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Mitigation of salt stress in tomato plants *(Solanum lycopersicum L.)* using melatonin and boron

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ABSTRACT
Tomato is an important economical and nutritional plant. A factorial experiment involving three variables was executed using a Randomized Complete Block Design with three replications. The effects of melatonin (0, 200 and 400 mg L^{-1}), boron (0, 5 and 10 mg L^{-1}), and sodium chloride (0, 2 and 4 g l^{-1}), together with their interactions, were examined by using the Statistical Packages of Social Sciences to analyse the data. Salinity significantly adversely affected phenotypic characteristics and yield. The administration of melatonin at second level and boron at first level, together with their combination, yielded enhanced performance, exhibiting the highest values for most examined features when compared to the control. The triple interaction second melatonin, first boron and without salt yielded the highest results across all processing techniques. The results indicate that the simultaneous use of melatonin and boron can effectively alleviate the adverse impacts of salt stress in tomato plants.

تخفيف الإجهاد الملحي في نباتات الطماطة (*Solanum lycopersicum* L.) باستخدام الميلاتونين والبورون

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الخلاصة
أُجريت تجربة عاملية بثلاثة متغيرات باستخدام تصميم القطاعات العشوائية الكاملة بثلاثة تكرارات. دُرست تأثيرات الميلاتونين (بتركيزات 0، 200، و400 ملغم لتر$^{-1}$)، والبورون (بتركيزات 0، 5، و10 ملغم لتر$^{-1}$)، وكلوريد الصوديوم (بتركيزات 0، 2، و4 غرام لتر$^{-1}$)، بالإضافة إلى تفاعلاتها، باستخدام برنامج SPSS لتحليل البيانات. أثرت الملوحة سلبًا بشكل ملحوظ على الخصائص المظهرية والحاصل. أدى استخدام الميلاتونين بالتركيز الثاني والبورون بالتركيز الأول، بالإضافة إلى تداخلاتهما، إلى تحسين الصفات، حيث سُجلت أعلى القيم لمعظم الخصائص المدروسة مقارنةً بالمجموعة الضابطة. حقق التفاعل الثلاثي بين الميلاتونين بالتركيز الثاني، والبورون بالتركيز الأول، وبدون ملوحة، أفضل النتائج في جميع المعاملات. تشير النتائج إلى أن الاستخدام المتزامن للميلاتونين والبورون يُمكن أن يُخفف بشكل فعال من الآثار السلبية للإجهاد الملحي على نباتات الطماطة.

الكلمات المفتاحية: إنزيم الكاتالاز، البرولين، الملوحة، *Solanum lycopersicum* L.

INTRODUCTION

Tomato (*Solanum lycopersicum* L.) is an important crop valued for both its nutritional benefits and its economic significance, and it also functions as a model organism for investigating genetics, fruit development, and environmental stress responses. Tomato are nutrient-rich vegetable crops extensively consumed by humans. They represent an excellent source of antioxidants such as vitamin C, lycopene, β-carotene, provitamin A, and folate, as well as vital minerals such as potassium. Moreover, tomatoes possess significant secondary metabolites, including as phytosterols, flavonoids, and polyphenols (Amr and Raie, 2022). Tomato (*Solanum lycopersicum* L.) is a member of the Solanaceae family, which includes around 100 genera and approximately 2,500 species. Tomatoes are widely cultivated in open fields and are also grown in smaller-scale production systems using protected agriculture techniques (Hadi and Obaid, 2024). Notwithstanding its importance, Tomatoes are very sensitive to environmental conditions like temperature, light, and irrigation variations during their growth stages. Although tomatoes exhibit moderate tolerance to soil salinity (Shahzadi *et al*., 2025). With the increase in global population and the escalation of environmental deterioration, soil salinization has become a significant limitation on agricultural output globally (Zhang *et al*., 2022).

Salinity, defined as the accumulation of salts in soil or irrigation water, represents a major obstacle to agricultural productivity worldwide, especially in arid and semi-arid regions. Globally, salinity affects nearly 20% of irrigated agricultural lands. Iraq ranks among the highest countries in the Arab and Asian regions in terms of the vast land areas degraded by salinization (Faisal *et al*., 2024). Salinity stress disturbs ionic equilibrium and induces water deficit in plant cells, leading to two principal kinds of stress: osmotic stress and ionic toxicity (Ortega-Albero *et al*., 2023). To cope with salinity stress, plants activate multiple defense strategies, such as triggering the salt overly sensitive (SOS) signaling pathway to regulate ion balance, enhancing osmotic regulators and antioxidant compounds, increasing the activity of antioxidant enzymes, and adjusting endogenous hormone responses (Jameel *et al*., 2024). Notwithstanding these adaptive responses, the inherent defensive capability of plants is constrained, suggesting the necessity for further techniques to enhance salt tolerance. Contemporary methods encompass the development of salt-tolerant cultivars (Zhang *et al*., 2024), these technologies frequently face

constraints regarding efficiency, cost-effectiveness, and practical implementation for fast enhancement. Alternatively, the use of plant growth regulators and micronutrients presents a viable approach, delivering prompt and efficient augmentation of plant tolerance to salt stress (Subhi and Kisko, 2025). Melatonin (MT) (N-acetyl-5-methoxytryptamine, MT) was initially discovered in 1958 from extracts of the cow pineal gland. It is regarded as a notable indole compound, having structural and functional similarity to indole-3-acetic acid (IAA) (Mannino *et al*., 2021). Melatonin is present in several plant parts, including seeds, roots, stems, leaves, and fruits (Zhou *et al*., 2024).

In plants, melatonin acts as an essential hormone that controls various physiological and developmental processes, including root development, seed germination, flower formation, leaf aging, and fruit ripening (Muhammad *et al*., 2024). It also promotes antioxidant activity and stimulates the role of osmolytes in eliminating reactive oxygen species (ROS) (Ahmad *et al*., 2023). Melatonin operates via both direct and indirect mechanisms. It directly neutralizes reactive oxygen species and binds heavy metals, while indirectly strengthening antioxidant defense mechanisms, boosting osmoprotectant and antioxidant levels, mitigating photosynthesis inhibition, and modulating hormonal signaling pathways (Ahmad *et al*., 2023). Melatonin also alleviates the detrimental effects of several abiotic stimuli - including salt, drought, heavy metal toxicity, low temperatures, UV radiation, and alkaline conditions - as well as biotic stresses in higher plants (Zeng *et al*., 2022).

