***=Significant at 0.1% level*

Effects on biomass weight

The total biomass (root + shoot) weight of tomato at germination stage reduced markedly (P<0.001) due to the single effect of salt stress and it also varied markedly (P<0.001) among the varieties (Table 2). Slightly increasing concentration of salt stress (3 dS m^{-1}) increases the biomass weight of tomato seedling then it decreased gradually. When salt stress was not imposed (control condition) the total biomass weight was found as 0.224 g 10-seedlings^{-1}, which reduced to 0.219 g 10-seedlings^{-1} at 9 dS m^{-1} salt stress. Among the varieties BARI Tomato 21 variety had the highest mean biomass weight of 0.262 g 10-seedlings^{-1}, while BARI Tomato 14 had 0.237 g 10-seedlings^{-1}. The interaction effect was not significant.

Effects on moisture content (MC)

The moisture content was markedly (P<0.001) varied due to salt stress and variety and their interaction (Table 2). Over the levels of salt stress, the MC varied from 91.8 to 93.6%; on the other hand among varieties highest %MC was (93.6%) found in BARI Tomato 21, and the variety BARI Tomato 14 had the lowest moisture content (92.1%). Considering the interaction between salt stress and variety the BARI Tomato 21 had the best performance to retain moisture even in high saline condition. Unfortunately, due to less capacity against osmotic effect the BARI tomato 14 had the lowest moisture content.

Effects on vigor index

The vigor index reduced markedly (P<0.001) due to salt stress; with the increase of the slightly concentration of salt it is increased then reduced rapidly (Table 2). Vigor index varied with a wide range from 354.9 to 1129.2 over the salt levels, with highest was found in slightly salt level (3 dS m^{-1}), and lowest was in 9 dS m^{-1} salt stress. Among the tested varieties, BARI Tomato 21 had greater vigor index (974.1) than BARI Tomato 14 (452.0). When interaction effect was considered the BARI Tomato 21 variety along with different levels of salt stress recorded the greater vigor index (1117.5, 1345.3, 756.1, 677.6, and 0 in 0, 3, 6, 9 and 12 dS m^{-1} salt stress, respectively) compared to BARI Tomato 14. In addition BARI Tomato 14 had greater decrease in vigor index than BARI Tomato 21 (Figure 2).

Table 2: Single and interaction effect of salt stress and variety on biomass weight, moisture content and vigor index of tomato at germination stage

Salt concentration	Tomato varieties: BARI Tomato 14	Tomato varieties: BARI Tomato 21	Salt concentration mean
Biomass weight (g10-seedlings^{-1})			
0 dSm^{-1}	0.216	0.232	0.224 b
3 dSm^{-1}	0.299	0.327	0.313 a
6 dSm^{-1}	0.224	0.265	0.244 b
9 dSm^{-1}	0.211	0.227	0.219 b
12 dSm^{-1}	0	0	
Variety mean	0.237	0.262	
Significance level: Variety-***, Salinity-*** and interaction-ns; %CV- 12.70; Standard error (±): Variety-0.013, Salinity-0.018 and interaction-0.026			
Moisture content (%)			
0 dSm^{-1}	93.9 A a	93.2 A a	93.6
3 dSm^{-1}	92.6 A a	93.7 A a	93.2
6 dSm^{-1}	91.9 A a	93.8 A a	92.9
9 dSm^{-1}	89.7 B b	93.9 A a	91.8
12 dSm^{-1}	0	0	
Variety mean	92.1	93.6	
Significance level: Variety-**, Salinity-ns , and interaction-*; %CV- 1.31; Standard error (±): Variety-0.49, Salinity-0.70 and interaction-0.99			
Vigor index			
0 dSm^{-1}	679.4 B b	1117.5 A b	898.5
3 dSm^{-1}	913.1 B a	1345.3 A a	1129.2
6 dSm^{-1}	183.3 B c	756.1 A c	469.7
9 dSm^{-1}	32.4 B d	677.6 A d	354.9
12 dSm^{-1}	0	0	
Variety mean	452.0	974.1	
Significance level: Variety-***, Salinity-*** and interaction-***; %CV- 2.76; Standard error (±): Variety-8.04, Salinity-11.3 and interaction-16.1			

