DEFENCE RESPONSES WITH TAURINE AS A NON-ESSENTIAL AMINO ACID IN WHEAT (*TRITICUM AESTIVUM* L.) PLANTS UNDER SALINITY CONDITIONS

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Abstract. Taurine is one of the non-essential amino acids that may improve plant resistance to abiotic stresses. The role of taurine in wheat plants subjected to salt stress remains uncertain. The study evaluated the effects of foliar taurine at 0, 5, 10 and 20 μ M on wheat seedlings grown under saline conditions (100 mM NaCl). Exogenous taurine significantly (P < 0.05) increased growth (shoot and root fresh weight), K, Ca, Chl a, b, Chl a + b, carotenoids, membrane stability index and antioxidant enzymes (CAT, POX, APX and SOD) under salinity stress. As well as leaf relative water content, soluble sugars and proline were significantly increased in the taurine-treated plants compared to the untreated plants under saline conditions. The molecular studies have demonstrated that taurine treated plants showed higher relative expression in HKT1 indicating the higher absorption of K. Meanwhile, there was an obvious downregulation in the genes of NHX1 and SOS1. These results imply that applied taurine can effectively decrease the uptake of Na and improve the tolerance of wheat plants to salinity stress.

Keywords: abiotic stress, enzymes activity, photosynthetic pigments, gene expression, wheat

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Introduction

Salinity is considered one of the main abiotic factors hindering agricultural development and threatening crop yield (Al-Shammari et al., 2023; Helaly et al., 2017: Abdelaal et al., 2020; El-Shawa et al., 2020; Abdou et al., 2023) and food supply due to the negative impact of salinity on the production of most crops (Li et al., 2022). Arid and semi-arid regions suffer from a worrying scarcity of water for irrigation. To overcome this deficiency, we resort to irrigation with high-salinity water. However, reliance on low-quality water sources negatively affects various soil properties (chemical, physical, and biological), as well as plant properties. These harmful effects are generally attributed to the accumulation of salts in the area of root spread (El-Sayed et al., 2021). The accumulation of salts in the soil, especially sodium salts, has a harmful effect on soil fertility and productivity, thus deteriorating its quality in the long term. Salinity has a negative impact on the agricultural production of crops. Also, it is among the most severe stresses of the environment that hinder crop productivity. In response to salinity, plants undergo cellular oxidative stress and reactive oxygen species are produced including hydrogen peroxide and superoxide (Lethin et al., 2022; Gul et al., 2023; Alshammari et al., 2024). The accumulation of dissolved salts in the soil, especially sodium chloride, sodium carbonate, and sodium sulfate, limits the cultivation of many plant species, especially plants that cannot tolerate salinity.

Wheat is considered one of the most important staple food crops at global level. It is considered the first and primary source of human nutrition in all countries of the world because it contains a high percentage of protein, which gives this wheat flour high quality and nutritional value. It occupies the largest cultivated area for crops due to its high ability to adapt to temperate environments, as it leads field crops in terms of cultivated area, reaching about 583 million tons from 214 million hectares. (FAO, 2015). However, wheat crops face many problems, including biotic and abiotic stress (Mosalem et al., 2021; Hafez et al., 2022; Khedr et al., 2023; Omara et al., 2023; Alafari et al., 2024). Salinity generally affects germination, root growth, photosynthesis, antioxidant activity, and yield in wheat (Alamer, 2023). Salt stress can negatively affect wheat cultivation and production, leading to water loss, nutrient deficiencies, damage to cell membranes, and disturbances in metabolic pathways (Alnusairi et al., 2021; Zhu et al., 2023). All the harmful effects of salt stress on wheat plants lead to decreased growth and production (Ali et al., 2017; Maslennikova et al., 2023).

Taurine is one of the non-essential amino acids that protect lipid peroxidation of cell membranes to promote growth in plants due to its functions as a reactive oxygen species scavenger (Ashraf et al., 2022; Hafeez et al., 2022). It functions as a natural regulator of antioxidant defense networks under abiotic stress (Rasheed et al., 2022). There are no comprehensive studies on the effectiveness of taurine in mediating the plant defense response against irrigation water salinity. Therefore, the current work was designed to assess the potential of taurine to regulate ROS metabolism, and osmotic adjustment in wheat under salinity stress conditions. Therefore, the current work was designed to assess the potential of taurine to regulate ROS metabolism, antioxidant system, photosynthetic activity, gene expression, and osmotic adjustment in wheat under salinity stress conditions.

