Impact of Salicylic Acid on Growth, Biochemical, and Yield Characteristics of brinjal (Solanum melongena L.) cv. Ajay under Salinity Stress

Govind Gupta
Sanjeev Agrawal Global Educational University Bhopal: SAGE University Bhopal
Yogendra Singh
yogendrasinghphd938@gmail.com
Sanjeev Agrawal Global Educational University Bhopal: SAGE University Bhopal
https://orcid.org/0000-0001-9808-8941
Mukul Kumar
Krishi Vigyan Kendra Raichur
Ranjeet Singh Raghav
Krishi Vigyan Kendra Raichur
Ujwal Virkhare
Sanjeev Agrawal Global Educational University Bhopal: SAGE University Bhopal
Yogita Chouhan
Sanjeev Agrawal Global Educational University Bhopal: SAGE University Bhopal
Amar Bahadur Singh
Sanjeev Agrawal Global Educational University Bhopal: SAGE University Bhopal
Subham Pareek
Agriculture University Kota
Harshit Jangid
JNKVV: Jawaharlal Nehru Krishi Vishwa Vidyalaya

Research Article

Keywords: Brinjal, chlorophyll, TSS, salinity, salicylic acid, total sugars

Posted Date: April 9th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9075496/v1

"Impact of Salicylic Acid on Growth, Biochemical, and Yield Characteristics of brinjal (*Solanum melongena* L.) cv. Ajay under Salinity Stress"

Govind Gupta[1], Yogendra Singh[1], Mukul Kumar[2], Ranjeet Singh Raghav[2], Ujwal Virkhare[3], Yogita Chouhan[4], Amar Bahadur Singh[5], Subham Pareek[6], and Harshit Jangid[7]

[1]Assistant Professor, School of Agriculture, Sanjeev Agrawal Global Educational University, Bhopal- 462022 (Madhya Pradesh)

[2]Scientist, Krishi Vigyan Kendra, Raisen-464551 (Madhya Pradesh)

[3]Teaching Assistant, School of Agriculture, Sanjeev Agrawal Global Educational University, Bhopal- 462022 (Madhya Pradesh)

[4]Teaching Assistant, School of Science, Sanjeev Agrawal Global Educational University, Bhopal- 462022 (Madhya Pradesh)

[5]Dean, School of Agriculture, Sanjeev Agrawal Global Educational University, Bhopal- 462022 (Madhya Pradesh)

[6]M. Sc. Research Scholar, College of Horticulture and Forestry, Jhalawar-326023, Agriculture University, Kota (Rajasthan)

[7]Ph. D. Research Scholar, Department of Horticulture (Fruit Science), Jawaharlal Nehru Krishi Vishwa Vidyalaya, Jabalpur - 482004 (Madhya Pradesh)

***Corresponding Author:** yogendrasinghphd938@gmail.com

Abstract:

The global food security is significantly influenced by salt stress which is a major restriction affecting the productivity and yield of agricultural and horticultural crops. The adaption of appropriate agronomic mitigation approaches can effectively manage the adverse impacts of sanity stress. A field experiment was conducted at the Experimental Research Farm of Sanjeev Agrawal Global Educational University, Bhopal (MP), during over two summer seasons (2024 and 2025), to determine the effects of four salinity levels (350, 1500, 2500, and 3500 ppm) and three salicylic acid concentrations (1.0, 1.5 and 2.0 mM) on the growth and yield characteristics of brinjal (*Solanum melongena* L) cv. 'Ajay'. The findings revealed that augmenting salinity concentrations up to 3500 ppm significantly decreased plant height, leaf numbers, fruit numbers in the plant physical characteristics. The salinity stress also adversely affected fruit biochemical characteristics comprising total leaf chlorophyll content, carotenoids content, relative water content, and fruit N, P, and K concentrations, ultimately resulting in a decreased in total yield. Nevertheless, the salinity levels of 350 ppm (control) and 1500 ppm demonstrated no significant effect on leaf area, fruit length, total leaf chlorophyll content, fruit phosphorus content, and total yield. In contrast, augmenting salinity levels up to 3500 ppm resulted in greater accumulation of leaf sugars, proline, electrolyte leakage, fruit TSS and ascorbic acid content in compared to the control. Consequently, the application of 1.5mM salicylic acid can effectively mitigate salinity stress in brinjal and improve overall yield.

Keywords: Brinjal; chlorophyll, TSS, salinity; salicylic acid; total sugars

Introduction

Eggplant also known as brinjal (*Solanum melongena* L.) is a significant summer vegetable crop widely cultivated in India. Its fruits are an excellent source of carbohydrates, protein, vitamins and essential minerals. One of main objectives of growers' is to improve the brinjal productivity whereas maintaining high fruit quality for both domestic and international markets as per consumption requirements (Mady et al. 2023). The quality and source of irrigation water are among most critical factors directly influencing the growth of brinjal plants and productivity. Because of increasing water scarcity, the use of drainage water has been suggested as an alternative source for watering eggplant. Nonetheless, salinity (S) stress has become a significant environmental challenge to crop growing in several regions in the world. Salinity stress adversely aspects plants at different stage of their life cycle, resulting in structural changes that disrupt the balance of water. Salinity stress impacts plant growth through numerous mechanisms, comprising ion toxicity, reduced water potential, ionic imbalance, and disturbances in ion homeostasis mechanisms, such as ion toxicity, reduced water potential, ionic imbalance, and disturbances in ion homeostasis (El-Sayed et al. 2015). Metabolic impairments impede the normal development of plants, resulting in a collective lessening in production and growth inhibition (Zhao et al. 2021).