The content of micronutrients in desiccated plant tissues differs among various species and genotypes. Boron in soil predominantly exists as boric acid ($B[OH]_3$), commonly found in the cytoplasm with a pH of around 7.5 (Ayub *et al*., 2021). Boron plays a vital role in the growth and functionality of plant cell walls and membranes (Roychowdhury *et al*. 2019). It forms cross-links with pectin, glycosylinositol phosphorylceramides (GIPCs), and rhamnogalacturonan-II (RG-II), which regulate cell wall porosity and tensile strength (Jiao *et al*., 2025). Insufficient B availability reduces RG-II dimerization in pumpkin, leading to the development of coarse and abnormally thick cell walls. Additionally, boron influences nutrient uptake from the soil by enhancing the absorption and translocation of key elements such as N, P, K, Fe, Zn, and Cu when supplied through leaves, buds, or seeds (Jiao *et al*., 2025).

Recent investigations have emphasized boron's protective function under stress settings, where it regulates physiological processes, strengthens cytosolic structures, and improves antioxidant defense systems (Tanveer *et al*., 2025). Karimi *et al*. (2018) ascribe these advantages to less cell membrane damage, enhanced glycine betaine accumulation, and better water availability. Moreover, the use of foliar boron has been demonstrated to substantially enhance soluble glucose levels, facilitating osmotic control (Yousefi *et al*., 2020).

This field study aims to mitigate salt stress in potted tomato plants by administering melatonin and boron, while simultaneously investigating their impact on the plants' morphological and physiological characteristics.

MATERIALS AND METHODS

The research was conducted at the botanical garden under the biology department of the college of science for women from October 2024 to April 2025. A factorial

experiment involving three variables was executed using a randomized full block design with three replications. Melatonin M0, M1, M2 (0, 2, 3 mg L^{-1}), boron B0, B1, B2 (0, 5, 10 mg L^{-1}), Along with sodium chloride treatments S0, S1, and S2 (0, 2, and 4 g l^{-1}) and their interactions, soil samples were randomly collected from pots at a depth of 15 cm and carefully homogenized. The composite samples were then analyzed in the postgraduate laboratory of the Department of Biology, College of Science, University of Baghdad, to perform various chemical and physical assessments, as presented in Table 1.

Table 1. Chemical and physical properties of experiment soil.

Physical			
Property		Value	
Salt concentration	S0	S1	S2
Soil texture	Sandy	Sandy	Sandy
Sand %	74. 3	66.6	90
Silt %	15.2	21.4	5.3
Clay %	10.5	12	4.7
Soil texture		Sandy Loam	
Bulk density (mg kg^{-1})	1	0.86	0.8
Chemical			
Property		Value	
Salt concentration	S0	S1	S2
pH	6.9	6.7	6.8
EC (dsm m^{-1})	13.5	43.2	41.9
N (mg kg^{-1})	75	155	232
P (mg kg^{-1})	28.9	31.9	45.9
K (mg kg^{-1})	32.6	39.5	81.4

During the plant's growth period, the seedlings were irrigated regularly with non-salted water, at 30 days stage from the date of planted (plants have 4-5 leaves) they were irrigated with three different treatments in the early morning (without salt, 2, 4 g l^{-1}) of NaCl. Salinity was added several times, and whenever irrigation was needed. The seedlings were watered with unsalted water after each irrigation with salt water throughout plant's life cycle. Weeds were controlled manually. Seeds of the salt-sensitive tomato *Solanum lycopersicum* Var. Seyran F1 (produced by Basf Nunhems Global, Netherlands, imported by Ard Unifert) were sterilized and planted in special germination trays on September 1, 2024. Three plants were randomly selected for planting on October 7, 2024, which 27 Pots (30 cm in height and 40 cm in diameter) for each replicate (i.e., a total of 81 experimental units) and their leaves were sprayed with melatonin and boron.

Growth and yield traits were recorded from three randomly selected plants, including plant height (cm), leaf area (dcm^2 $plant^{-1}$), number of leaves, and shoot dry weight (g), fruit quantity (fruit $plant^{-1}$), fruit weight (g), leaf total chlorophyll content ($\mu g/cm^2$), proline concentration, catalase enzyme activity (mmol min mg^{-1}), and yield per plant (g $plant^{-1}$).

The leaf area was calculated by calculating the maximum length and width of one leave (middle) according to the equation (1).

$$LA = 0.347LW - 10.7 \quad (1)$$

Whereas: LA is the leaf area (cm^2 $plant^{-1}$), L is the length (cm) and W is the width (cm). (Blanco and Folegatti, 2003).

The total chlorophyll content of leaves in the plants was calculated for 81 experimental units using a chlorophyll meter as shown in Appendices 8 A according to the equation (2).

$$Ch = 7.953+1.026*CCI -0.0045*CCI^2 \quad (2)$$

Whereas: ch is the total chlorophyll content of leaves ($\mu g/cm^2$).

Also, Proline Content of Leaves in ($\mu mol\ g^{-1}$ FW), was extracted and quantified by adding 10 ml of 3% aqueous sulfosalicylic acid to 0.5 g of fresh leaf tissue. The tissue was thoroughly ground and filtered. From the filtrate, 2 ml was mixed with 2 ml of ninhydrin reagent, prepared by dissolving ninhydrin in a glacial acetic acid and phosphoric acid mixture, followed by the addition of 2 ml of glacial acetic acid. The mixture was incubated in a water bath for one hour. After cooling, 4 ml of toluene was added, and the mixture was thoroughly shaken. The aqueous phase was separated, and the upper toluene layer was collected for analysis. Optical density was measured at 520 nm using a UV/Visible spectrophotometer (LKB-Biochrom 4050), and proline concentration was calculated using a standard curve.