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*CV= Co-efficient of variation, *=Significant at 5.0% level, **=Significant at 1.0% level,*
****=Significant at 0.1% level, ns= Not significant*

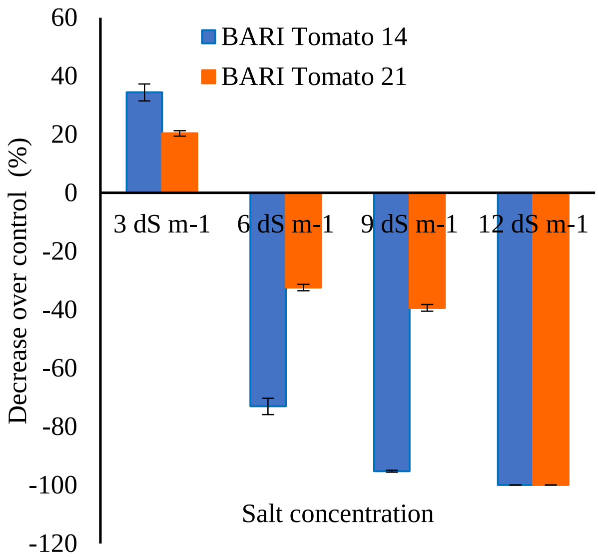

Figure 2: Vigor index decrease over control (%).Vertical bar indicates standard error of means

Salinity induced changes in tomato varieties at vegetative stage

Effects on plant height

Two tomato varieties (BARI Tomato 14 and BARI Tomato 21) along with three salt concentrations control, 3 and 6 dS m^{-1} were tested in the vegetative stage. The plant height of tomato varieties at vegetative stage markedly (P<0.001) affected due to both salt stress and variety (Table 3). Considering single effect of salt stress, the plant height varied from 115.8 cm to 125.5 cm over the salt concentrations. The highest and lowest plant height was recorded in 3 dS m^{-1} and 6 dS m^{-1} salt stress, respectively. Regarding single effect of variety, the highest plant height (132.4 cm) was found in BARI Tomato 21 variety and lowest plant height was found in BARI Tomato 14.

Table 3: Single and interaction effect of salt stress and variety on plant height (cm) of tomato at vegetative stage

Salt concentration	**Tomato varieties**		**Salt concentration mean**
	BARI Tomato 14	**BARI Tomato 21**	
0 dSm^{-1}	110.0	133.8	121.9 a
3 dSm^{-1}	114.2	136.8	125.5 a
6 dSm^{-1}	104.8	126.7	115.8 b
Variety mean	109.7 B	132.4 A	

Significance level: Variety-***, Salinity-* and interaction-ns; %CV- 4.01; Standard error (±): Variety-2.29, Salinity-2.80 and interaction-3.96

Similar capital letters in a row or similar small letters in a column are not markedly different at 5% level by DMRT
*CV= Co-efficient of variation, *=Significant at 5.0% level, ***=Significant at 0.1% level, ns= Not significant*

Effects on total sugar content

Increasing concentration of salt gradually decreased the total sugar content in leaf (P<0.01). At 0 dS m^{-1} salt stress total sugar content was 2.56 g 100g^{-1} fresh leaf; which increased to 2.63 in 3 dS m^{-1} salt stress level and 2.92 in 6 dS m^{-1} salt stress (Table 4). Among the tested varieties, BARI Tomato 21 variety had the highest total sugar of 2.74 and BARI Tomato 14 variety recorded mean of 2.66 respectively. The percent increase of total sugar content due to salt stress stress has been shown in Fig. 3a.