Natural and eco-friendly alternatives have gained considerable increasing attention for improving plant growth performance, flowering, fruit set, the overall productivity of horticultural crops, particularly vegetables under salinity stress conditions. Therefore, foliar application of growth regulator such as Salicylic acid (SA) is one of the most appropriate strategies utilized to mitigate the adverse impacts of salinity (Balasubramaniam et al. 2023). The salicylic acid (SA) an endogenous plant growth regulator is crucial for the regulating of severe physiological processes in plants (Horváth et al. 2007) and is involved in the adaptation of plants to abiotic stresses, comprising salinity stress (Simaei et al. 2012). The salicylic acid (SA) alleviates various abiotic stresses through functioning as a signaling molecule (Jayakannan et al. 2015). Previous investigations have been demonstrated its powerful biostimulatory potential in improving salt tolerance through modulating the ascorbate-glutathione pathway, stopping growth decline and decreasing ion toxicity (Asensi-Fabado et al. 2011, Kaya et al. 2020). Additionally, salicylic acid (SA) accelerates the accumulation of osmoprotectants, activates antioxidant enzymes, and augments cell turgor in response to stress conditions (Dutra et al. 2017, Costa et al. 2022).

Furthermore, the salicylic acid (SA) is an essential ingredient in the resistance of plants against both biotic and abiotic stresses situations (Jahan et al. 2019). The exogenous application of salicylic acid (SA) has been reported to regulate various plant physiological processes such as stomatal closure, membrane stability of cell, seed germination, ion uptake, permeability, and photosynthetic activity, consequently augmenting specifically pigment content, plant growth rate, and fruit yield (Muthulakshmi et al. 2017, Tohma et al. 2011). It also enhances the content of proline and the activation of antioxidant enzymes (Faghih et al. 2019). The many horticultural crops, comprising strawberry (*Fragaria ananassa*) (Roshdy et al. 2021), peppers (*Capsicum annuum*) (Bin-Jumah et al. 2021), and common beans (*Phaseolus vulgaris*), (Karami Chame et al. 2016), have been investigated for the beneficial effects of salicylic acid (SA) in relation to salinity stress conditions.

The exogenous application of salicylic acid (SA) through seed soaking, nutrient solutions, irrigation, or foliar application has been demonstrated to increase significant stress tolerance to mechanisms in horticultural plants (Khan et al. 2014, Palma et al. 2013). The impacts of this constituent are dose-dependent, with lower concentrations generally stimulating plant functions whereas higher concentrations potentially exerting inhibitory effects. Additionally, recent molecular investigation demonstrations that salicylic acid (SA) controls gene expression, which improves plant resistance to abiotic stress. In addition, salicylic acid (SA) increases the accumulation of osmoprotectors, improving turgescent in plant cells under stress and antioxidant enzyme activation (Dutra et al., 2017; Costa et al., 2022).

The several investigations have revealed that foliar application of salicylic acid (SA) mitigates salt stress in horticultural crops, especially in tomatoes (Mimouni et al. 2016), pumpkins (Rafique et al. 2011), and bell peppers (Kaya et al. 2020, Amirinejad et al. 2017). Nevertheless, this effect is influenced through the species, application approaches, salicylic acid (SA) concentration, and growing environmental conditions. Ribeiro et al. (2020) estimated the characteristics of watermelon in association to exogenous treatment with water salinity levels and salicylic acid (SA) concentrations. They found that the application of salicylic acid (SA) did not fully mitigate the negative impacts of salinity levels, nevertheless, it slightly significantly enhanced morphophysiology characteristics of the plants up to a concentration of 0.85 mM.

The salicylic acid (SA) demonstrations a high biostimulatory capability for salinity tolerance through promoting the positive regulation of the ascorbate-glutathione pathway (AsA-GSH), which improves tolerance to ion toxicity and oxidative stress, consequently inhibiting the unexpected decline in plant growth (Asensi-Fabado and Munné Bosch, 2011; Hasanuzzaman et al. 2019; Kaya et al. 2020). The present investigation aimed to determine the effects of foliar application of salicylic acid (SA) at various concentrations on the growth, leaf and fruit chemical composition, fruit yield, and quality of brinjal plants under salinity stress conditions. Therefore, the purpose of this investigation was to alleviate the adverse impacts of salinity stress, and increase brinjal plant capability to withstand salinity stress conditions.

