Journal of Applied Horticulture, 27(1): 51-56, 2025
https://doi.org/10.37855/jah.2025.v27i01.10
Journal of Applied Horticulture
ISSN: 0972-1045

Potential impacts of gibberellic acid to promote salinity tolerance in tomato

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Abstract

Salinity is an important concern for crop production, especially in dry areas and gibberellic acid has shown promise in improving salinity tolerance. The purpose of this research was to examine the ability of gibberellic acid (GA_3) to mitigate salinity stress in tomato plants. The experiment used BARI Hybrid Tomato-5 to investigate the effects of two GA_3 dosages (0 and 100 ppm) on plant growth, physiology, and yield parameters in normal and stressed conditions (50, 100, and 150 mM NaCl). Salinity revealed a negative effect on tomato plants in terms of plant height, leaf and branch numbers, flowering and fruiting phases, and physiological features such as photosynthetic pigments, relative leaf water content, electrolyte leakage, proline content, and stomatal conductance including Na^+ and K^+ ions of plants. The foliar spray of GA_3 was useful in enhancing the salt tolerance of tomato plants and stimulated the growth of unstressed plants, resulting in increasing tomato yield.

Key words: Tomato, salinity, abiotic stress; gibberellic acid, tomato, photosynthetic pigments

Introduction

Tomato (*Lycopersicon esculentum* Mill.) is the second-most popular vegetable consumed worldwide after potato and a rich source of vitamins and minerals (Athinodorou *et al.*, 2021). It provides an ample amount of nutrients including potassium, folic acid, vitamin C, carotenoids, vitamin A, β-carotene, and lycopene (Salim *et al.*, 2020). Various factors can influence tomato productivity and fruit nutritional quality. Salinity is one of the most important environmental stresses in the world's arid and semi-arid regions, affecting agricultural production significantly. Regarding this matter, salinity impacts around 20% of the world's farmed land roughly 50% of its irrigated land, leading to a yield drop of main crops of over 50% (Maach *et al.*, 2021). Moreover, salinity can result in a number of ionic and osmotic disorders that can inhibit the absorption of water and essential ions, reduce turgidity, and cause metabolic disorders which display as altered growth regulator levels, enzymatic inhibition, and metabolic imbalance, including photosynthesis, which eventually cause plant death (Arif *et al.*, 2020; Hasanuzzaman *et al.*, 2022). In salt stress, Na^+ decreases essential nutrients such as K^+ and Ca^{2+} in plants (Iqbal and Ashraf, 2013). Increased salinity levels in soil change its physical composition, decreasing its hydraulic and water-holding capacities as well as its porosity (Sassine *et al.*, 2020). Salinity affects almost all features of tomato growth, including germination, physiological development and growth during reproduction (Rosca *et al.*, 2023). Salinity significantly affects the tomato plant by causing a drastic reduction in growth and yield (Tanveer *et al.*, 2020). Tomato production reduced drastically even at 5 dSm^{-1} salinity due to smaller, fewer, and less dry matter accumulation within the fruits, which all have a direct effect on fruit yields (Sora, 2023).

Gibberellic acid (GA_3) supplementation applied exogenously to various crops resulted in enhanced growth of seedlings and plants and improved post-harvest survival, increased resistance to abiotic stressors such as heat, salinity, and drought (Vetrano *et al.*, 2020). Turan *et al.* (2014) demonstrated that GA_3 enhances salt-stressed plants germination and seedling growth. Gibberellic acid (GA_3) increased under salinity and modulated by improving redox metabolism, sugar signaling, and osmolyte production (Rao *et al.*, 2016). Exogenous GA_3 application has increased electrolyte leakage, chlorophyll content, relative water content and plant growth by counteracting the harmful effects of salt stress in pea crops (Gurmani *et al.*, 2022). The use of GA_3 proved to be helpful in reducing the detrimental impacts of salt stress on lettuce plant development and biochemical parameters (Miceli *et al.*, 2019).