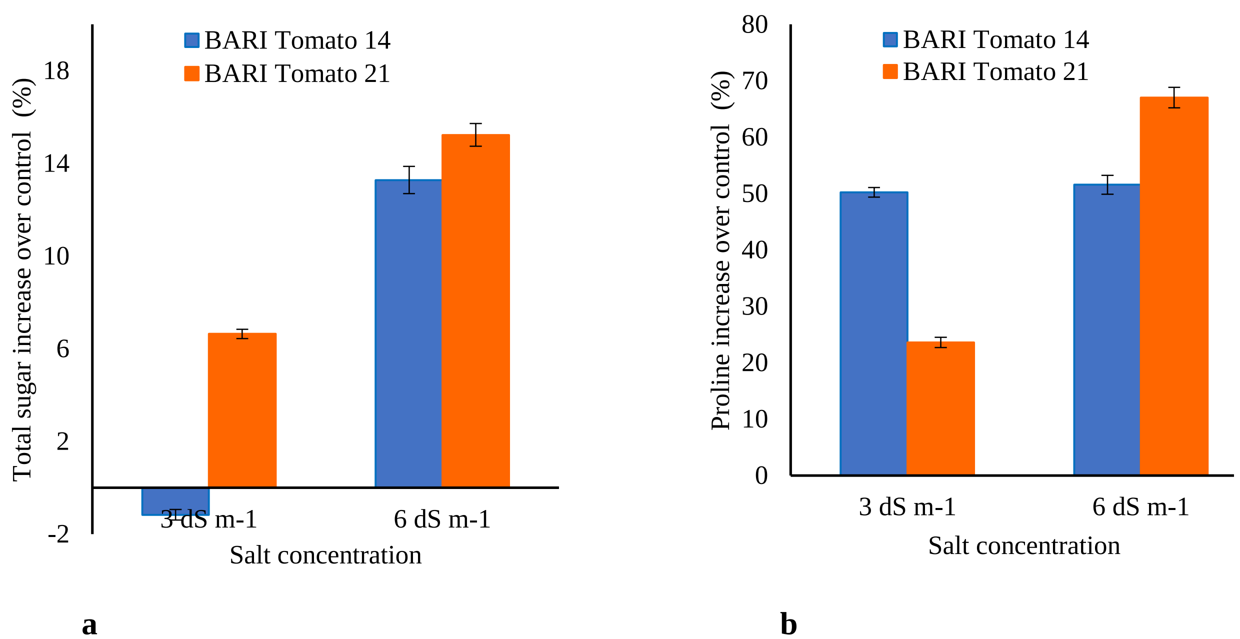

Figure 3: Percent increase of total sugar content (a) and proline (b) due to salt stress over control. Vertical bar indicates standard error of means

Effects on proline content

Proline content deviated from 29.81 to 50.45 mg $100g^{-1}$ fresh leaf over the salt stress levels. Proline content progressively increased with increasing salt stress, highest being in 6 dS m^{-1} salt stress condition. The varietal difference for proline accumulation was not significant. Considering interaction effect both the varieties consistently increases proline content with increasing salt concentration (P<0.001). The highest proline of 51.39 mg $100g^{-1}$ fresh leaf was observed in BARI Tomato 21 with 6 dS m^{-1} salt stess, whereas lowest of 28.86 mg $100g^{-1}$ fresh leaf was noted in BARI tomato14 with salt stress control condition. The extent of increase of proline content was greater in BARI Tomato 21 compare to BARI Tomato 14 (Fig. 3b).

Effects on chlorophyll-a content

The chlorophyll-a content of fresh leaf of tomato varieties at vegetative stage was markedly (P<0.001) influenced by single effect of salt stress, variety and their interaction effect (Table 5).