Materials and Methods

The field experiment was conducted at the Research Experimental Farm of School of Agriculture, Sanjeev Agrawal Global Educational University, Bhopal (Madhya Pradesh), during over two summer seasons (2024 and 2025) to evaluate the influence of different salinity levels of drainage water utilized for irrigation of brinjal plants. Moreover, the investigation also inspected the influence of foliar application of salicylic acid (SA) and its interaction with saline irrigation water on the growth, yield, and quality characteristics of brinjal (*Solanum melongena* L.) cv. Ajay. The investigational site is located at an altitude of approximately 500 m above mean sea level, at 35.75°N latitude and 77.24°E longitude. The experiment was conducted in an open field conditions using plants grown in plastic pots. The plastic pots were arranged in a Randomized Complete Block Design (RCBD) with three replications to minimize experimental variability and maintain treatment uniformity among various treatments. A total sixteen treatments were implemented in the experiment, as presented in Table 1. There were three plastic pots utilized as replicates for every treatment. The brinjal cv. Ajay plants were treated with three levels of salicylic acid (SA) (1.0 mM, 1.5 mM and 2.0 mM), applied as foliar spray, along with a control treatment. The salicylic acid concentrations were evaluated on the basis of previous investigations conducted on other horticultural crops such as vegetables (Silva et al. 2019, Ribeiro et al. 2020). To ensure continuous soil moisture, 2.5 L of water was added to every plastic potted pots, and brinjal plants were watered twice a week with the salinity solution. The foliar application of salicylic acid (SA) was initiated 20 days after transplantation, and repeated at 20-day intervals, resulting in a total of three applications at 20, 40 and 60 days after transplantation (DAT). The brinjal plants were sprayed using a hand sprayer to ensure through coverage of the foliage. The various salinity levels irrigation water were prepared by dissolving of salts in water with an electrical conductivity of 0.5 dS m^{-1}. The salts utilized were sodium chloride (NaCl), magnesium chloride ($MgCl_2 \cdot 6H_2O$), and calcium chloride ($CaCl_2 \cdot 2H_2O$), in the following proportions: 7:2:1 respectively. This ratio represent the predominant ionic composition of the major irrigation water sources in the western Bhopal region. The prepared saline water was subsequently diluted to obtain three salinity levels (1500, 2500, and 3500 ppm). The control treatment consisted of irrigation water with a salinity level of 350 ppm. The findings of the chemical analysis of the three diluted water levels are shown in Table 2.

Table 1. Treatment Combinations of Salinity (S) irrigation water levels and salicylic acid (SA)

Treatment notation	Treatment combinations
T_1	Control 350 ppm
T_2	Salinity 1500 ppm
T_3	Salinity 2500 ppm
T_4	Salinity 3500 ppm
T_5	Salicylic Acid (1.0 mM)
T_6	Salicylic Acid (1.5 mM)
T_7	Salicylic Acid (2.0 mM)
T_8	Salinity 1500 ppm + Salicylic Acid (1.0 mM)
T_9	Salinity 2500 ppm + Salicylic Acid (1.0 mM)
T_{10}	Salinity 3500 ppm + Salicylic Acid (1.0 mM)
T_{11}	Salinity 1500 ppm + Salicylic Acid (1.5 mM)
T_{12}	Salinity 2500 ppm + Salicylic Acid (1.5 mM)
T_{13}	Salinity 3500 ppm + Salicylic Acid (1.5 mM)
T_{14}	Salinity 1500 ppm + Salicylic Acid (2.0 mM)
T_{15}	Salinity 2500 ppm + Salicylic Acid (2.0 mM)
T_{16}	Salinity 3500 ppm + Salicylic Acid (2.0 mM)

Table 2. Analysis of the chemical composition of the saline water, as expressed in meq/L.

Levels	CO_3^{-}	HCO_3^{-}	Cl^{-}	SO_4^{2-}	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}
(Control) 350 ppm	-	2.91	1.42	0.16	1.71	1.42	1.17	0.26
1500 ppm	-	2.91	9.77	0.27	2.16	3.21	7.22	0.35
2500 ppm	-	2.91	21.56	0.56	2.63	6.12	16.12	0.57
3500 ppm	-	2.91	32.22	0.87	3.23	9.42	22.67	0.76

The imported brinjal seeds of the hybrid cultivar 'Ajay' (sourced from Mahyco Seeds Ltd., India), characterized by oval-shaped, white fruits were sown in foam trays in the nursery on 1 March, 2024 and again 1 March, 2025 during two growing seasons. However, after 40 days of sowing, the healthy seedlings were transplanted into plastic pots (40 cm diameter) filled with 15 kg of sandy clay loam soil. Following ten days of transplantation, irrigation with saline water was started. The physical and chemical characteristics of the potted soil are summarized in Table 3. However, the weather parameters during the growing season, comprising air temperature and relative humidity, are presented in Table 4.

Table 3. The physical characteristics and chemical composition of the potted soil

The Soil Physical Characters				Soil Chemical Substances								
Sand	Clay	Silt	Texture	pH	Cation (meq/L)					Anion (meq/L)		
					Ca++	Mg++	CO_3^-	Na+	K+	HCO_3	Cl^-	$SO4^-$
68.21	25.36	10.72	Sand Clay Loam	7.69	0.58	0.41	0.00	0.91	0.19	0.52	1.04	0.47

Table 4 Average monthly air temperature and relative humidity at the experimental site during the two growing seasons (2024 and 2025).