Gibberellic acid plays a critical role in the regulation of plant growth under salt stress conditions. However, evidence on the actual applications of gibberellic acid against salt stress in tomato production under tropical circumstances is limited. Given the information presented above, our purpose was to determine the effect of gibberellic acid on the morpho-physio-chemical traits as well as yield of tomato plants under salinity stress.

Materials and methods

Raising of plants: Tomato (BARI Hybrid Tomato-5) was employed as test material for this study. This experiment was conducted at the Central Research Farm of Sher-e-Bangla Agricultural University, Dhaka-1207 (90°33' E longitude and 23°77' N latitude) in November 2022 to May 2023. The plants were cultivated in earthenware pots that were 30 cm tall, 25 cm wide, and 14.72 L in volume. A 2:1:1 (v/v/v) ratio of air-dried soil, sand, and farmyard manure was used to fill the pots, along with the recommended dose of fertilizers. The shallow red-brown terrace soil with silty clay in the experimental plot belonged to the general soil type. Two seedlings were transplanted in each pot. The requisite activities such as irrigation, weeding, and applying pesticides were carried out as required throughout the periods of growth.

Treatments and design: The tomato variety was tested with four different levels of salt concentrations *viz.,* 0, 50, 100 and 150 mM NaCl and two doses of gibberellic acid (GA_3) *viz.,* 0 and 100 ppm were used as a mitigating agent against salinity. Each of the treatments was replicated three times maintaining Completely randomized design (CRD). The salts were implemented through irrigation water in three splits at 30, 50 and 70 DAT. Using a hand sprayer, the GA_3 solution was applied through foliar spray to the plants during the initial stages of flowering and fruiting to lessen the consequences of Na^+ stress.

Photosynthetic pigments: In order to determine the chlorophyll concentration, fresh leaves weighing 1.0 g were homogenized in 80% acetone before being centrifuged for 10 minutes at 5,700 g. The absorbance of the supernatant was measured at 645 and 663 nm, and the concentration of total chlorophyll was computed using 80% acetone as a baseline (Arnon,1949). Chlorophyll concentration was determined as follows:

$$\text{Chlorophyll a (mg g}^{-1}\text{ FW)} = \frac{(12.7 \times A663 - 2.69 \times A645) \times V}{1000 \times W}$$

$$\text{Chlorophyll b (mg g}^{-1}\text{ FW)} = \frac{(22.9 \times A645 - 4.68 \times A663) \times V}{1000 \times W}$$

$$\text{Total Chlorophyll (mg g}^{-1}\text{ FW)} = \frac{(20.2 \times A645 + 8.02 \times A663) \times V}{1000 \times W}$$

$$\text{Carotenoids (mg g}^{-1}\text{ FW)} = \frac{1000 \times A470 \times V/(W \times 1000) - (1.82 \times \text{Chl a}) - (85.02 \times \text{Chl b})}{198}$$

Where V represents volume, W represents tissue weight, A663, A645 and A470 indicate absorbance at 663 nm, 645 nm and 470 nm, respectively. The concentration of total chlorophyll is expressed in mg g^{-1} FW.

Relative leaf water content (RLWC): The method developed by Barrs and Weatherley (1962) was used to determine RLWC. A sample of 100 mg of leaf tissue was obtained from plants under stress as well as control. The leaves were placed in a petri dish and soaked in distilled water for two hours. Later, they were taken out, blotted dry and weighed again (turgid weight). Following a 24-hour oven-drying period at 110°C, the leaves were re-weighed to determine their dry weight. The calculation for the relative leaf water content was as follows:

$$\text{RLWC (\%)} = \frac{\text{Fresh weight - Dry weight}}{\text{Turgid weight - Dry weight}} \times 100$$