Moreover, the two grams of fresh leaf tissue were homogenized in 0.1 M potassium phosphate buffer (pH 7.8) at a 1:2 (w/v) ratio. The homogenate was filtered through gauze and centrifuged at 10,000 × g for 30 minutes. To determine catalase enzyme activity, 0.2 ml of the supernatant was incubated with 1 ml of a reaction mixture containing 65 mM H_2O_2 and 60 mM phosphate buffer (pH 7.4) at 25°C for 4 minutes. The reaction was terminated by adding 1 ml of 32.4 mM ammonium molybdate. Absorbance was measured at 405 nm, and catalase activity was calculated using the specified equation (3).

$$CEA = ((Sample - Blank\ 1))/ ((Blank\ 2 - Blank\ 3)) \times 271 \quad (3)$$

Whereas: CEA is the Catalase Enzyme Activity (mmol/min/mg), Blank 1: contains 1 ml of the base material (the H_2O_2 with the buffer solution), 1 ml of molybdate and 0.2 ml of the sample, Blank 2: contains 1 ml of the base material (the H_2O_2 with the buffer solution), 1 ml of molybdate, and 0.2 ml of the buffer solution and the Blank 3: contains 1 ml of buffer, 1 ml of molybdate, and 0.2 ml of buffer.

The Statistical Packages of Social Sciences SPSS 2019 was utilized to analyse the data and evaluate the effects of salinity, melatonin, boron, and their interactions on the studied traits. The experiment followed a factorial design (3×3×3) within a RCBD with 3 replications. Significant differences among treatment means were assessed using the Least Significant Difference (LSD) test (SPSS, 2019).

RESULT AND DISCUSSION

Table 2 showed the increasing salinity levels caused decline in plant height, as S2 had the lowest rates (156.29) cm, compared to the control S0 (169.32) cm. The effect of melatonin gave highest average at M2 (166.07) cm. A significant variation was observed in the treatment of boron, the highest height was reached at B1 (163.31) cm. Significant differences were observed in the interaction between melatonin and boron, with the highest value recorded in M2B1 (167.36) cm. The interaction between melatonin and salt resulted the highest value at S0M2 (175.95) cm. Furthermore, the interaction between B and S result a significant difference, where the highest value was not significantly different among the values S0B1,

S0B2 and S0B0 (170.33), (170.08) and (167.56) respectively. The interaction between MBS exerts highly significant differences, where the highest plant was at S0M2B1 and S0M2B2 (177.36) (177.13) cm. The present study examined the effects of the melatonin and boron, individually and in combination, on moderately salt-sensitive plants under saline conditions. Tomato plants showed reduced vegetative growth and plant height as salinity increased due to sodium-induced cytosolic damage and disruption of metabolic processes such as photosynthesis. Melatonin shares the same biosynthetic precursor (tryptophan) and pathway as the auxin IAA (indole-3-acetic acid), which explains their similar roles in promoting growth. Under salt stress, MT improved plant height compared to untreated plants (Li *et al*., 2019). Boron application also alleviated salt stress effects. As an essential micronutrient, boron supports cell wall integrity by binding pectin polysaccharides and regulates hormone production and transport, particularly auxin (Thakur *et al*., 2025), thereby enhancing plant growth under salinity.

Table 2. The effect of melatonin and boron and their interactions on plant height under salt stress.

S	M	B			S x M	Mean: S
		B0	B1	B2		
S0	M0	161.63 G	163.76 EF	164.16 EF	163.18 C	169.32 A
	M1	167.70 D	169.86 C	168.96 CD	168.84 B	
	M2	173.36 B	177.36 A	177.13 A	175.95 A	
S1	M0	157.30 KL	159.80 HIJ	158.96 J	158.69 E	161.11 B
	M1	159.66 IJ	161.33 GH	161.23 GHI	160.74 D	
	M2	162.73 FG	164.83 E	164.16 EF	163.91 C	
S2	M0	154.50 NO	155.80 LMN	153.83 O	154.71 F	156.29 C
	M1	155.43 MN	157.13 KL	154.86 NO	155.81 F	
	M2	158.66 JK	159.90 HIJ	156.50 LM	158.35 E	
L.S.D.		LSD: SMB=1.570			LSD: SM=1.3661	LSD: S=0.5233
S x B		B0	B1	B2		
S0		167.56 A	170.33 A	170.08 A		
S1		159.90 BC	161.99 B	161.45 B	LSD: SB=1.3661	
S2		156.20 D	157.61 CD	155.06 D		
M x B		B0	B1	B2	Mean: M	
M0		157.81 D	159.79 CD	158.98 D	158.86 C	
M1		160.93 BCD	162.77 ABCD	161.68 ABCD	161.80 B	
M2		164.92 ABC	167.36 A	165.93 AB	166.07 A	
L.S.D.		LSD: MB=1.3661			LSD: M=0.5233	
Mean: B		161.22 C	163.31 A	162.20 B	LSD: B=0.5233	

The data in Table 3 revealed that increasing levels of salinity hurt the leaf number, with the maximum value observed under the S0 (35.148), and the lowest value was at S2

(29.963), while melatonin gave highest rate in M2 (34.481). On the other hand, boron, B1 producing highest rate (33.629). Furthermore, the interaction between M and B showed significant differences, with the highest value observed at M2B1 (35.889). Similarly, the interaction between M and S reached its maximum at S0M2 (37.888). In addition, the interaction between B and S showed significant differences, as highest level at S0B1 and S0B0 (36.111) (35.444) respectively. Moreover, the triple interaction M, B and S showed significant differences as highest rate at S0M2B1 (38.667), followed by S0M2B0 (38.333), with no significant differences between them. When tomato plants are exposed to salinity, the number of leaves decreases due to slower cell division and expansion, accumulation of sodium and chloride in the tissues, which causes cytotoxicity, decreased photosynthetic efficiency, and decreased activity of growth-stimulating hormones (such as auxin and cytokinin). The Exogenous melatonin enhanced plant growth by increasing (number of leaves), as shown in the table 3 by regulating the photosynthesis process because it contributes to the synthesis and protection of chlorophyll, modifying stomatal conduction, transpiration and carbohydrate metabolism process (Ahmad *et al*., 2023). Boron has been used to mitigate the effects of salt stress on plants. Boron is an essential element for optimal plant growth and development. Its key roles include maintaining cell wall structure and stability, assisting pollen tube growth and fertilization, enabling sugar transport and carbohydrate metabolism, maintaining cell membrane integrity, and regulating hormone levels and gene expression (Thakur *et al*., 2025). The application of exogenous boron improved photosynthetic system efficiency, resulting in increased vegetative growth.