Months	Air Temperature (°C)		Relative Humidity (%)	
Seasons	2024	2025	2024	2025
March	27.1	28.5	35.4	36.5
April	32.2	34.6	42.4	43.6
May	36.5	37.6	47.4	49.6
June	34.5	35.7	60.50	61.45
July	27.2	29.4	72.65	74.75

Observations for Plant Physical and Chemical Characteristics: The physical and chemical characteristics of the brinjal plants were evaluated after 80 days after transplantation under each experimental treatment.

Plant Height (cm): Plant height of brinjal plants (cm) were documented using a measuring scale, and the recently fully expanded fourth leaf from the apex was designated for study.

Number of Leaves per Plant: Number of leaves per plant was documented manually for each treatment, and the mean values were determined and expressed as leaves per plant.

Leaf Area (cm²): Leaf area (cm²) was calculated based on the relationship between unit area and leaf fresh weight, following the technique pronounced by (Koller, 1972).

Leaf Total Chlorophylls and Carotenoids (mg/100 g fresh weight): Leaf chemical analysis for total chlorophylls and carotenoids (mg/100 g fresh weight) was implemented spectrophotometry using acetone leaf extracts, following the method pronounced by (Lichtenthaler, 1987).

Proline Content (mg/g fresh weight): Proline content (mg/g fresh weight) was extracted in 3% (w/v) aqueous sulfosalicylic acid, responded with acid ninhydrin reagent, and was consequently measured spectrophotometrically at 520 nm (Bates et al. 1973).

Total Sugar Content (g/100 g dry weight): Total sugar content (g/100 g dry weight) of dried leaves was estimated using the phenol–sulfuric acid method, as recommended by (Smith et al. 1956).

Electrolyte Leakage (EL %): Electrolyte leakage percentage (EL %) was ascertained through analyzing 0.3 g of fresh leaf tissue collected from the middle portion of the leaf. The samples were placed in test tubes containing 15 mL of distilled water and incubated at 25°C for two hours. Subsequently, the initial electrical conductivity (EC_1) was estimated using an electrical conductivity meter. The samples were subsequently autoclaved at 120°C for 20 minutes, and the final electrical conductivity (EC_2) was subsequently determined. The electrolyte leakage was determined following method recommended by (Lutts et al. 1996), using the formula: $EL (\%) = (EC_1 / EC_2) \times 100$).

Relative Water Content (%): The relative water content (RWC, %) was estimated following the technique described by (Korkmaz et al. 2010). Briefly, from plant samples in every replication, leaf discs (1 cm in diameter) were taken from the center of fully expended leaves and weighed (FW). The discs were floated on distilled water for 5 hours in the dark. Subsequently, the eliminating excess surface moisture with paper hand towel, the turgid weight (TW) of the leaf discs was measured. After a 48-hours drying period at 75 °C, the dry weights (DW) of the discs were determined.

The relative water content (RWC) was determined using the formula: $RWC\ (\%) = \frac{FW-DW}{TW-DW} \times 100$

Fruit Physical and Chemical Characteristics: The fruits from each plot were harvested at the proper horticultural maturity stage, and they were counted and weighed at every picking. The following physical parameters were documented:

Fresh fruit weight (g): The fresh fruit weight (g) were documented using a digital weighing balance. The average values were expressed as fresh fruit weight (g).

Fruit Diameter (Cm) and Fruit Length (cm): Fruit diameter and fruit length (cm) were determined using a vernier caliper, and the average values were expressed as fruit diameter (cm) and fruit length (cm).

Total Yield per Plant (g): The total yield per plant was determined by weighing each harvested fruit on a digital weighing balance. The cumulative weight was expressed as yield per plant (g).

Total Soluble Solids (%): Total Soluble Solids (%), were estimated as a percentage using a digital hand-held "Prochet" refractometer, following the technique pronounced by (A.O.A.C., 2012).

Ascorbic Acid Content (mg/100 g fresh weight): The ascorbic acid content (mg/100 g fresh weight) was estimated using 2, 6-dichlorophenolindophenol dye and oxalic acid, following the method pronounced by (Rao and Deshpande, 2006).

Leaf Nutrient Analysis in Brinjal: Leaf nutrient analysis in brinjal, including nitrogen (N), phosphorus (P), and potassium (K) contents (%) was performed using a composite sample dried leaves following the methods outlined by (A.O.A.C., 2012). Nitrogen content (%) was estimated using the micro-Kjeldahl method, phosphorus content (%) was determined colorimetrically using the hydroquinone–sodium sulfite method, and potassium content (%) was estimated with a flame photometer (PFP7, Jenway, Staffordshire, UK).

Statistical Analysis

Statistical analysis was conducted on data from both seasons using CoStat software (Version 6.4, CoHort Software, USA). Analysis of variance (ANOVA) was performed, and treatment means were compared using the least significant difference (LSD) test at the 5% probability level, following (Snedecor and Cochran, 1980).