Electrolyte leakage: The leaves surrounding the flowers were harvested from plants cultivated under standard and late-sown circumstances. Electrolyte leakage was used to assess the permeability of the cell membrane in a methodical manner as described by Lutts *et al.* (1996). The leaf segments were cleaned with deionized water, then placed into sealed vials with 10 mL of deionized water and incubated for a night at 25°C. After 24 hours, the electrical conductivity of the bathing solution (C_1) was measured. After equilibration at 25°C and exposing the samples to a scalding water bath for ten to fifteen minutes, the final conductivity reading (C_2) was obtained (Kaushal *et al.*, 2013). The formula of electrolyte leakage (EL) was as follows:

$$\text{Electrolyte leakage (EL) (\%)} = \frac{C_1}{C_2} \times 100$$

Proline content: The proline level was determined by homogenizing fresh leaves in 10 mL of 3% aqueous sulfosalicylic acid solution. The filtrate was combined with 2 mL of acid-ninhydrin and 2 mL of glacial acetic acid before being immersed in a 100° C water bath for 1 hour. This one was divided with 4 mL of toluene and measured at 520 nm with a spectrophotometer, T80 + UV/VIS China (Bates *et al.*, 1973).

Stomatal conductance: A portable leaf porometer (model SC1; Decagon Devices, Pullman, WA, USA) was used to measure the stomatal conductance of the top completely expanded leaves (Kaushal *et al.*, 2013).

Na and K contents in plant: Plant samples were oven dried for 48 hours at 80°C. Dried materials were crushed and acid digested in an HNO_3:$HClO_4$ (5:1 v/v) combination at 80°C. Na and K concentrations were determined using a flame atomic absorption spectrophotometer (Nahar *et al.*, 2016).

Statistical analyses: An analysis of variance (ANOVA) was executed on the collected data, and then, the Duncan's Multiple Range Test (DMRT) values (P<0.05) was applied for comparing various treatment means using SPSS software (IBM SPSS, version 26.0, Chicago, IL, USA). The means were assessed utilizing descriptive statistics, which were expressed as Mean ± SE.

Results

Plant height: Plant height significantly differed ($P < 0.05$) with gibberellic acid (GA_3) application under salinity stress (Table 1). Under control conditions, the tallest plant was recorded in GA_3 (100 ppm) treatment. The collected data showed that plant height decreased in 150 mM NaCl by 24.79% over control plants. Likewise, raised plant height in the salt-stressed condition was found in GA_3 (100 ppm), in 10.18% more than untreated control.

Number of branches per plant: The number of branches per plant differed significantly ($P < 0.05$) by the salinity stress (Table 1). Among the different salinity stresses, control showed the maximum number of branches per plant while, 150 mM NaCl showed the minimum number of branches by 48.28% reduction over control plants. On the other hand, plants treated with GA_3 (100 ppm) increased the branch number by 13.8% in salinity stressed plant compared to control.

Number of leaves per plant: Under conditions of salinity stress, the number of leaves per plant varied significantly ($P < 0.05$) (Table 1). The control plant displayed the maximum number of leaves per plant. In contrast, 150 mM NaCl showed

the minimum number of leaves per plant by 48.27% decreased over control plants. However, GA_3 (100 ppm) stimulate the growth parameter in salt stressed plants which ultimately increased the leaf number by 13.79% over control plants.

Days to flower bud initiation: Days to flower bud initiation after transplanting varied greatly ($P < 0.05$) by the salinity stress (Table 1). The lowest days required for first flower bud initiation after transplanting were observed from control plants whereas, plants with 150 mM NaCl stress required extra 12 days for flower bud initiation over control plants. On the other side, data observed from GA_3 (100 ppm) application in stressed plants reduced days number by 6 days in 150 mM NaCl affected plants.

Days to fruit setting: Days to fruit initiation after transplanting differed significantly ($P < 0.05$) by the salinity stress (Table 1). Data revealed that salinity affected plants (150 mM NaCl) required the maximal number of days for first fruit initiation by 17 days more over control plants. However, GA_3 (100 ppm) application stimulated the early fruiting in salt stressed plants which ultimately reduced the days number by 7 days over 150 mM NaCl affected plants.