In Table 4, there was a significant effect on the leaf area, it was noted that salinity recorded the highest value at S0 (451.93) cm^2, the lowest value was at S2 (346.41) cm^2. Melatonin positively influenced leaf area, and greatest value obtained at M2 (427.77) cm^2. Boron recorded highest value at B2 (405.79) cm^2. Moreover, significant differences were observed in the interaction between M and B, where highest rate was at M2B1 (443.22) cm^2. The interaction between M and S, significant differences were observed, with highest value recorded at S0M2 (516.91) cm^2. In addition, Significant differences were also observed in the interaction between B and S, with highest rate recorded at S0B1 (466.88) cm^2. Moreover, the triple interaction showed significant differences, with highest rate recorded at S0M2B2 (552.16) cm^2, followed by S0M2B1 (551.23) cm^2. The leaves area exposed to salinity decreases due to impaired cell expansion resulting from reduced water uptake due to the osmotic effect of salinity, accumulation of sodium (Na^+) and chloride (Cl^-) ions in leaf tissue, which inhibits cell growth and reduces cell division, and a decrease in photosynthetic activity due to damage to plastids and increased oxidative stress. plays a crucial role in multiple physiological and metabolic processes, including the regulation of photosynthesis, stimulation of antioxidant enzymes such as catalase (CAT) and peroxidase (POD), control of stomatal conductance and transpiration, promotion and protection of chlorophyll synthesis, regulation of carbohydrate metabolism, enhancement of nitrogen and sulfur metabolism, modulation of secondary metabolite biosynthesis (such as flavonoids and phenolics), and regulation of mitochondrial activity (Brengi *et al*., 2022). Boron has been used to mitigate the effects of salt stress on plants. Boron is an essential element for optimal plant growth and development. Its key roles include maintaining cell wall structure and stability, enabling sugar transport and carbohydrate metabolism, maintaining cell membrane integrity, and

regulating hormone levels and gene expression (Thakur *et al*., 2025). The application of exogenous boron improved photosynthetic system efficiency, resulting in increased vegetative growth, it sustains the stability of chloroplast membranes-an essential component for the proper assembly of photosystems and effective electron transport during photosynthesis (Younis *et al*., 2024).

Table 3. The effect of melatonin and boron and their interactions on leave number under salt stress.

S	M	B			S x M	Mean: S
		B0	B1	B2		
S0	M0	32.333 DEF	33.333 CDE	31.667 EFG	32.444 C	35.148 A
	M1	35.667 CB	36.333 AB	33.333 CDE	35.111 B	
	M2	38.333 A	38.667 A	36.667 AB	37.888 A	
S1	M0	30.333 FGH	31.333 EFG	29.667 GHI	30.444 D	31.629 B
	M1	32.333 DEF	33.333 CDE	28.333 HI	31.333 CD	
	M2	33.333 CDE	34.333 BCD	31.667 EFG	33.111 C	
S2	M0	25.667 J	28.333 HI	27.333 IJ	27.111 E	29.963 C
	M1	30.333 FGH	32.333 DEF	28.333 HI	30.333 D	
	M2	34.333 BCD	34.667 BCD	28.333 HI	32.444 C	
L.S.D.		LSD: SMB=2.4605			LSD: SM=1.9694	LSD: S=0.8202
S x B		B0	B1	B2		
S0		35.444 A	36.111 A	33.889 AB		
S1		32.000 CB	33.000 B	29.889 CD	LSD: SB=1.9694	
S2		30.111 CD	31.778 CB	28.000 D		
M x B		B0	B1	B2	Mean: M	
M0		29.444 F	31.000 DEF	29.556 F	30.000 C	
M1		32.778 BCD	34.000 ABC	30.00 EFF	32.259 B	
M2		35.333 AB	35.889 A	32.222 CDE	34.481 A	
L.S.D.		LSD: MB=1.9694			LSD: M=0.8202	
Mean: B		32.518 B	33.629 A	30.592 C	LSD: B=0.8202	

Table 4. The effect of melatonin and boron and their interactions on leaf area under salt stress.

S	M	B			S x M	Mean: S
		B0	B1	B2		
S0	M0	400.46 J	412.56 G	410.40 H	407.81 CD	451.93 A
	M1	427.166 E	436.83 C	429.23 D	431.07 B	
	M2	447.33 B	551.23 A	552.16 A	516.91 A	
S1	M0	374.70 O	382.23 N	384.46 M	380.46 E	395.52 B
	M1	388.83 L	394.13 K	395.16 K	392.71 DE	
	M2	409.26 I	415.86 F	415.03 F	413.38 C	
S2	M0	326.76 X	339.93 U	333.73 W	333.47 G	346.41 C
	M1	351.56 S	356.76 R	349.90 T	352.74 F	
	M2	360.20 Q	362.56 P	336.26 V	353.01 F	
L.S.D.		LSD: SMB=19.060			LSD: SM=17.202	LSD: S=0.3534
S x B		B0	B1	B2		
S0		424.99 B	466.88 A	463.93 A		
S1		390.93 C	397.41 BC	398.22 BC	LSD: SB=17.202	
S2		346.18 D	353.09 D	339.97 D		
M x B		B0	B1	B2	Mean: M	
M0		367.31 C	378.24 C	376.20 C	373.91 C	
M1		389.19 CB	395.91 ABC	391.43 CB	392.17 B	
M2		405.60 ABC	443.22 A	434.49 AB	427.77 A	
L.S.D.		LSD: MB=17.202			LSD: M=0.3534	
Mean: B		387.36 C	405.79 A	400.70 B	LSD: B=0.3534	