Results

Plant Physical Characteristics

All the vegetative growth characteristics of brinjal plants cv Ajay were adversely affected by the augmenting salinity levels of irrigation water up to 3500 ppm, as illustrated in Figure 1& 2. The plant height (cm) and the number of leaves were highest in the control plants (350 ppm). In contrast, no significant variations in leaf area was observed between plants irrigated with salinity levels of 350 and 1500 ppm. Furthermore, the application of 1.5 mM salicylic acid (SA) was more effective in increasing plant height, number of leaves, and leaf area as compared to the 1.0 mM and 2.0 mM salicylic acid concentration. The results further demonstrated that a significant interaction between salinity stress and salicylic acid (SA) application in influencing the vegetative growth of brinjal plants cv. Ajay. The highest augmentation in morphological characteristics was observed in the plants irrigated with 1500 ppm saline water and treated with 1.5 mM salicylic acid, nevertheless the lowest values of growth characteristics were documented under 3500 ppm salinity combined with 2.0 mM salicylic acid (SA).

Fig. 1. The influence of salinity (S) levels, salicylic acid (SA) treatments, and their combined interaction on plant height (cm) and number of leaves per plant in brinjal cv. Ajay was evaluated during two consecutive summer seasons (2024 and 2025). Significant differences ($p < 0.05$) are showed by various colours: **Dark Red** represents the influence of salinity (S) levels, **Light Green** indicates the influence of salicylic acid (SA) levels, and **Purple** represents the combined interaction between salinity (S) and salicylic acid (SA) levels.

Fig. 2. The influence of salinity (S) levels, salicylic acid (SA) treatments, and their combined interaction on leaf area (cm^2) in brinjal cv. Ajay was evaluated during two consecutive summer seasons (2024 and 2025). Significant differences ($p < 0.05$) are revealed by various colours: **Dark Red** represents the impact of salinity (S) levels, **Light Green** illustrations the effect of salicylic acid (SA) levels, and **Purple** represents the combined interaction between salinity (S) and salicylic acid (SA) levels.

Plant Chemical Components

The regarding of photosynthetic pigments, the total chlorophyll content (mg/100g FW) of control plants and those plants irrigated with 1500 ppm saline water indicated only slightly differences. The highest carotenoid content (mg/100g FW) were determined in the control treatment at 350 ppm demonstrated in Figure 3. In contrast, an augmenting salinity levels up to 2500 ppm and 3500 ppm resulted in a perceptible and proportional decrease in both total chlorophyll content and carotenoid concentrations. Nevertheless, the foliar application of salicylic acid (SA) at all tested concentrations significantly enhanced the chlorophyll and carotenoid concentrations, with the greatest improvement observed at 1.5mM SA concentration. Ultimately, the results further indicated that the application of salicylic acid (SA) up to 1.5 mM significantly enhanced total chlorophyll and carotenoid contents in salinity- stressed brinjal plants, particularly in those plants irrigated with 1500 ppm saline water.