Materials and methods

The layout of experiment and growth conditions

For 3 min, the surface of Triticum aestivum L seeds; Cv. Giza 168 was sterilized with a 0.5% sodium hypochlorite solution. After giving them a good cleaning with distilled water, they were planted in 25-cm-diameter plastic pots. All pots contained a mixture of peat, compost, and sand (4:1:1). Pots were filled to capacity with 250 mL of pure Hoagland's solution before sowing. After the seedlings grew for 15 days, the pots were divided into two groups. A modified Hoagland's solution containing 100 mM/L NaCl was given to one group, and conventional Hoagland's solution was given to the other every other day. Taurine (Loba Chemie; India) was applied daily for a week as a foliar spray (10 mL per pot) to both the control and NaCl-treated groups at varying concentrations (0, 5, 10, and 20 μ M). An equal volume of distilled water (10 mL) was given to the control group. The seedlings were left to grow for another week, and then the samples were collected to determine the growth parameters, chlorophyll pigments, photosynthetic activity, oxidative damage characteristics, osmolytes, antioxidant enzymes and gene expression. Five replications of a fully randomized block design were used to arrange the pots.

Sodium, potassium, calcium, and sodium/potassium ratio

The flame photometric method (Jenway, UK) was used to determine the nutrients (Na, K and Ca) concentrations (Havre, 1961).

Photosynthetic pigments

The spectrophotometric method developed by Lichtenthaler and Wellburn (1983) was used to quantify the concentrations of chlorophyll (Chl) a and b, as well as carotenoids, in fresh leaves. A 0.05 g sample of fully grown young leaves was utilized to extract pigments using 80% acetone. The pigments' extract was quantified by comparing it to a blank solution of pure 80% acetone at wavelengths of 663 nm, 644 nm, and 452.5 nm for Chla, Chlb, and carotenoid concentrations, respectively.

Membrane stability index and H_2O_2

The membrane stability index (MSI) was assessed by finely cutting 0.1 g of fresh leaf tissue and placing it in test tubes with 10 mL of distilled water. Subsequently, the tubes were subjected to boiling at a temperature of 40°C to measure the electric conductivity (EC1). The same tubes were then boiled at a temperature of 100°C, and the electric conductivity (EC2) was recorded once again (Abd Elbar et al., 2021). The percentage of MSI was determined using the following formula: MSI = 1 - (EC1/EC2) Multiplied by 100. (1)

The hydrogen peroxide (H_2O_2) concentration was determined by extracting fresh leaf samples in 0.1% TCA using a pestle and mortar. Following centrifugation at a force of 12000 rpm the acceleration due to gravity for a duration of 15 min, a measured amount of the liquid remaining above the sediment was combined with 0.5 mL of a solution containing 10 millimoles of potassium phosphate buffer at a pH of 7.0, as well as 1 millimole of potassium iodide in a 1 mL volume. Afterwards, the optical density of the mixture was measured at a wavelength of 390 nm (El-Mogy et al., 2022), and the calculations were performed using a standard curve of H₂O₂.

Enzymatic antioxidants

The method described by Beyer Jr and Fridovich (1987) was used to assess the activity of superoxide dismutase (SOD). In summary, a portion of the enzyme was exposed to both light and darkness to observe the reduction of nitroblue tetrazolium at a wavelength of 560 nm. The activity of superoxide dismutase (SOD) was measured in enzyme units (EU) per milligram of protein. The activity of catalase (CAT) was determined using the assay method described by Weydert and Cullen (2010). The change in optical density at 240 nm was measured. An extinction coefficient of 36 × 103 mM-l cm-l was utilized for the calculation and expressed as EU mg⁻¹ protein. To determine the activity of ascorbic peroxidase (APX), 0.1 mL of the enzyme was combined with 1 mL of potassium phosphate buffer (100 mM, pH 7.0), 0.1 mM EDTA, 0.5 mM ascorbate, and 0.1 mM H₂O₂. The vanishing of H₂O₂ was detected through a modification in absorbance at 290 nm (Nakano and Asada, 1981).