Table (5) show that salt had a significant effect on shoot dry weight, with highest value observed at S0 (333.50 g) and the lowest under S2 (257.83 g). The highest value recorded with melatonin at M2 (321.61 g). Boron, gave highest weight at B1 (311.04 g). The interaction between M and B showed a significant effect, with highest weight recorded at M2B2 (324.70) g followed by M2B1 (323.26). The interaction between M and S recorded highest weight at S0M2 (349.99 g), and the interaction between B and S obtained highest values at both S0B2 and S0B1 (339.02) (335.21) g respectively. The interaction among the three factors gave significant differences, the highest value at S0M2B2 (356.30) g. Tomato plants exhibit varied responses to salt stress, as vegetative growth parameters-including shoot dry weight-decline significantly with increasing salinity compared to the control (Shyaa and Kisko, 2024). Salinity reduces plant dry

weight mainly due to osmotic stress, ionic toxicity, and impaired photosynthesis, which promote excessive production of reactive oxygen species (ROS) such as H_2O_2 and O_2^-. These free radicals damage chlorophyll and associated proteins, leading to reduced growth. Melatonin mitigates these adverse effects by regulating photosynthesis, stimulating antioxidant enzymes (CAT, POD), enhancing chlorophyll synthesis, and improving nitrogen and carbohydrate metabolism (Ghorbani *et al*., 2023). Its application enhances plant growth by increasing plant height, leaf number, and leaf area through improved photosynthetic efficiency (Brengi *et al*., 2022). Boron is an essential micronutrient for maintaining cell wall integrity and structure through its role in pectic polysaccharide cross-linking. It supports osmotic balance by regulating plasma membrane proteins such as proton pumps and aquaporins and influences the uptake and transport of key nutrients (Ca, Mg, K). These functions are vital for plant growth, yield, and tolerance to stress under saline conditions.

Table 5. The effect of melatonin and boron and their interactions on shoot dry weight under salt stress.

S	M	B			S x M	Mean: S
		B0	B1	B2		
S0	M0	308.36 HIJ	318.53 FGHI	321.53 EF	316.14 C	333.50 A
	M1	327.20 ED	336.73 CD	339.23 C	334.39 B	
	M2	343.30 BC	350.36 AB	356.30 A	349.99 A	
S1	M0	298.53 JKL	309.90 GHI	301.90 IJK	303.44 D	313.52 B
	M1	317.66 EFGH	319.50 EFG	314.40 FGH	317.19 C	
	M2	315.86 FGH	321.10 EF	322.80 EF	319.92 C	
S2	M0	252.83 N	256.36 N	249.60 N	252.93 G	257.83 C
	M1	277.13 M	288.53 L	273.30 M	279.65 F	
	M2	291.43 L	298.33 JKL	295.00 KL	294.92 E	
L.S.D.		LSD: SMB=10.358			LSD: SM=6.8121	LSD: S=3.4525
S x B		B0	B1	B2		
S0		326.29 AB	335.21 A	339.02 A		
S1		310.68 C	316.83 CB	313.03 CB	LSD: SB=6.8121	
S2		273.80 D	281.07 D	272.63 D		
M x B		B0	B1	B2	Mean: M	
M0		286.57 D	294.93 BCD	291.01 CD	290.84 C	
M1		307.33 ABCD	314.92 ABC	308.98 ABCD	310.41 B	
M2		316.86 AB	323.26 A	324.70 A	321.61 A	
L.S.D.		LSD: MB=6.8121			LSD: M= 3.4525	
Mean: B		303.59 C	311.04 A	308.23 B	LSD: B= 3.4525	

Table 6 shown that salinity had a negative effect, as the highest value was at S0 (8.9690). Melatonin gave highest value at M2 (9.4573), while clear significant differences were observed with boron, as highest value at B1 (8.6872). The interaction between M and B, recorded highest value at M2B1 (9.9810). Interact between M and S recorded highest value at S0M2 (9.7136). The same with interaction between B and S were showed highest value at S0B1 (9.3810). The interaction among M, B and S, where significant differences were observed, as it gave highest value at S0M2B1 (10.714). Melatonin helps plants improve growth and reproduction through several mechanisms: Stimulating flowering and fruit set. Melatonin regulates the balance of plant hormones (auxin, gibberellins, cytokinins), stimulating flower formation and improving the fruit set process, thus increasing the number of fruit produced, and reducing flower and new fruit drop: By increasing the efficiency of antioxidants (CAT, POD, SOD) and reducing the accumulation of free radicals, it protects floral tissue and new fruit from damage caused by salinity or stress. Boron is an element essential for successful fertilization and fruit set in fruit plants. It plays key roles in improving flower formation and fertilization, leading to increased fruit set and, consequently, fruit number, and strengthening cell walls in ovaries and young fruits. It is a component of pectin within cell walls, which maintains the cohesion of floral tissue and prevents fruit drop (Alpaslan and Güneş, 2001).

Table 7 found that when salinity increases the fruit weight decreases, as highest value was at S0 (157.26) g, and lowest value at S2 (130.30) g. Melatonin showed significant differences where the highest fruit weight was recorded at the M2. (149.97) g, in the boron treatment, the highest fruit weight was recorded at concentration B1 (146.97 g). The M-B interaction exhibited a clear and significant effect, as the highest value was found at M2B1 (152.23) g. Similarly, the interaction between B and S, a significant difference was found, fruit weight reached its maximum at the S0B2 (158.96 g) and S0B1 (158.21 g). The treatment of fruit with combination of M and S, gave a highest value at S0M2 (162.23) g. In addition, triple interaction of three factors have increase the weight of treated fruits, where highest value was at S0M2B1 (164.40) g. Melatonin enhances fruit weight under salt stress through several mechanisms: it stimulates photosynthesis, increasing the accumulation of sugars and carbohydrates necessary for fruit growth, reduces oxidative stress by limiting ROS (such as H_2O_2 and O_2^-), protecting fruit cells, regulates plant hormones to support fruit development and increase size, and improves nutrient uptake, including NPK, (Ghorbani *et al*., 2023). Boron, an element essential for fruit growth, contributes to increased fruit mass under salinity by strengthening fruit cell walls to prevent tissue breakage or premature fruit drop, enhancing the transport of sugars and nutrients from leaves to developing fruits, and mitigating damage from sodium and chloride accumulation, thereby maintaining normal fruit growth (Alpaslan and Güneş, 2001).