Table 5: Single and interaction effect of salt stress and variety on chlorophyll content of tomato leaves at vegetative stage

Salt concentration	Tomato varieties		Salt concentration mean
	BARI Tomato 14	BARI Tomato 21	
Chlorophyll-a content			
0 dSm^{-1}	2.39 A a	2.26 A a	2.32
3 dSm^{-1}	2.07 A b	1.60 B b	1.83
6 dSm^{-1}	1.73 A c	1.27 B c	1.50
Variety mean	2.06	1.71	
Significance level: Variety-***, Salinity-*** and interaction-**; %CV- 4.27; Standard error (±): Variety-0.038, Salinity-0.046 and interaction-0.066			
Chlorophyll-b content			
0 dSm^{-1}	0.49	0.42	0.45 a
3 dSm^{-1}	0.36	0.33	0.34 b
6 dSm^{-1}	0.32	0.30	0.31 b
Variety mean	0.39	0.35	
Significance level: Variety-ns, Salinity-** and interaction-ns; %CV- 17.13; Standard error (±): Variety-0.032, Salinity-0.039 and interaction-0.055			
Total chlorophyll content			
0 dSm^{-1}	2.84 A a	2.73 A a	2.78
3 dSm^{-1}	2.45 A b	1.93 B b	2.16
6 dSm^{-1}	2.07 A c	1.57 B c	1.82
Variety mean	2.34	2.07	
Significance level: Variety-***, Salinity-*** and interaction-*; %CV- 6.03; Standard error (±): Variety-0.064, Salinity-0.078 and interaction-0.111			

Similar capital letters in a row or similar small letters in a column are not markedly different at 5% level by DMRT

*CV= Co-efficient of variation, *=Significant at 5.0% level, **=Significant at 1.0% level,*
****=Significant at 0.1% level, ns= Not significant*

The greater chlorophyll-a content of 2.32 mg g^{-1} fresh leaf was recorded in non-saline condition which decreased gradually with increasing salt stress. The 3 and 6 dSm^{-1} salt concentration recorded leaf chlorophyll-a content as 1.83 and 1.50 mg g^{-1} fresh leaf, respectively. Among the varieties, BARI tomato14 had the markedly higher chlorophyll-a content (2.06 mg g^{-1} fresh leaf). The lowest chlorophyll-a content was found in BARI Tomato 21 (1.71 mg g^{-1} fresh leaf). Considering interaction effect over the salt concentrations BARI tomato14 variety had the best performance to accumulate chlorophyll-a in leaf.

Effects on chlorophyll-b

Like chlorophyll-a content, chlorophyll-b content of leaf of tomato varieties markedly (P<0.001) influenced by the tested treatments. In absence of salt stress (0 dSm-1) the mean chlorophyll-b content was appeared as 0.45 mg g^{-1} (Table 5). Chlorophyll-b content gradually decreased with increasing salt stress; as such 3 and 6 dS m^{-1} salt stress gave chlorophyll-b content of 0.34 and 0.31 mg g^{-1} fresh leaf, respectively.

Effects on total chlorophyll

The total chlorophyll content of fresh leaf of tomato varieties at vegetative stage was markedly (P<0.001) influenced by single effect of salt stress, variety and their interactions (Table 5). The greater total chlorophyll content of 2.78 mg g^{-1} fresh leaf was recorded in non-saline condition which gradually decreased with the increasing salt stress. The 3 and 6 dS m^{-1} salt concentration recorded leaf total chlorophyll content as 2.16 and 1.82 mg g^{-1} fresh leaf, respectively. Among the varieties BARI Tomato14 variety had the markedly greater total chlorophyll content (2.34 mg g^{-1} fresh leaf) while the value for BARI Tomato 21 was 2.07. When interaction effect was considered the 0 dSm^{-1} salt stress across the BARI tomato14 variety had the highest total chlorophyll content (2.45 mg g^{-1}) than other variety.

Correlation among different plant parameters

Plant height was negatively correlated will all the tested biochemical parameters although the extent was not significant. The biochemical parameters were highly influenced by each other. The total chlorophyll content was significantly correlated with total sugar content and proline content of tomato leaf (Table 6). Increasing total sugar and proline content reduced the chlorophyll a, chlorophyll b and total chlorophyll content. The total sugar content had a very highly significant positive relation with proline content, indicating that increasing total sugar content also significantly increase the proline content of tomato.