Relative water content, proline, and total soluble sugars

The estimation of leaf relative water content (RWC) was conducted following the method described by Abd El-Gawad et al. (2021). Weighed leaf discs from six fully inflated leaves were immersed in distilled water for 2 h at a temperature of 25° C. The weight of the leaf discs was recorded when they became turgid. Subsequently, the discs were thoroughly dehydrated in an oven set at a temperature of 110° C for a duration of 24 h (DW). The formula for calculating the Relative Water Content (RWC) is as follows:

The quantification of proline was performed using the ninhydrin assay based on spectrophotometric analysis at a wavelength of 520 nm, following the method described by Bates et al. (1973). The quantification of total soluble sugars was performed at a wavelength of 490 nm using the phenol and sulphuric acid method, as outlined by Chow and Landhäusser (2004).

Relative expression of transporter proteins

The manufacturer's protocol was followed to extract total mRNA from different treatments using 0.5 g fresh leaves and a Sigma-Aldrich total RNA extraction kit. The isolated RNA was quantified spectrophotometrically and verified on 1% agarose gel. An RNA reverse transcription was done. The reaction mixture included 10 pml/µl oligo dT primer, 2.5 µl 5X buffer, 2.5 µl MgCl2, 2.5 µl 2.5 mM dNTPs, 4 µl oligo (dT), 0.2 µl (5 Unit/µl) Promega reverse transcriptase, and 2.5 µl RNA. In a thermal cycler PCR, RT-PCR was amplified at 42°C for 1 h and 72°C for 20 min. RNA samples were reverse transcribed to complementary cDNA using a reaction mixture of 2.5 µl dNTPs, 2.5 µl MgCl2, 1.0 µl oligo dT primer (10 pml/µl), 2.5 µl 5X buffer, and 0.2 µl (5 Unit/µl) reverse transcriptase (Promega, Germany). RT-PCR amplification was done in a thermal cycler at 42°C for 1.5 h and 80°C for 20 min. Quantitative Triplicate real-time PCR was performed on 1 µL diluted cDNA using the Rotor-Gene 6000 system (Germany). *Table 1* lists the primer sequences used in qRT-PCR. Gene expression analysis using SYBR® Green was conducted using primers for plasma membrane Na+/H+ antiporters (SOS1), tonoplast-localized NHX1, and β -Actin housekeeping gene

(reference gene). A reaction volume of 20 μ L was utilized. The 20 μ L reaction mixture includes 2 μ L template, 10 μ L SYBR Green Master Mix, 2 μ L reverse primer, 2 μ L forward primer, and sterile dist. water. These settings were used for PCR assays: After 15 min, 40 cycles of 950°C for 30 s and 600°C for 30 s were performed. To generate Δ CT values, target gene CT was subtracted from β -Actin gene CT for each sample. The relative gene expression was calculated using the 2- $\Delta\Delta$ Ct method (Livak and Schmittgen, 2001).

Gene name		Sequence	NCBI accession
SOS1	F	5'-GTTGTCGGTGAGGTCGGAGGG-3'	AY326952
	R	5'-TCATCTTCTCCTACCGCCCTGC-3'	
HKT1	F	5'-TGCTAATGTTTATCGTGCTG-3'	HQ845286
	R	5'-AGGCTGATCCTCTTCCTAAC-3'	
NHX1	F	5'-CACCAGCCACGGATCTTTCT-3'	AY461512.1
	R	5'-TTCACGATCAGTGGAGTGCC-3'	
Actin	F	5'-TGCTATCCTTCGTTTGGACCTT-3'	AB181991
	R	5'-AGCGGTTGTTGTGAGGGAGT-3'	

Table 1. The primer sequences used in qRT-PCR

Statistical analysis

Data are mean (\pm SE) of three replicates and for testing significance of data Tukey's Multiple Range Test was performed using One-Way ANOVA and the least significant difference (LSD) was calculated at p < 0.05.