Table 6. The effect of melatonin and boron and their interactions on number of fruits under salt stress

S	M	B			S x M	Mean: S
		B0	B1	B2		
S0	M0	7.1423 U	8.5716 L	8.7143 K	8.1427 C	8.9690 A
	M1	8.7223 K	8.8573 J	9.5713 D	9.0503 B	
	M2	9.1423 H	10.714 A	9.2846 G	9.7136 A	
S1	M0	6.8773 W	6.9713 V	6.8716 W	6.9067 D	8.2707 B
	M1	7.8570 R	8.1423 P	8.7143 K	8.2379 C	
	M2	9.7163 C	9.8576 B	9.4283 F	9.6674 A	
S2	M0	6.1713 X	7.2853 T	7.4143 S	6.9570 D	8.0666 C
	M1	8.1276 Q	8.4143 N	8.2140 O	8.2520 C	
	M2	8.5146 M	9.3713 F	9.0863 I	8.9907 B	
L.S.D.		LSD: SMB=0.501			LSD: SM=0.4408	LSD: S=0.0033
S x B		B0	B1	B2		
S0		8.3356 CB	9.3810 A	9.1901 AB		
S1		8.1502 C	8.3237 CB	8.3381 CB	LSD: SB=0.4408	
S2		7.6045 C	8.3570 CB	8.2382 C		
M x B		B0	B1	B2	Mean: M	
M0		6.7303 F	7.6094 E	7.6667 E	7.3355 C	
M1		8.2356 D	8.4713 CD	8.8332 BC	8.5134 B	
M2		9.1244 B	9.9810 A	9.2664 B	9.4573 A	
L.S.D.		LSD: MB=0.4408			LSD: M=0.0033	
Mean: B		8.0301 C	8.6872 A	8.5888 B	LSD: B=0.0033	

Table 8 indicate significant differences in leaf chlorophyll content, compared to untreated plants. The harmful effect of salt on chlorophyll pigments was obvious at S2 with the lowest value (40.965), and highest value at S0 (48.861) Treatment of melatonin gave a positive effect, Melatonin treatment at the M2 concentration resulted in the highest chlorophyll content (47.932). Nevertheless, boron treatment increases the content of chlorophyll, compared to the control, the highest chlorophyll content was recorded at B1 (46.591). Significantly, an increase in chlorophyll content was observed when the plant was treated with a combination of M and B. The chlorophyll content value was high at M2B1 (49.380). B and S interacted significantly, leading to notable differences, as the highest value was at S0B1 (43.19). The interaction between three factors was also significant, where the highest value at S0M2B1 (54.230). Tomato plant exhibits sensitivity to mild salt stress, resulting in a decline in chlorophyll content and

photosynthetic efficiency as NaCl concentration increases, as seen in Table 8, corroborating the findings of researchers (Chen *et al*., 2025) Salinity affects total chlorophyll in plants by causing ion toxicity, which causes intracellular accumulation of Na^+ and Cl^- ions, leading to nutrient imbalances, particularly K and Mg deficiencies, which are essential components of chlorophyll (Singh *et al*., 2023). Salt stress disrupts electron flow in the electron transport chain, perhaps resulting in the photo-oxidation of thylakoid membrane proteins (Kappachery *et al*., 2024). Salt-induced osmotic stress leads to decreased stomatal conductance. High salinity also impairs the ability of roots to absorb water, causing cellular dehydration that slows photosynthesis and damages membranes and chloroplasts (Singh *et al*., 2024). Melatonin reduces sodium and chloride accumulation in plant leaves. Since melatonin enhances root growth, it contributed to increasing the levels of major nutrients (N, P, K, and Ca) in salt-stressed cucumber plants (Beringi *et al*., 2022). These nutrients, especially K and Mg, are essential components of the chlorophyll molecule. Therefore, melatonin promoted higher chlorophyll content, leading to improved plant growth. The application of exogenous boron enhanced photosystem efficiency and chlorophyll content, as indicated in Table 9. The elevation in chlorophyll levels is attributed to boron's pivotal role in chlorophyll synthesis, as it sustains the stability of chloroplast membranes-an essential component for the proper assembly of photosystems and effective electron transport during photosynthesis. Boron influences the activity of enzymes implicated in chlorophyll biosynthesis, facilitating the transformation of precursors into chlorophyll, excessive boron concentrations lead to the overproduction of ROS in the leaves, resulting in photo-oxidative damage to organic molecules and the chloroplast structure, ultimately causing a decline in chlorophyll content (Younis *et al*., 2024).

Table 7. The effect of melatonin and boron and their interactions on fruit weight under salt stress

S	M	B			S x M	Mean: S
		B0	B1	B2		
S0	M0	147.33 M	152.76 I	156.20 G	152.10 D	157.26 A
	M1	156.63 FG	157.46 ED	158.23 D	157.44 B	
	M2	159.83 C	164.40 A	162.46 B	162.23 A	
S1	M0	140.63 P	144.16 O	143.83 O	142.87 F	148.62 B
	M1	146.10 N	150.23 K	148.53 L	148.29 E	
	M2	151.63 J	157.03 EF	155.40 H	154.69 C	
S2	M0	126.63 V	128.16 U	125.66 W	126.82 H	130.30 C
	M1	129.83 T	133.26 R	130.16 T	131.08 G	
	M2	131.46 S	135.26 Q	132.23 S	132.98 G	
L.S.D.		LSD: SMB=1.9779			LSD: SM=1.9734	LSD: S=0.2593
S x B		B0	B1	B2		

S0	154.60 B	158.21 AB	158.96 A	
S1	146.12 D	150.47 C	149.25 CD	LSD: SB=1.9734
S2	129.31 E	132.23 E	129.35 E	
M x B	B0	B1	B2	Mean: M
M0	138.20 B	141.70 AB	141.90 AB	140.60 C
M1	144.19 AB	146.98 AB	145.64 AB	145.60 B
M2	147.64 AB	152.23 A	150.03 A	149.97 A
L.S.D.		LSD: MB=1.9734		LSD: M=0.2593
Mean: B	143.34 C	146.97 A	145.86 B	LSD: B=0.2593

Table 8. The effect of melatonin and boron and their interactions on total chlorophyll under salt stress.