Table 1. Gibberellic acid effect on morpho-physiological traits of salt stressed tomato plant

Bioregulators	NaCl (mM)	Plant height (cm)	No. of branches/ plant	No. of leaves/ plant	Days to flower bud initiation	Days to fruit setting
Control	0	110.00 ± 6.70ab	5.80 ± 0.32ab	14.50 ± 0.75ab	36.00 ± 1.15cd	46.0 ± 2.31c
	50	100.33 ± 8.78bc	4.90 ± 0.58cd	12.25 ± 0.58e	40.00 ± 1.73bc	52.00 ± 1.73bc
	100	90.33 ± 2.83c	4.00 ± 0.12e	10.00 ± 0.29f	44.00 ± 2.89ab	57.00 ± 2.89ab
	150	82.73 ± 5.20abc	3.00 ± 0.26bc	7.50 ± 0.17cd	48.00 ± 2.31a	63.00 ± 3.46a
GA_3 (100 ppm)	0	125.17 ± 11.46a	6.50 ± 0.29a	16.25 ± 0.87a	30.00 ± 1.15d	43.00 ± 1.15c
	50	108.67 ± 10.88ab	5.50 ± 0.17b	13.75 ± 1.15bc	37.00 ± 1.73bc	49.00 ± 5.20bc
	100	97.90 ± 5.95bc	4.50 ± 0.32cd	11.25 ± 0.75de	40.00 ± 3.46bc	52.00 ± 1.73bc
	150	93.93 ± 3.82bc	3.80 ± 0.23de	9.50 ± 0.29e	42.00 ± 1.73abc	56.00 ± 2.31ab

Values represent means ± SE ($n = 3$) along with DMRT values ($P < 0.05$). Different letters in a column for a trait indicate significant differences. DMRT = Duncan multiple range test; SE = Standard error

Photosynthetic pigment content: Photosynthetic pigments were significantly affected ($P < 0.01$) by salinity stress (Fig. 1). Compared to control, chlorophyll *a,* chlorophyll *b*, total chlorophyll and carotenoid contents were reduced by 29.45%, 48.18%, 41.18% and 16.22% with 150 mM NaCl affected plants, respectively. However, plants with GA_3 (100 ppm) application in salt stressed plants increased chlorophyll *a,* chlorophyll *b*, total chlorophyll and carotenoid contents by 6.44%, 8.76%, 7.91% and 10.81%, respectively compared to control. On the other hand, GA_3 with control treatment gave the highest number of photosynthetic pigments.