Results

Growth-related traits

Effect of taurine at different concentrations (0, 5, 10, and 20 μ M) on shoot fresh weight, and root fresh weight of wheat grown in saline and normal soil are presented in *Figure 1A*, *B*. Wheat plants cultivated in salty soil exhibited a marked reduction in shoot fresh weight compared to those grown in normal soil. Adding taurine to plants grown in either saline or normal soil conditions considerably increases the fresh weight of wheat shoots in a concentration-dependent manner. Taurine increased fresh shoot weight more in wheat plants grown in normal soil than in salty soil.



Figure 1. Shoot fresh weight (A) and root fresh weight (B) of wheat grown in saline and normal soil as affected by taurine at different concentrations (0, 5, 10, and 20 μ M). Means with various letter combinations are significant at $P \le 0.05$

Taurine significantly enhances the weight of fresh wheat roots when added at concentrations of 10 and 20 μ M to plants growing in normal soil conditions, compared to plants that were not treated with taurine (0 μ M) and plants treated with 5 μ M taurine. Compared to the control group (0 μ M), the root weight of plants grown in saline soil conditions treated with various amounts of taurine (5, 10, and 20 μ M) did not show any significant change.

Sodium, potassium, calcium, and sodium/potassium ratio

Effect of taurine at different concentrations (0, 5, 10, and 20 µM) on sodium, potassium, calcium, and sodium/potassium ratio of wheat grown in saline and normal soil are presented in Figure 2A, B, C, D. Wheat plants cultivated in salty soil conditions exhibited a greater concentration of sodium compared to plants grown in normal soil conditions, regardless of the taurine levels. Applying taurine at various concentrations (5, 10, and 20 µM) to wheat plants cultivated under salty soil conditions resulted in a considerable reduction in sodium content compared to the control group (0 μ M). There was no notable decrease in sodium concentration observed when comparing taurine levels of 10 µM and 20 µM. When plants grown in salty soil were given different amounts of taurine (5, 10, and 20 μ M), the amount of sodium in those plants did not change significantly when compared to the control group (0 µM). The potassium concentration in wheat plants cultivated in salty soil was significantly lower than in those planted in normal soil. The addition of 10 and 20 µM taurine to plants cultivated in saline soil significantly increases the potassium concentration in comparison to the control (0 μ M) and the low taurine concentration (5 μ M). No significant differences in potassium concentration were observed between 10 and 20 µM taurine levels under saline conditions. The wheat plants grown in saline soil showed a significant decrease in calcium levels compared to those cultivated in normal soil. Under saline conditions, adding taurine (20 μ M) was recorded to significantly increase the potassium concentration compared to the control (0 µM). No significant differences in potassium concentration were observed between 5, 10, and 20 µM taurine levels. Under normal conditions, adding taurine (10 and 20 µM) was recorded to significantly increase the potassium concentration compared to the control (0 µM). There were no significant differences in potassium concentration among the 5, 10, and 20 µM taurine levels. Under saline conditions, the sodium/potassium ratio of wheat plants was higher than that of plants grown in normal soil conditions, regardless of the taurine levels. When wheat plants were treated with different amounts of taurine (5, 10, and 20 µM), there was a significant decrease in sodium levels compared to the control group (0 μ M).

Photosynthetic pigments

Effect of taurine at different concentrations (0, 5, 10, and 20 μ M) on photosynthetic pigments in wheat plants under normal and saline conditions are presented in *Figure 3A, B, C, D*. Chlorophyll a and b contents dropped significantly in wheat plants under salinity stress compared to normal conditions. Taurine at different concentrations (5, 10, and 20 μ M) significantly improved both types of chlorophyll molecules (a and b) in salt and normal conditions compared to control (0 μ M). Under saline conditions, plants administered 20 μ M taurine showed a remarkable increase in chlorophyll-a compared to 5 μ M and a nonsignificant change compared to 10 μ M. Taurine at 10 μ M significantly increased chlorophyll b molecules under saline conditions compared to the

control (0 μ M) and other taurine concentrations (5 μ M, and 20 μ M). Besides, plants supplemented with taurine showed a dose-dependent increase in chlorophyll b molecules under normal conditions. Saline stress significantly reduced total chlorophyll content in plants compared to normal conditions. Taurine concentrations of 5, 10, and 20 μ M were effective in reducing the negative impact of stress on total chlorophyll levels in wheat plants. The highest impact was recorded for 10, and 20 μ M compared to 5 μ M. There were no significant differences in carotenoid levels between wheat plants grown under normal and saline conditions. Taurine supplementation at 10 and 20 μ M increased carotenoid levels under saline conditions. Taurine supplementation at concentrations of 5, 10, and 20 μ M increased carotenoid levels in a concentration-dependent manner under normal conditions.