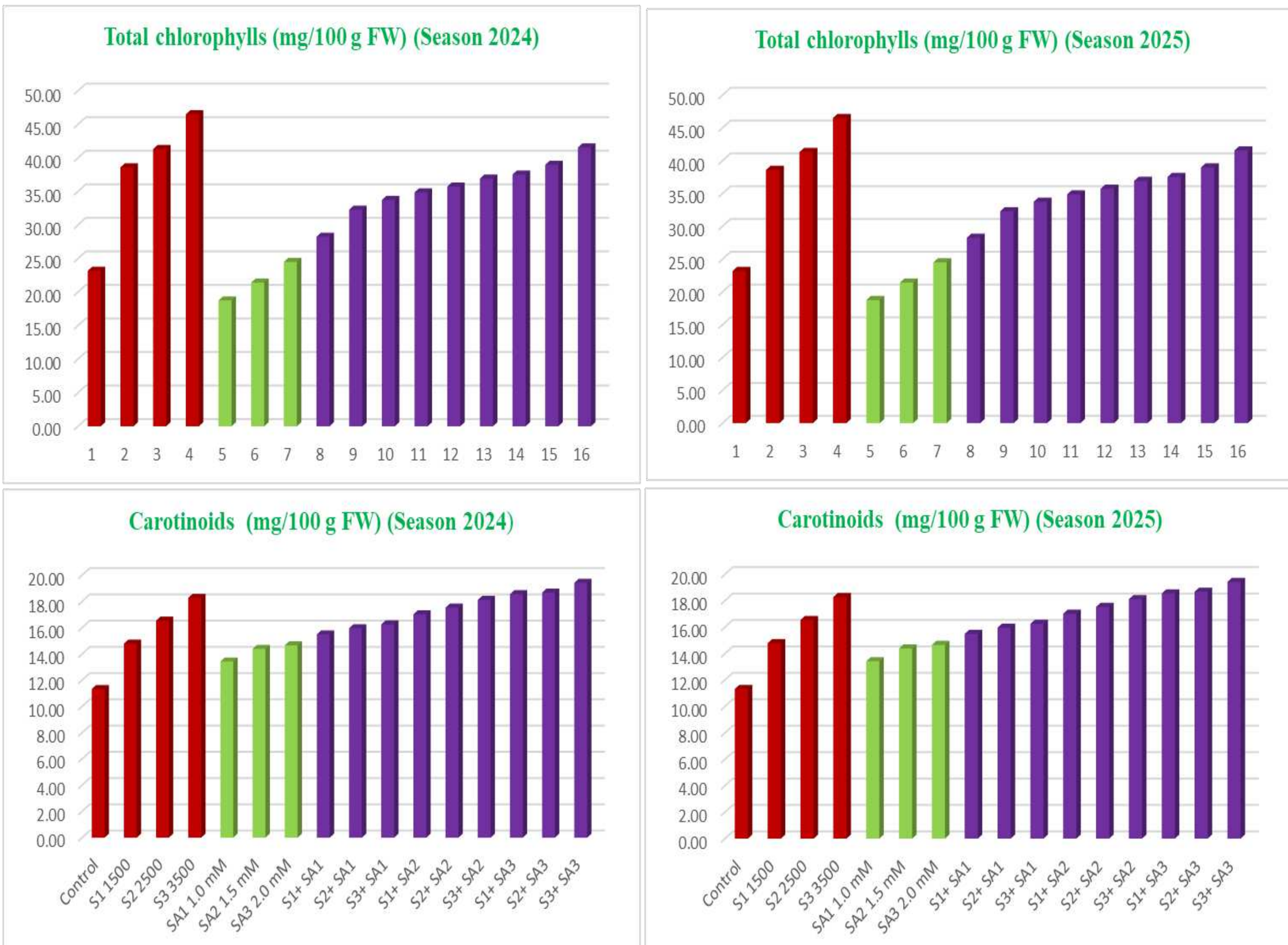

Fig. 3. The impacts of salinity (S) concentration, salicylic acid (SA) treatments and their combined interaction on the total leaf chlorophyll content (mg /100g FW) and carotenoids content (mg /100g FW) in brinjal plants cv. Ajay was assessed during two consecutive summer seasons (2024 and 2025). The significant differences ($p < 0.05$) are showed through various colours: **Dark Red** represents the impact of salinity (S) levels, **Light Green** shows the impact of salicylic acid (SA) concentrations, and **Purple** represents the combined interaction between salinity levels (S), and salicylic acid (SA) concentrations.

Nevertheless, the concentrations of proline and total sugars contents in the leaves, which function as osmolytes, are as exhibited in the Figure 4. The proline and total sugar concentrations significantly increased with enhancing salinity levels up to 3500 ppm in compared to the control (350 ppm). The foliar application of salicylic acid (SA), particularly at 1.5 mM, significantly increased the accumulation of leaf proline and total sugars levels. Furthermore, the 1.5 mM salicylic acid (SA) treatment was proved to be most effective in increasing proline levels under all salinity stress conditions whereas the highest total sugars contents under up to 3500 ppm salinity levels were observed with salicylic acid (SA) application of 1.5 and 2.0 mM.

Fig. 4. The effect of salinity (S) levels, salicylic acid (SA) treatments, and their combined interaction on the proline content (mg/100g FW) and total sugar (g/100 g FW) in brinjal plants cv. Ajay was determined during two consecutive summer seasons (2024 and 2025). Significant differences ($p < 0.05$) are indicated through various colours: **Dark Red** represents the impact of salinity (S) levels, **Light Green** indicates the impact of salicylic acid (SA) concentration, and **Purple** represents the combined interaction between salinity (S) and salicylic acid (SA) levels.

The consequences demonstrated in Figure 5 show that the electrolyte leakage percent (EL%) in brinjal leaves was maximum at the 3500 ppm salinity concentration, demonstrating that severe salinity stress level unfavorably affected membrane permeability. The findings showed that among the salicylic acid (SA) treatments, 1.0 mM salicylic acid (SA) treatment resulted in the lowest electrolyte leakage, followed by 1.5 mM, whereas 2.0 mM salicylic acid treatment exhibited the highest values of electrolyte leakage (EL %) in brinjal leaves. Overall, the data discovered that augmenting the salicylic acid concentration consistently decreased electrolyte leakage, even under the furthermost intense salinity level of 3500 ppm. This recommends that salicylic acid application facilitated alleviate the detrimental impacts of salanity stress on cell membrane stability.

Additionally, salicylic acid at 1.5 mM treated control plants at 1500 ppm exhibited significantly lower electrolyte leakage compared to salicylic acid at 2.0 mM treated plants subjected to higher salinity levels.

The results illustrates in Figure 5 demonstration that a significant reductions in relative water content with each augmentation in salinity level up to 3500 ppm, compared with plants exposed to 350 and 1500 ppm saline water. Conversely, the foliar application of salicylic acid (SA) at 1.5 mM resulted in the greatest augmenting in relative water content across all assessed salinity concentrations. Furthermore, the improvement in leaf relative water content was predominantly remarkable at the 1500 ppm salinity level when plants were treated with 1.5 mM salicylic acid.