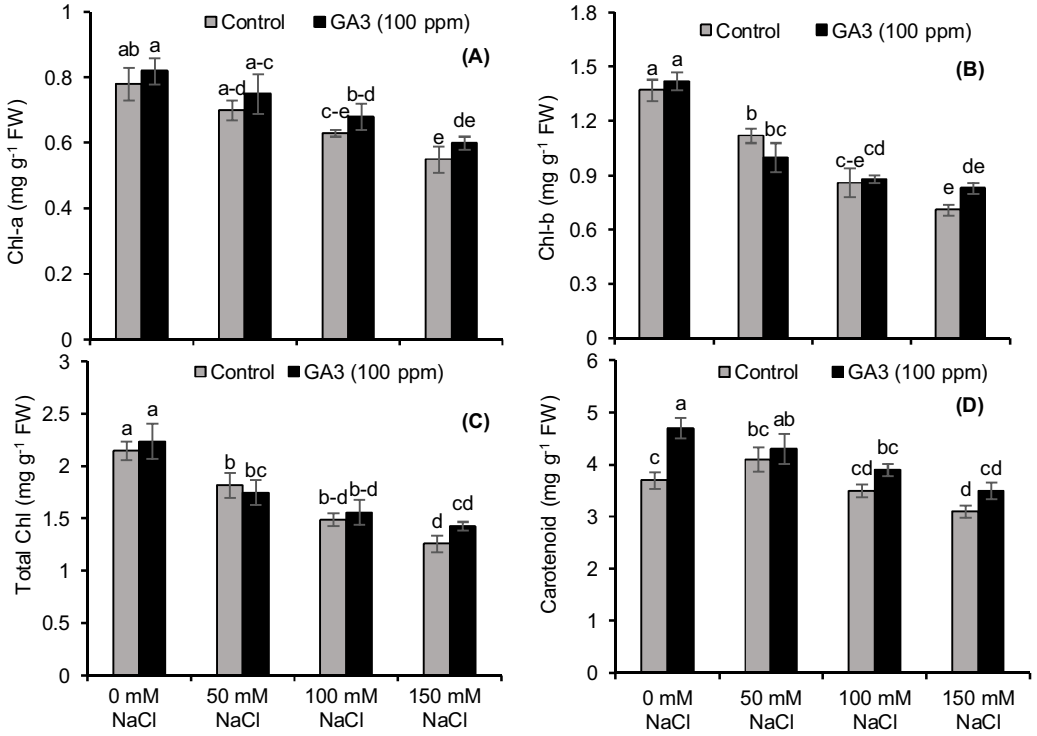

Fig. 1. Gibberellic acid effect on photosynthesis pigments (A) chlorophyl-a, (B) chlorophyl-b, (C) total chlorophyl and (D) carotenoid content of salt stressed tomato plant. Values represent mean ± SE ($n = 3$); vertical bars indicate SE. Different letters within a trait indicate significant differences.

Leaf relative water content: Salinity considerably decreased ($P < 0.01$) the relative water content (Table 2). RWC of tomato plant decreased 21.34% by 150 mM NaCl compared to control plant. However, plants treated with GA_3 (100 ppm) application enhanced RWC by 19.57% under salinity stress.

Electrolyte leakage: The application of GA_3 and salinity stress had a substantial ($P < 0.05$) impact on electrolyte leakage (Table 2). The treatment of GA_3 had no effect on electrolyte leakage under untreated control conditions and plants exhibited the lowest level of electrolyte leakage. Conversely, when subjected to salt stress, plants under 150 mM NaCl performed the highest levels of electrolyte leakage. Under salt stress conditions, electrolyte leakage was much higher in all treatments than that of control plants.

Nevertheless, GA_3 was able to effectively reduce the electrolyte leakage when compared alone to the stressed plants.

Proline content: Salinity stress had a substantial impact ($P < 0.01$) on proline concentration (Table 2). In salt-stressed plants, proline content increased significantly in comparison to control. On the other hand, when GA_3 (100 ppm) was applied to salt-stressed plants, the amount of proline was considerably lower than in control and untreated stressed plants. GA_3 displayed a noticeable decrease of proline content by 52.79% over control.

Stomatal conductance: Significant ($P < 0.01$) changes in stomatal conductance were found (Table 2). The stomatal conductance varied as a result of the combined effects of

salinity and GA_3. Under control conditions, GA_3 (100 ppm) treated plants showed the highest stomatal conductance. On the other hand, higher salt stress caused a maximum reduction of stomatal conductance. However, stomatal conductance increased under stressful condition in GA_3 (100 ppm) by 44.07% with 150 mM NaCl.

Table 2. Gibberellic acid effect on leaf relative water content, electrolyte leakage, proline content and stomatal conductance of salt stressed tomato plant

Bioregulators	NaCl (mM)	LRWC (%)	Electrolyte leakage (%)	Proline content (µg g^{-1})	Stomatal conductance (mmol m^2 s^{-1})
Control	0	52.63 ± 2.65bcd	12.43 ± 0.38bc	1.97 ± 0.04d	188.10 ± 11.84ab
	50	52.33 ± 3.87bcd	13.41 ± 0.70abc	3.45 ± 0.12ab	171.70 ± 13.48b
	100	48.23 ± 2.00cd	14.56 ± 1.27ab	3.73 ± 0.17a	110.67 ± 8.72c
	150	41.40 ± 1.03d	15.67 ± 0.87a	3.97 ± 0.43a	67.87 ± 6.00d
GA_3 (100 ppm)	0	65.27 ± 4.74a	11.94 ± 0.57c	2.17 ± 0.09d	219.70 ± 17.44a
	50	60.37 ± 3.32ab	12.90 ± 0.25bc	2.26 ± 0.02d	220.30 ± 11.84a
	100	54.90 ± 5.83abc	13.44 ± 0.29abc	2.57 ± 0.09cd	150.77 ± 17.49b
	150	51.70 ± 2.65bcd	13.96 ± 0.66abc	2.93 ± 0.17bc	80.53 ± 3.06cd

Values represent means ± SE (n = 3) along with DMRT values (P <0.05). Different letters in a column for a trait indicate significant differences. LRWC = Leaf relative water content; DMRT = Duncan multiple range test; SE = Standard error.