Membrane stability index and H_2O_2

Effect of taurine at different concentrations (0, 5, 10, and 20 μ M) on membrane stability index (%), and H₂O₂ concentration in wheat plants under normal and saline conditions are presented in *Figure 4A*, *B*. Salinity induced a substantial reduction in the membrane stability index of wheat plants relative to normal conditions. The membrane stability index improved with taurine treatment at 5, 10, and 20 μ M concentrations under normal and salinity conditions. No significant variations in the membrane stability index were detected among the various concentrations compared to the control under saline conditions. Identical outcomes were documented under normal conditions. In wheat plants, salinity significantly increases H₂O₂ content compared to normal conditions. The administration of taurine resulted in a decrease in H₂O₂ contents, under salinity conditions. This reduction was dependent on the concentration of taurine. Adding 10 μ M of taurine under normal conditions resulted in a significant decrease in H₂O₂ levels compared to the control group and the other treatments (5 and 20 μ M).



Figure 2. Concentration (mg g-1 DW) of sodium (A), potassium (B), calcium (C), and sodium/potassium ratio (D) of wheat grown in saline and normal soil as affected by taurine at different concentrations (0, 5, 10, and 20 μ M). Means with various letter combinations are significant at $P \le 0.05$



Figure 3. Effect of taurine at different concentrations (0, 5, 10, and 20 μ M) on photosynthetic pigments in wheat plants under normal and saline conditions. Means with various letter combinations are significant at $P \le 0.05$



Figure 4. Effect of taurine at different concentrations (0, 5, 10, and 20 μ M) on (A) membrane stability index (%), and (B) H₂O₂ concentration in wheat plants under normal and saline conditions. Means with various letter combinations are significant at $P \le 0.05$

Enzymatic antioxidants

Investigating the impact of various doses of taurine $(0, 5, 10, \text{ and } 20 \ \mu\text{M})$ on the activity of catalase (CAT), superoxide dismutase (SOD), ascorbate peroxidase (APX), and peroxidase (POD) in wheat plants cultivated under both normal and saline

conditions is presented in *Figure 5A, B, C, D*. The presence of salinity stress significantly elevated the activity of CAT, SOD, APX, and POD enzymes in wheat plants as compared to plants cultivated under normal conditions.



Figure 5. Effect of taurine at different concentrations (0, 5, 10, and 20 μ M) on catalase (A; CAT), superoxide dismutase (B; SOD), ascorbate peroxidase (C; APX), and peroxidase (D; POD) in wheat plants under normal and saline conditions. Means with various letter combinations are significant at $P \leq 0.05$

Under salinity stress, statistical analysis revealed that adding different amounts of taurine (5, 10, and 20 μ M) had a big effect on the activities of CAT, SOD, APX, and POD compared to control (0 μ M).

Wheat plants subjected to salinity stress and treated with 10 and 20 μ M taurine demonstrated the most pronounced increase in enzymes activity (CAT, APX, and POD). Wheat plants subjected to 10 μ M taurine demonstrated the most pronounced increase in SOD enzyme activity, with no significant differences noted between 5 μ M and 20 μ M taurine treatments.

Conversely, there were no notable alterations in the activities of CAT, SOD, and APX in wheat plants under normal conditions. Under normal conditions, the activity of APX was significantly increased in wheat plants at 10 μ M, 20 μ M taurine concentration compared to control and taurine 5 μ M.