Table 6: Correlation between different growth and biochemical parameters

	Plant height	Chloro phyll a	Chloro phyll b	Total chl.	Total sugar
Plant height	1.00				
Chlorophyll a	-0.24	1.00			
Chlorophyll b	0.03	0.76***	1.00		
Total chl.	-0.20	0.99***	0.83***	1.00	
Total sugar	-0.05	-0.83***	-0.63**	-0.83***	1.00
Proline	-0.21	-0.79***	-0.62**	-0.79***	0.78***

***=Significant at 1.0% level, ***=Significant at 0.1% level*

Discussion

Salinity stress is one of the most critical abiotic factors limiting tomato development and productivity, particularly in the coastal regions of Bangladesh where salt intrusion has intensified due to climate change and reduced freshwater availability (Sultana et al., 2021; Haque et al., 2024b). In the present study, two tomato varieties—BARI Tomato 14 and BARI Tomato 21-were evaluated at both germination and vegetative stages under graded saline water irrigation treatments. The results revealed distinct varietal differences in physiological and metabolic reactions, demonstrating that BARI Tomato 21 exhibited greater tolerance compared to BARI Tomato 14.

Germination percentage, root length, shoot length, biomass, and vigor index were markedly affected by saline water irrigation treatments. A slight stimulatory effect was observed at 3 dS m^{-1}, whereas germination was drastically reduced beyond 6 dS m^{-1}, and completely inhibited at 12 dS m^{-1}. Among the two varieties, BARI Tomato 21 maintained a greater germination rate (78.3%) compared to BARI Tomato 14 (55.9%), suggesting superior salt tolerance during the early development stage. This trend aligns with previous reports where low levels of salt stress enhanced seed metabolic activity, possibly due to osmotic priming effects of Na^+ ions, and act as a plant nutrient like table salt for human consumption (Shila et al. 2016; Ahmed et al. 2017). But greater salt stress levels impaired water uptake and enzymatic activities essential for germination (Demir & Mavi, 2008; Akter et al., 2021). Similar findings were reported by Rahman et al. (2016), who observed genotype-specific tolerance to salt stress in tomato, where tolerant lines showed markedly greater germination and seedling vigor.

At the vegetative stage, salt stress caused significant reductions in plant height, but the magnitude varied between varieties. While both varieties suffered under high salt stress, BARI Tomato 21 maintained taller plants (132.4 cm) and better root development under 3–6 dS m^{-1} conditions compared to BARI Tomato 14. This suggests that BARI Tomato 21 possesses better osmotic adjustment capacity and greater water-use efficiency, which have been linked to improved salt tolerance in tomato and other crops (Naeem et al., 2020; Haque et al., 2025b). Similar trends were observed by Cuartero & Fernández-Muñoz (1999) and Ibrahim et al. (2022), where tolerant tomato varieties exhibited sustained vegetative development under moderate salt stress due to enhanced physiological resilience.

Plants exposed to salt stress accumulate specific osmoprotectants and metabolic regulators that help in stress mitigation. In this study, three critical metabolic parameters—proline, soluble sugars, and chlorophyll—were analyzed to better understand varietal differences in salt stress tolerance. Proline content increased progressively with increasing salt stress, reaching the highest levels at 6 dS m^{-1}. Although varietal differences were statistically insignificant, BARI Tomato 21 recorded slightly greater proline accumulation (51.39 mg 100 g^{-1} FW) compared to BARI Tomato 14 (49.51 mg 100 g^{-1} FW). Proline is known to act as a compatible solute that protects plant cells by maintaining osmotic balance, scavenging reactive oxygen species (ROS), and stabilizing proteins and membranes under stress (Ashraf & Foolad, 2007; Aazami et al., 2010). Our findings are consistent with Parida & Das (2005) and Dutta et al. (2025), who reported that tolerant varieties accumulate more proline under salt stress stress, suggesting that proline can serve as a potential metabolic marker for screening salt-tolerant tomato varieties.