Yield components: The treatment of GA_3 and the salt stress had a significant (P < 0.01) impact on all yield contributing attributes. The highest number of flower clusters/plant was found in GA_3 (100 ppm) treatment that was 41.37% more than the control (Table 3). The lowest flower cluster number was found in salinity stress condition. On the other hand, the foremost value was obtained in the GA_3 (100 ppm) treatment under salinity stress (150 mM NaCl), which was 29.68% higher than the control condition.

The maximum number of flowers per plant was attained from GA_3 (100 ppm) treatment (Table 3). In comparison to control, GA_3 (100 ppm) produced 45% more flower $plant^{-1}$ but under salt stress conditions (150 mM NaCl), control plants had the fewest flower $plant^{-1}$, that was 55.56% less than control. Conversely, the highest value of flower $plant^{-1}$ under salt stress conditions (150 mM NaCl) was seen in the GA_3 (100 ppm) treatment, which was 33.34% greater than the control condition.

The highest number of fruits per plant was observed in GA_3 (100 ppm) treatment that was 48.57% more than the control condition (Table 3). However, salinity affected plants showed the lowest fruit number $plant^{-1}$. In contrast, the highest value was observed in GA_3 (100 ppm) application under salinity stress (150 mM NaCl) condition which was 29.68% more than control condition. A remarkable reduction of fruit yield per plant was recorded with the salinity stress (Table 3). The highest yield was obtained from GA_3 (100 ppm) application, and it exceeded the control treatment by 48.80% in normal condition. On the contrary, in salinity stress (150 mM NaCl) higher value was gained from GA_3 (100 ppm) application and it was 24.70% higher than control treatment.

Table 3. Gibberellic acid effect on yield traits and yield of salt stressed tomato plant

Bioregulators	NaCl (mM)	No. of flower clusters/plant	No. of flowers/ plant	No. of fruits/ plant	Yield/plant (kg)
Control	0	9.67 ± 0.67b	18.00 ± 1.04bc	17.50 ± 0.64b	1.66 ± 0.09b
	50	7.77 ± 0.23cd	16.00 ± 0.64cd	14.00 ± 0.87c	1.33 ± 0.09bc
	100	6.20 ± 0.20e	12.00 ± 0.29e	9.00 ± 0.58d	0.86 ± 0.02de
	150	3.93 ± 0.07f	8.00 ± 0.40f	6.50 ± 0.17e	0.62 ± 0.02e
GA_3 (100 ppm)	0	13.67 ± 0.67a	26.10 ± 1.67a	26.00 ± 1.44a	2.47 ± 0.29a
	50	9.67 ± 0.33b	20.00 ± 1.27b	15.00 ± 1.15c	1.42 ± 0.08b
	100	8.77 ± 0.23bc	18.00 ± 1.04bc	14.50 ± 0.64c	1.38 ± 0.07bc
	150	6.80 ± 0.20de	14.00 ± 0.52de	11.00 ± 0.46d	1.03 ± 0.04cd

Values represent means ± SE (n = 3) along with DMRT values (P < 0.05). Different letters in a row for a trait indicate significant differences. DMRT = Duncan multiple range test; SE = Standard error.

Mineral (Na^+ and K^+) content: Mineral contents were significantly affected (P < 0.01) by salinity stress (Fig. 2). Compared to control, Na^+ content was increased by 67% with 150 mM NaCl treated plants. However, plants with the treatment of GA_3 (100 ppm) application reduced Na^+ content by 50.97% in salt stressed plants compared to control. On the other hand, higher salt stress (150 mM NaCl) caused a maximum reduction of K^+ content by 52.02% over control plants, whereas plants treated with GA_3 (100 ppm) application increased K^+ content by 65.88% in salt stressed plants than that of control.