Relative water content, proline, and total soluble sugars

Effect of taurine at different concentrations (0, 5, 10, and 20 μ M) on relative water content (RWC), proline, and total soluble sugars in wheat plants under normal and saline conditions are presented in *Figure 6A, B, C*. Wheat plants' relative water content decreased significantly when exposed to saline conditions as compared to normal conditions. Taurine (5, 10, and 20 μ M) considerably improved the RWC of wheat plants under saline conditions in a concentration-dependent manner. After subjecting wheat plants to taurine, there were no significant changes in the RWC under normal conditions

(*Fig. 6A*). Wheat plants exposed to salinity exhibited a significant increase in proline levels compared to those grown under normal conditions. Taurine at concentrations of 5, 10, and 20 μ M improved the proline content of wheat plants under saline conditions in a concentration-dependent manner. When exposed to taurine at different concentrations (5, 10, and 20 μ M), wheat plants did not show any significant changes in proline concentration under normal conditions (*Fig. 6B*). A significant increase in the accumulation of total soluble sugars was observed in wheat plants under salinity compared to normal conditions. The study revealed that the treatment with 10, and 20 mM of taurine had the most significant effect when plants were exposed to salinity stress. Wheat plants did not exhibit any significant changes in total soluble sugars when exposed to different concentrations of taurine (5, 10, and 20 μ M) under normal conditions (*Fig. 6C*).



Figure 6. Effect of taurine at different concentrations (0, 5, 10, and 20 μ M) on relative water content (RWC), proline, and total soluble sugars in wheat plants under normal and saline conditions. Means with various letter combinations are significant at $P \le 0.05$

Relative expression of transporter genes

To investigate the tissue-specific expression of HKT1, NHX1, and SOS1 genes, we performed qRT-PCR to test their relative expression in wheat plants. *Figure* 7 displays the impact of taurine concentrations (0, 5, 10, and 20 μ M) on the expression of HKT1, NHX1, and SOS1 genes in wheat grown in normal and saline soil. Under saline conditions, the expression of HKT1 was significantly reduced in wheat plants treated with taurine at 0, and 5 μ M compared to normal growth conditions. The level of HKT1 in taurine-treated plants was significantly improved as compared to the control. Likewise, the expression of HKT1 was significantly enhanced in taurine-treated plants

grown under normal conditions (*Fig.* 7A). The expression levels of NHX1 and SOS1 transcripts were significantly higher in wheat plants grown under saline conditions when compared to those grown under normal conditions. The transcripts of NHX1 and SOS1 decreased significantly in plants treated with varying taurine concentrations and grown under saline conditions (*Fig.* 7B, C). In contrast, NHX1 and SOS1 transcripts significantly improved in plants treated with varying taurine concentrations and grown under normal conditions.



Figure 7. The relative expression levels of HKT1 (A), NHX1 (B), and SOS1 (C) of wheat grown in saline and normal soil as affected by taurine at different concentrations (0, 5, 10, and $20 \ \mu$ M). Means with various letter combinations are significant at $P \le 0.05$

Discussion

It is common for crops to experience environmental stresses. Salinity stress is a major environmental factor that significantly affects agricultural productivity (Gupta et al., 2022). Extreme environmental conditions can trigger various cellular events within plants, which can cause morphological, physiobiochemical and anatomical changes (Abdelaal et al., 2020; Moghanm et al., 2020; AlKahtani et al., 2021a). This can result in water deficiency, osmotic stress, ion toxicity, and oxidative damage. These changes can lead to a reduction in leaf surface expansion, yellowing and browning of leaves, epinasty, stunted growth, senescence, necrosis, altered phenology, and ultimately, plant death (Mall et al., 2021; Rao et al., 2021). Soil salinity impacts plant growth and survival by altering nutrient availability and disturbing water balance (El-Flaah et al., 2021; Mohamed et al., 2022). Soil conditions can be intensified due to natural and human activities, such as evaporation and deforestation. Taurine is a newly discovered growth regulator that shows potential for regulating plant defence mechanisms (Hafeez et al., 2022). This study aims to determine if taurine can enhance the salt tolerance of wheat plants.