Total soluble sugar content increased markedly with increasing salt stress, suggesting a role in osmotic adjustment and energy supply under stress. BARI Tomato 21 exhibited the highest total sugar content (2.74 g 100 g^{-1} fresh leaf) compared to BARI Tomato 14 (2.66 g 100 g^{-1} fresh leaf). The accumulation of sugars under saline conditions has been widely documented as a mechanism to reduced cytoplasmic osmotic potential, thereby maintaining water influx into cells (Parida & Das, 2005; Naeem et al., 2020). Similar findings were reported by Rahman et al. (2016), who demonstrated that salt-tolerant tomato varieties accumulate markedly more sugars than sensitive ones, enhancing cell turgor and stress resilience.

Unlike proline and sugars, chlorophyll-a, chlorophyll-b, and total chlorophyll contents decreased markedly under increasing salt stress, suggesting salt-induced damage to the photosynthetic apparatus. However, BARI Tomato 14 maintained relatively greater chlorophyll content compared to BARI Tomato 21, suggesting that chlorophyll retention alone may not be the best predictor of salt tolerance. Similar patterns were observed by Ibrahim et al. (2022) and Naeem et al. (2020), who found that chlorophyll degradation under salt stress results from oxidative damage and chloroplast instability. Interestingly, tolerant varieties often compensate for reduced chlorophyll by improving metabolic mechanisms such as osmoprotectant accumulation and antioxidant enzyme activity.

Comparative analysis revealed that BARI Tomato 21 outperformed BARI Tomato 14 in most development and metabolic traits under salt stress. Its tolerance can be attributed to enhanced osmotic adjustment via greater proline and sugar accumulation, better water retention and reduced cellular dehydration, improved seedling vigor and biomass allocation and adaptive metabolic reprogramming under salt stress. These results suggest that BARI Tomato 21 is a promising candidate for cultivation in moderately salt-affected coastal areas of Bangladesh. The integration of metabolic markers such as proline and soluble sugars with morphological traits can improve screening efficiency for future breeding programs.

This study highlights the importance of metabolic reactions in determining salt stress tolerance among tomato varieties. While both BARI Tomato 14 and BARI Tomato 21 experienced development suppression under high salt stress, the latter exhibited better adaptive reactions through enhanced osmotic regulation and stress mitigation mechanisms. The findings provide a strong basis for the use of metabolic markers in breeding programs aimed at developing salt-resilient tomato varieties suitable for coastal Bangladesh.

Conclusion

This study demonstrated that salt stress imposes profound adverse effects on the germination, development, and metabolic composition of tomato varieties, but the extent of tolerance varied markedly between BARI Tomato 14 and BARI Tomato 21. While increasing salt stress progressively reduced germination percentage, root and shoot length, biomass, vigor index, and chlorophyll content, a slight stimulatory effect was observed at 3 dS m^{-1}, suggesting that low salt levels may act as a mild development enhancer. Among the two varieties, BARI Tomato 21 consistently outperformed BARI Tomato 14, exhibiting greater germination rates, greater seedling vigor, and better biomass retention under salt stress. The superior tolerance of BARI Tomato 21 is primarily associated with its ability to accumulate greater levels of osmoprotectants, including proline and soluble sugars, which help maintain cellular osmotic balance and mitigate salt-induced oxidative damage. In contrast, BARI Tomato 14 exhibited moderate tolerance, showing relatively better chlorophyll retention but reduced overall development and vigor under saline conditions. Based on these findings, BARI Tomato 21 is strongly recommended for cultivation in moderately salt-affected coastal soils of Bangladesh, where it can potentially improve tomato productivity and farmer profitability. However, further field-based evaluations using more varieties and plant growth phases across different coastal agro-ecological zones are necessary to validate these results under real farming conditions.

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Conflict of interest

There is no conflict of interest to declare.

Data availability

All the associate data were included in the manuscript.

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