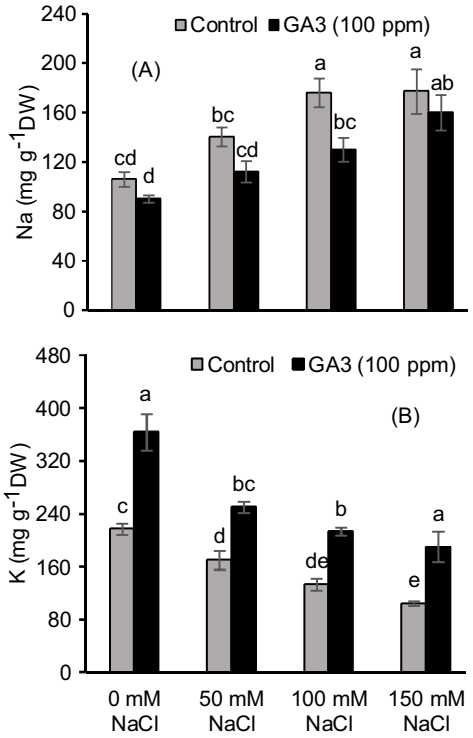

Fig. 2. Gibberellic acid effect on mineral (A) sodium and (B) potassium content of salt stressed tomato plant. Values represent mean ± SE (n = 3); vertical bars indicate SE. Different letters within a trait indicate significant differences.

Discussion

The results of this experiment show that gibberellic acid reduces the effects of salt in tomato plants by regulating their growth and development. The salinity stress had a significant impact on the growth characteristics and development barriers of tomato plants, causing a delay in flowering and fruiting (Table 1). The most common symptom of salt stress in plants is generally a decline in their growth rate (Zahra *et al.*, 2020). The use of plant regulators creates a favorable environment by releasing nutrients that promote the growth characteristics of plants. Applying the proper amount of particular plant regulators during salt stress situations can enhances the growth, development, and production of a number of crops (Iqbal and Ashraf, 2013). Experiments conducted with GA_3 demonstrated statistically significant improvements in all growth indices, such as the height of the plant, the number of branches, and the number of leaves produced by each plant

(Azab, 2018). Additionally, plant growth regulators enhance vegetative development by raising metabolic and photosynthetic activity which in turn facilitates greater photosynthetic product transport and utilization, ultimately leading to earlier flowering (Sarkar *et al.*, 2014).