S	M	B			S x M	Mean: S
		B0	B1	B2		
S0	M0	44.760 J	47.136 H	45.993 I	45.963 C	48.861 A
	M1	47.866 FG	49.470 D	47.820 G	48.385 B	
	M2	50.546 C	54.230 A	51.926 B	52.234 A	
S1	M0	42.193 M	43.746 K	41.340 O	42.426 D	45.853 B
	M1	45.840 I	47.740 G	44.756 J	46.112 C	
	M2	48.460 E	50.513 C	48.093 F	49.022 B	
S2	M0	37.743 Q	39.416 P	36.863 R	38.007 E	40.965 C
	M1	41.930 N	43.670 K	41.440 O	42.347 D	
	M2	42.213 M	43.396 L	42.013 MN	42.541 D	
L.S.D.			LSD: SMB=1.2311		LSD: SM=1.0514	LSD: S=0.077

S x B	B0	B1	B2	
S0	47.724 CB	50.279 A	48.580 AB	
S1	45.498 CD	47.333 CB	44.730 D	LSD: SB=1.0514
S2	40.629 E	42.161 E	40.105 E	
M x B	B0	B1	B2	Mean: M
M0	41.565 D	43.433 CD	41.399 D	42.132 C
M1	45.212 BC	46.960 AB	44.672 BCD	45.614 B
M2	47.073 AB	49.380 A	47.344 AB	47.932 A
L.S.D.		LSD: MB=1.0514		LSD: M=0.077
Mean: B	44.617 B	46.591 A	44.472 C	LSD: B=0.077

Table 9 noted that there direct relationship between salt and proline with highest value appearing at S2 (99.258) and the lowest value at S0 (64.000), while the melatonin gave the highest value at M0 (83.740) and the lowest value at M2 (77.703), for boron, found that highest rate recorded at B2 (82.703) and the lowest rate at B1 (78.778), while in the interaction between M and B, observed highest value recorded at M0B2 (85.332), and the lowest value recorded at M2B1 (76.000), when interacting between B and S, the highest value was given at S2B2 (101.33), when interacting between M and S, found that highest value recorded at S2M0 (101.89) and lowest value recorded at S0M2 (61.222), while the interaction among the three factors found a clear significant difference, as it gave highest value at S2M0B0 (105.00). Plants may respond variably to salt stress by markedly enhancing qualitative features, such as total chlorophyll, proline content, and yield per plant, in comparison to untreated control plants; this phenomenon is attributed to disruptions in physiological systems (Shyaa and kisko, 2024). Table 9 illustrates that proline content escalates with increasing sodium chloride concentration, these molecules act as markers of plant stress. The proline concentration in tomato leaves markedly elevated under salt stress relative to non-stressed plants. The administration of exogenous melatonin resulted in a decrease in proline accumulation in plants subjected to salt stress (Brengi *et al*., 2022). Salt stress enhances the antioxidant defense system in tomato plants, consistent with previous research (Ghorbani *et al*., 2023). Boron modulates osmotic equilibrium, hence diminishing proline accumulation (Table 9). Boron may enhance antioxidant enzyme systems or directly eliminate ROS, therefore reducing oxidative stress levels (Younis *et al*., 2024).

Table 9. The effect of melatonin and boron and their interactions on proline content under salt stress.

S	M	B			S x M	Mean: S
		B0	B1	B2		
S0	M0	63.667 M	66.667 L	69.000 L	66.440 F	64.000 C
	M1	62.333 MN	63.667 M	67.000 L	64.333 F	
	M2	59.333 O	60.667 NO	63.667 M	61.222 G	
S1	M0	83.667 G	79.333 HI	85.667 G	82.889 C	79.259 B
	M1	80.333 H	77.333 IJ	80.667 H	79.444 D	
	M2	77.333 IJ	74.667 JK	74.333 K	75.444 E	
S2	M0	105.00 A	99.333 CD	101.33 CB	101.89 A	99.258 A
	M1	100.33 C	94.667 EF	103.33 AB	99.444 A	
	M2	97.333 DE	92.667 F	99.333 CD	96.444 B	
L.S.D.		LSD: SMB=2.6917			LSD: SM=2.6865	LSD: S=0.8972
S x B		B0	B1	B2		
S0		61.778 F	63.667 EF	66.556 E		
S1		80.444 C	77.111 D	80.222 C	LSD: SB=2.6865	
S2		101.89 A	95.556 B	101.33 A		
M x B		B0	B1	B2	Mean: M	
M0		84.111 A	81.778 A	85.332 A	83.740 A	
M1		81.000 A	78.556 B	83.666 A	81.074 B	
M2		78.000 B	76.000 B	79.111 B	77.703 C	
L.S.D.		LSD: MB=2.6865			LSD: M=0.8972	
Mean: B		81.037 B	78.778 C	82.703 A	LSD: B=0.8972	

The data in Table 10 indicate that the activity of the catalase enzyme in plant leaves is influenced by salt concentration. In S0 treatment, the highest rate was (169.03), compared to S2, which exerted the lowest rate (138.63). In the treatment with melatonin the highest rate was reached at M2 (165.14). A significant difference was also noticed when boron is used, where the highest value was at B2 (159.26). The interaction between M and B also had a significant effect, reaching the highest value at M2B2 (168.55). In B and S interaction, Notable differences were recorded, as demonstrated in the table, as it gave the highest value at S0B2 (173.00), and the second interaction of M and S also showed a significant difference, with the highest value reaching at S0M2 (175.55). Similarly, significant differences were found when the combination of M, B and S are used, the highest value for enzyme activity was found at S0M2B2 (177.66). Under conditions of high salinity, the activities of catalase (CAT) and peroxidase (POD) significantly decline due to enzyme inactivation and damage, suppression of gene expression, and ionic and nutrient imbalances. Excessive sodium interferes with the uptake of essential cofactors, such as K^+, Ca^{2+}, and Mg^{2+}, which are crucial for optimal enzymatic function. Ionic toxicity also impairs metabolic regulation (Habibi *et al*., 2025). Melatonin application alleviates the adverse effects of salt stress. It plays a crucial role in multiple physiological and metabolic processes, including the regulation of photosynthesis, stimulation of antioxidant enzymes such as catalase. Exogenous melatonin markedly enhances the activity of the catalase. Application of boron has been employed to mitigate the impact of salt stress on plants. Boron is crucial for optimal plant growth and development. The principal roles encompass, maintaining cell wall structure and stability and regulating hormone levels and gene expression (Thakur *et al*., 2025). Boron may enhance antioxidant enzyme systems or directly eliminate ROS, therefore reducing oxidative stress levels (Younis *et al*., 2024). Boron influences plant responses to abiotic stresses by maintaining cell integrity, osmotic balance, and water relations.