This study found that wheat plants grown in salty soil showed a significant reduction in both root and shoot fresh weight compared to those cultivated in normal soil. In line with our findings (Abbas et al., 2018) found that significant reduction in shoot and root biomass was recorded in wheat plants grown under salinity stress. Several scientific studies have reported a reduction in shoot and root biomass due to salt stress across various plant species (Sitohy et al., 2020; Abdelaal et al., 2021, 2022). The results have supported earlier observations of growth reduction due to NaCl treatment. The salinity likely hurts the plants by increasing the osmotic potential of salt in the growing medium. As a result, the root cells were unable to extract the necessary water from the medium (Safdar et al., 2019). The restricted uptake of critical nutrients may cause a reduction in plant growth under salinity stress (Parihar et al., 2015). Taurine significantly improved plant growth-related attributes under salinity stress. This improvement can be attributed to enhanced elemental uptake and homeostasis, along with improved relative water content of plants (Isayenkov and Maathuis, 2019). Hao et al. (2004) found that the application of taurine resulted in enhanced growth characteristics of wheat plants.

One mechanism of salt tolerance involves the uptake and accumulation of inorganic ions, including Na+ and K+, which affect the Na+/K+ ratio (Hussain et al., 2021). In the present study, the salinity levels caused a significant decrease in the concentration of K and an increase in the concentration of Na in wheat plants. The K+/Na+ ratio was also significantly reduced in a concentration-dependent manner. (Sairam et al., 2002) suggested that a lower sodium/potassium ratio in wheat varieties predicts sensitivity or tolerance in plant response. Previous studies suggest that low leaf Na and K:Na discrimination can increase salt tolerance in wheat cultivars (BorzouEI et al., 2020; El-Hendawy et al., 2017). According to our findings, the plant showed a higher accumulation of Na+ ions and a lower accumulation of Ca2+ ions. The present findings are in line with Alharbi et al. (2025), and Sitohy et al. (2020). Administration of taurine reduced the harmful effects of Na+ ions and enhanced the levels of important nutrient ions, including Ca2+, and K+ in the presence of salt stress. In previous literature, taurine has been shown to increase the uptake of essential nutrients and decrease the uptake of Na+ ions in plants experiencing alkalinity (Rasheed et al., 2022) and salinity (Ashraf et al., 2023) stress. Under salinity stress, wheat plants exhibited a significant decrease in chlorophyll a, b, and total contents, as well as carotenoids. The primary reasons for abnormal photosynthesis are the decrease in chlorophyll biosynthesis and the breakdown of chlorophyll (ALKahtani et al., 2020, 2021b; El-Shawa et al., 2020). Based on our findings, it was observed that the level of chlorophyll molecules (a and b) decreased significantly under stress. Several studies have found that excessive salinity stress causes changes in the levels of photosynthetic pigments (Faseela et al., 2020; Taïbi et al., 2016). Prior studies have documented a decrease in chlorophyll and carotenoids in pepper (Sarafi et al., 2018), Arabidopsis (Surgun et al., 2016), and wheat (Catav et al., 2018). The accumulation of toxic ions and the reduction in available water resulting from salt stress have adverse effects on chlorophyll production and hasten the degradation of chlorophyll molecules (Kaya et al., 2020). The pea plants treated with taurine exhibited the highest chlorophyll content, which can be attributed to enhanced ion absorption and diminished oxidative damage (Ashraf et al., 2022). Under salt conditions, the membrane stability index of wheat plants was observed to decrease. According to our findings, the membrane stability index of wheat plants significantly increased under normal and salt conditions after taurine treatment. It is possible that the

observed effect could be attributed to the heightened actions of antioxidant enzymes (Gomathi and Rakkiyapan, 2011). The present results manifested higher oxidative damage, reflected as a lower relative membrane stability index, and more accumulation of H_2O_2 . Our findings are in parallel with Abdel Latef et al. (2019) and Esfandiari and Gohari (2017). The administration of taurine leads to a decrease in levels of H_2O_2 that is concentration-dependent. The findings of Ashraf et al. (2023) show that taurine supplementation can reduce oxidative damage in pea plants under salinity and iron deficiency stress. The present findings align with Hafeez et al. (2022) who reported that taurine supplementation reduced oxidative damage in clover plants under Mn+2 stress.