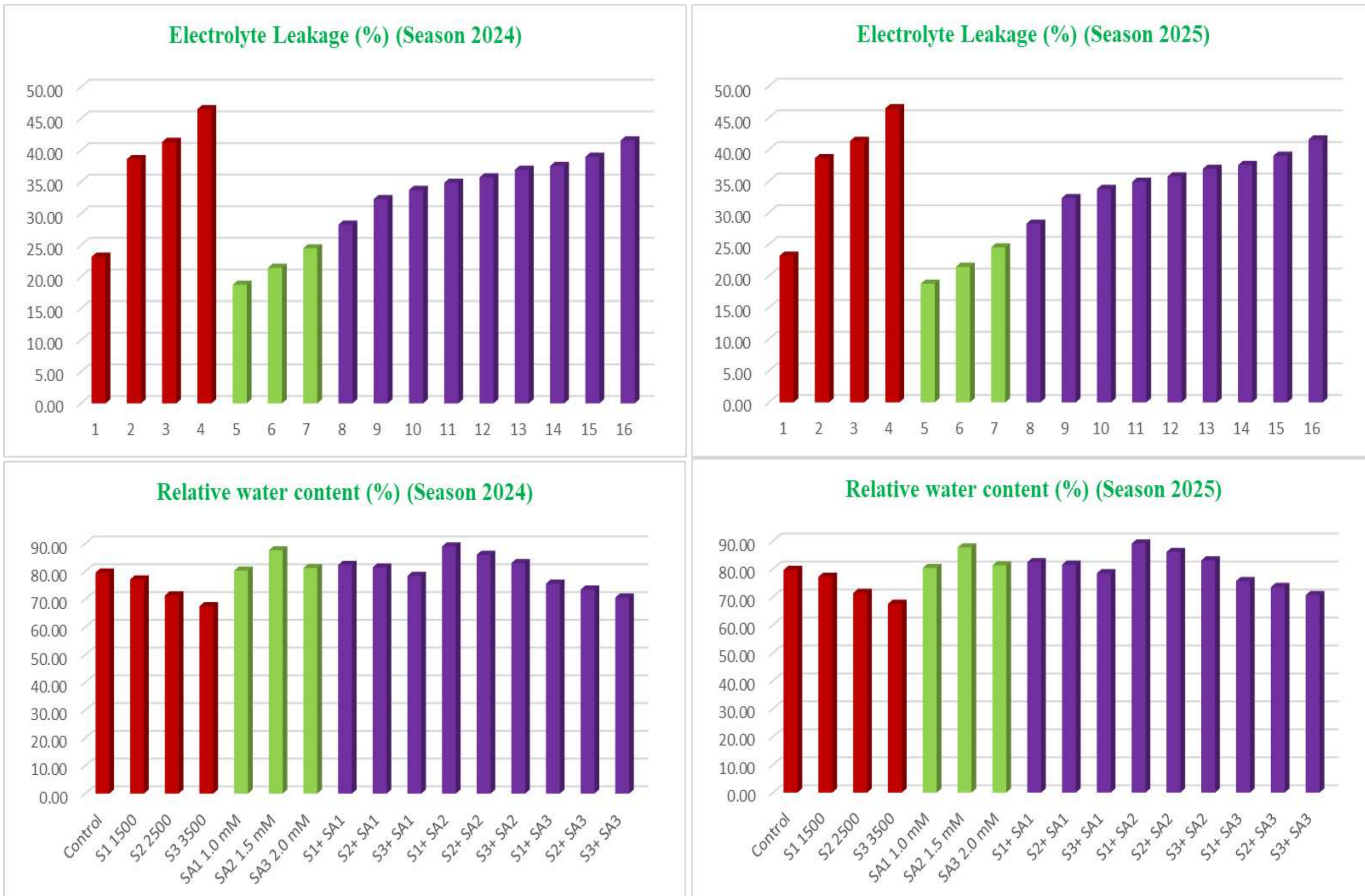

Fig. 5. The effect of salinity (S) concentrations, salicylic acid (SA) treatments, and their combined interaction on the electrolyte leakage (EL %) and relative water content (%) in brinjal cv. Ajay was evaluated during two consecutive summer seasons (2024 and 2025). Significant differences ($p < 0.05$) are presented by various colours: **Dark Red** represents the influence of salinity (S) levels, **Light Green** indicates the effect of salicylic acid (SA) levels, and **Purple** represents the combined interaction between salinity (S) and salicylic acid (SA) levels.

Fruit Physical Characteristics

The data exhibit in Figure 6 shows that the fresh fruit weight, fruit length, and fruit diameter progressively reduced as the salinity concentration augmented up to 3500 ppm. Nonetheless, no statistically significant difference in fruit length (cm) was observed between the control and the 1500 ppm salinity treatment. Among the salicylic acid treatments, the 1.5 mM concentration resulted the most significant enhancement in all of the calculated fruit physical characteristics compared with the 1.0 mM and 2.0 mM concentrations. The combination of 1500 ppm saline water with a 1.5 mM salicylic acid (SA) foliar application recorded the maximum fruit physical characteristics, although the lowest values of the these characteristics were observed in plants exposed to 3500 ppm salinity level along with 2.0 mM salicylic acid concentrations.