Photosynthesis rate is the key determinant of plant survival in unbalanced environments. Results showed that photosynthetic pigments varied throughout the experiment, with the greatest decrease shown in salt-stressed plants that were not treated with gibberellic acid (Fig. 1). Salinity causes metabolic dysfunctions, which in turn impair photosynthetic pigment activity. Evidence from several studies has shown that salt stress can decrease photosynthetic pigment activity (El-Esawi *et al.*, 2018; Taheri *et al.*, 2020). The increase in photosynthetic efficacy observed in plants treated with GA_3 as opposed to those subjected to salt stress may be attributed to the growth-promoting properties of GA_3 (Esan *et al.*, 2020). Plant water status is evaluated by measuring RWC, which may be an indication of plant metabolic activity (Table 2). It was also clear from our experiment that salinity stress lowers RWC by preventing water transportation of plant cells. The availability of water for plant usage decreases as salinity increases, and roots are unable to absorb this water because of adverse osmotic pressure (Shrivastava and Kumar, 2015). The application of gibberellic acid results in an improvement in the water status of tomato plants. As a result of gibberellic acid treatment, salt-stressed tomatoes have an increased osmotic potential, which allows their tissues to absorb more water (Esan *et al.*, 2020). Electrolyte leakage caused by salinity stress creates an excess of reactive oxygen species (ROS), which in turn induces oxidative stress in plants and impaired membrane permeability (Table 2). According to Gurmani *et al.* (2022) electrolyte leakage was shown to be higher in salt stress situations, but it was found to be reduced in both saline and non-saline environments after GA_3 was treated externally. Concerning this particular aspect, proline is also relevant because it contributes to the regulation of the water balance. In our experiment, we observed that tomato plants exposed to salinity had a higher proline content, but that gibberellic acid significantly reduced this level (Table 2). In relation to the stress of salt, proline concentration in tomato genotypes was found to increase, leading to an upregulation of enzyme activity for proline synthesis and a downregulation of enzyme activity for its metabolism (Moxley *et al.*, 2011; Shrivastava and Kumar, 2015). The decreased generation of proline can be attributed to the fact that gibberellic acid improves the water status of plants. The concentration of proline was found to be higher in saline soil conditions relative to non-saline conditions; however, the application of GA_3 resulted in a decrease in proline levels when subjected to salinity stress (Gurmani *et al.*, 2022). The salt treatment greatly decreased the efficiency of the plant`s photosynthesis by blocking stomatal conductance in the leaves (Table 2). Crop productivity, respiration, starch metabolism, nitrogen fixation, and photosynthesis are all hampered by high salt levels (Zahra *et al.*, 2020). The use of GA_3 significantly enhances stomatal conductance in both saline and non-saline environments (Gurmani *et al.*, 2022). When the application of GA_3 was taken into consideration, it resulted in a higher yield of tomato plants. For both normal and salinity stress, GA_3 treatment improved in plant yield qualities, which declined in salt stress (Gurmani *et al.*, 2022). In order to achieve the highest number of flowers per cluster, it was found that GA_3 increased floral production while decreasing flower abscission caused by salinity stress. Uddain *et al.* (2019) found that as GA_3 levels increased, tomato plants produced more flower clusters per plant, which is consistent with our results. These findings were also consistent with the claim made by Choudhury *et al.* (2013) that PGRs have a considerable potential to accelerate the development of flowers and fruits of tomato plants in addition to raising yields.

Plants rely on a steady supply of potassium ions and a decrease in sodium ions to survive when exposed to salt (Gupta *et al.*, 2014). The internal concentration of K^+ decreased at high external NaCl concentrations as a result of competition between Na^+ and K^+ ions (Fig. 2). Salinity hinders the growth and development of plants owing to osmotic stress, excessive chloride and sodium ion absorption, and nutritional imbalance (Zahra *et al.*, 2020). The beneficial benefits of GA_3 on plants have been documented in various research. The decreased amount of sodium ion seen in the GA_3 application, which stimulates tomato growth by preventing its tissues from the harmful impacts of salinity and ensures ionic balance in the tomato genotype. Salt increased sodium ions and decreased K^+, however exogenous GA_3 decreased Na^+ transportation in tomato genotypes under saline conditions (Esan *et al.*, 2020).

In summary, the application of gibberellic acid (GA_3) effectively mitigates the damaging impacts of salt stress on tomato plants. There were noticeable improvements in a number of morpho-physiological indicators and yield measures. As evidence of GA_3 effectiveness in promoting plant growth in salt-stressed environments, treatment with the substance led to increases in plant height, branch count, and leaf count. Additionally, GA_3 decreased the time required for the start of flowering and fruiting. GA_3 application considerably increased yield-contributing characteristics such as flower cluster, flower, and fruit numbers, indicating a beneficial impact on total production. In addition, GA_3 contributed to an increase in stress tolerance by modulating leaf relative water content, photosynthetic pigments, electrolyte leakage, stomatal conductance and proline concentration. The mineral content study demonstrated that GA_3 significantly decreased sodium (Na^+) levels while raising potassium (K^+) content in salt-stressed plants. Based on the results, we suggest that GA_3 is a potential growth regulator to reduce the damaging impacts of salt stress on tomato plants, providing a possible approach for sustainable agriculture in saline regions.

Author Contributions: M.M.R. proposed and designed research programs; M.S.R. and M.Z.K.R. analyzed data. J.U. supervised the research process and drafted manuscript. All authors have read the manuscript.

Conflicts of Interest: The authors declare no conflicts of interest.

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Received: September, 2024; Revised: September, 2024; Accepted: November, 2024