The current results demonstrate a notable increase in CAT, SOD, APX, and POD activities when subjected to salinity stress. Under salt stress, it is often recognized that the activation of antioxidant enzymes that scavenge reactive oxygen species (ROS), such as SOD, POD, APX, and CAT, helps to reduce the formation of ROS (Hasanuzzaman et al., 2021). The present findings are in parallel with Jabeen et al. (2021). According to our findings, plants treated with taurine exhibited increased activity levels of SOD, POD, APX, and CAT enzymes. In the same way, giving plants taurine increased the activity of SOD, POD, and CAT, which lowered oxidative damage caused by alkaline (Rasheed et al., 2022) and salt stress (Ashraf et al., 2022). The optimal water status of plant cells is crucial for growth and productivity. RWC measures the water content and maximum capacity of a leaf under full turgidity (Mullan and Pietragalla, 2012). In the present work, salinity significantly reduced the RWC of wheat plants, but taurine improved RWC under normal and salt conditions. The study findings align with previous research (Ashraf et al., 2023; Ghogdi et al., 2012; Pour-Aboughadareh et al., 2021) that indicates a reduction in plant RWC due to salinity stress. Proline is considered a compatible solute that assists in cellular osmotic adjustments. Its levels increase in plants experiencing salt-induced stress (Hosseinifard et al., 2022). Under stress, plants tend to produce an excess amount of proline as a mechanism to maintain their osmotic balance or cell turgor (Ozturk et al., 2021). Salinity led to a significant increase in the proline content of wheat plants compared to normal conditions. Similarly, salinity caused a significant increase in proline content in all wheat cultivars. "Arg" showed generally higher proline content at all salinity levels (Jamali et al., 2015). Taurine supplementation led to an increase in the proline content of wheat plants, which was also observed by Huang et al. (2021) under salinity stress. Sugars, in addition to their role as a source of energy, also act as osmoprotectant in plants. They help the plants cope with various environmental stresses such as drought, salinity, and extreme temperatures. We observed a significant increase in total soluble sugars in salinity-stressed wheat plants compared to normal conditions. The findings of the study are consistent with previous research (Saleh et al., 2015). The addition of taurine at varying concentrations in salt-stressed plants significantly increased the amount of total soluble sugars. The present findings are in parallel with Ashraf et al. (2023).

Three types of sodium transport pathways-high-affinity K+ transporter (HKT1), salt overlay sensitive (SOS1), and NHX1 play an active role in the exclusion and extrusion of Na+ ions through plasma membrane Na+/H+ exchange transporters. Plants can tolerate more sodium if they reduce sodium uptake and increase cytoplasmic potassium levels (Assaha et al., 2017). Sodium and potassium ions are transported together through the roots to the leaves, using HKT pathways (Ali et al., 2021). We investigated the abundance of HKT1 transcripts to understand the impact of salinity on wheat plants.

We observed that the expression of HKT1 was reduced in wheat plants under saline conditions compared to normal conditions. However, the expression of HKT1 was enhanced in taurine-treated plants grown under both saline and normal conditions. Besides, we also investigated the plasma membrane Na+/H+ antiporter SOS1, which controls long-distance Na+ transport (Shi et al., 2000). This refers to a process where Na+ is transported out of the cell into the extracellular space after it has entered the cell (Zhu, 2001). We found that saline conditions enhanced the expression level of SOS1 and NHX1 in wheat plants. The study findings align with previous research (Jiang et al., 2021; Sathee et al., 2015). The addition of taurine at varying concentrations in salt-stressed plants notably reduced the expression of SOS1 and NHX1.

Conclusion

Taurine, a non-essential amino acid, may boost plant abiotic stress resistance. Taurine's role in salt-stressed wheat is unknown. The study examined the impact of foliar taurine (0, 5, 10, and 20 μ M) on wheat seedlings in saline (100 mM NaCl) environments. In this study, exogenous taurine significantly (P < 0.05) improved growth (shoot and root fresh weight), K, Ca, Chl a, b, Chl a + b, carotenoids, membrane stability index, and antioxidant enzymes (CAT, POX, APX, and SOD) under salinity stress. Taurine-treated plants had higher leaf relative water content, soluble carbohydrates, and proline than untreated plants in saline. Molecular investigations showed that taurine-treated plants had greater HKT1 expression, indicating higher K absorption. Meanwhile, NHX1 and SOS1 genes were downregulated. These findings suggest that taurine can reduce Na absorption and improve wheat plant salinity tolerance.

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