Table 11 indicate that there were noticeable differences in the plant yield traits. And indirect relationship between salinity and plant yield, the highest total yield was recorded under the S0 treatment (1414.3 g), while the lowest was observed at S2 (1053.4 g). Regarding melatonin treatment, the highest yield was obtained at M2 (1422.9 g). Likewise, when boron treatment was applied, a significant difference was observed, with the highest rate at B1 (1284.9) g, when B reacts with S, a significant difference is also found, the highest value was at S0B1 (1488.5) g. as M reacts with S, the result displays significant differences, the highest value was at S0M2 (1577.0) g. The interaction between M and B showed a significant difference, with the highest value observed at M2B1 (1525.6) g. regarding the triple interaction of M, B and S, there were notable differences, the highest average was obtained was S0M2B1 (1761.4) g. Cl^- poisoning leads to inhibited growth, leaf chlorosis, and reduced plant biomass (Desai *et al*., 2023). Melatonin enhances plant productivity under salt-stress conditions through several mechanisms. It promotes vegetative and reproductive growth by regulating plant hormones, thereby stimulating the development of more leaves, flowers, and fruit set. Additionally, it improves nutrient uptake, particularly NPK, supporting overall growth and yield (Ghorbani *et al*., 2023). Boron is essential for increasing plant productivity. It enhances fruit set by supporting pollen tube growth, increases fruit weight and quality by strengthening cell walls and preventing small fruit drop, and improves the transport of sugars and nutrients from leaves to developing organs (buds, flowers, and fruits) (Alpaslan and Güneş, 2001). Boron also facilitates carbohydrate translocation, leading to higher concentrations of glucomannan and soluble sugars, which contribute to longer shelf life and increased individual fruit weight (Dong *et al*., 2021).

Table 10. The effect of melatonin and boron and their interactions on catalase content under salt stress.

S	M	B			S x M	Mean: S
		B0	B1	B2		
S0	M0	153.00 HI	162.00 F	166.33 E	160.44 C	169.03 A
	M1	166.66 E	171.66 D	175.00 BC	171.11 B	
	M2	172.33 D	176.66 AB	177.66 A	175.55 A	
S1	M0	141.66 M	147.66 L	150.33 JK	146.55 E	157.11 B
	M1	151.00 IJK	157.66 G	162.33 F	157.00 C	
	M2	161.33 F	168.33 E	173.66 CD	167.77 B	
S2	M0	121.33 Q	128.33 P	132.00 O	127.22 G	138.63 C
	M1	130.66 O	137.33 N	141.66 M	136.55 F	
	M2	149.66 KL	152.33 HIJ	154.33 H	152.11 D	
L.S.D.		LSD: SMB=4.902			LSD: SM=4.2371	LSD: S=0.7301
S x B		B0	B1	B2		
S0		164.00 CB	170.11 AB	173.00 A		
S1		151.33 ED	157.88 CD	162.11 CB	LSD: SB=4.2371	
S2		133.88 G	139.33 FG	142.66 EF		
M x B		B0	B1	B2	Mean: M	
M0		138.66 E	146.00 DE	149.55 CDE	144.74 C	
M1		149.44 CDE	155.55 BCD	159.66 ABC	154.88 B	
M2		161.11 ABC	165.77 AB	168.55 A	165.14 A	
L.S.D.		LSD: MB=4.2371			LSD: M=0.7301	
Mean: B		149.74 C	155.77 B	159.26 A	LSD: B=0.7301	

Table 11. The effect of melatonin and boron and their interactions on productivity of one plant under salt stress.

S	M	B			S x M	Mean: S
		B0	B1	B2		
S0	M0	1052.3 P	1309.4 H	1361.1 G	1241.0 C	1414.3 A
	M1	1366.2 G	1394.7 F	1514.5 C	1425.1 B	
	M2	1461.2 E	1761.4 A	1508.4 C	1577.0 A	
S1	M0	967.18 S	1005.0 Q	988.37 R	986.9 E	1234.7 B
	M1	1147.9 M	1223.2 K	1294.3 I	1221.8 C	
	M2	1473.3 D	1547.9 B	1465.1 E	1495.4 B	
S2	M0	781.49 U	933.73 T	931.73 T	882.3 F	1053.4 C
	M1	1055.2 P	1121.3 N	1069.1 O	1081.9 D	
	M2	1119.3 N	1267.6 J	1201.5 L	1196.1 C	
L.S.D.		LSD: SMB=86.369			LSD:SM=77.637	LSD: S=2.1233
S x B		B0	B1	B2		
S0		1293.2 CB	1488.5 A	1461.3 AB	LSD: SB=77.637	
S1		1196.1 CDE	1258.7 CD	1249.3 CD		
S2		985.3 F	1107.5 DEF	1067.4 EF		
M x B		B0	B1	B2	Mean: M	
M0		933.7 F	1082.7 EF	1093.7 DE	1036.7 C	
M1		1189.8 CDE	1246.4 BCD	1292.6 BC	1242.9 B	
M2		1351.3 B	1525.6 A	1391.7 AB	1422.9 A	
L.S.D.		LSD: MB=77.637			LSD: M=2.1233	
Mean: B		1158.2 C	1284.9 A	1259.3 B	LSD: B=2.1233	

CONCLUSION

Salinity stress markedly reduced growth and yield characteristics in tomato plants. Nonetheless, the foliar treatment of melatonin at 400 mg/L (M2) and boron at 5 mg/L (B2), particularly in conjunction (M2B1), significantly alleviated the adverse impacts of salt. The M2B1S0 interaction exhibited the greatest values for many morphological and physiological parameters, including plant height, leaf area, dry weight, fruit production, and chlorophyll content. This therapy decreased proline build-up and augmented antioxidant activity, signifying greater stress tolerance. The concurrent administration of melatonin and boron can improve tomato performance in both saline and non-saline circumstances, providing an effective technique for enhancing crop output in salt-affected regions.

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