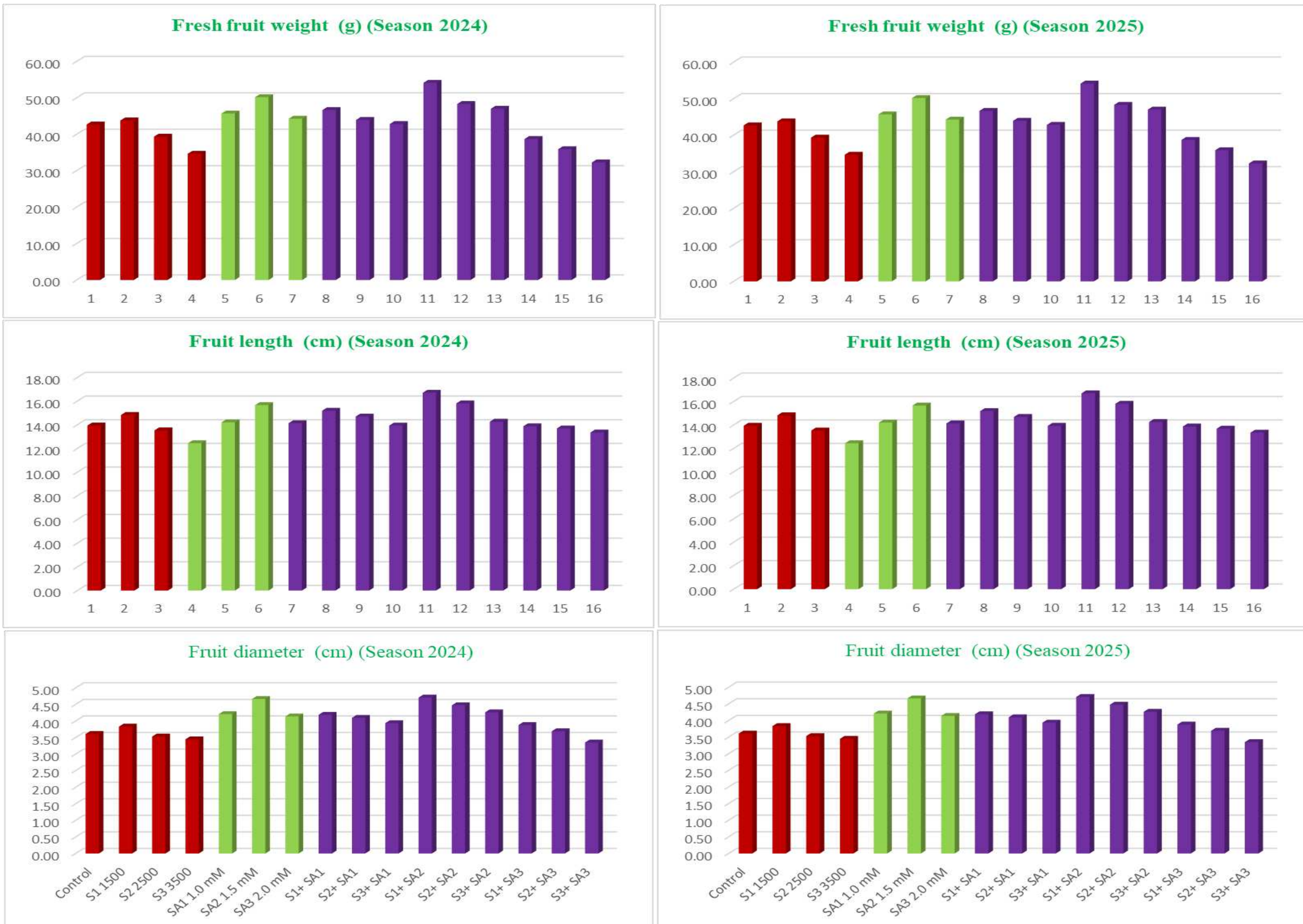

Fig. 6. The influence of salinity (S) concentrations, salicylic acid (SA) treatments, and their combined interaction on the fresh fruit weight (g), fruit length (cm) and fruit diameter (cm) in brinjal plants cv. Ajay was estimated during two consecutive summer seasons (2024 and 2025). The significant differences ($p < 0.05$) are indicated through different colours: **Dark Red** represents the influence of salinity (S) concentrations, **Light Green** indicates the impact of salicylic acid (SA) levels and **Purple** represents the combined interaction between salinity levels (S) and salicylic acid (SA) levels.

Fruit Chemical Characteristics

The findings illustrates in Figure 7 show that the values of ascorbic acid content (mg/100 g FW), and total soluble solids (%) in fruit increased gradually as the salinity level increased, despite the fact that the increase in total soluble solids (TSS) was not statistically significant. Hence no substantial changes were observed in the total soluble solids (TSS) in response to salicylic acid (SA) application. Conversely, the foliar application of salicylic acid (SA) at 1.5 mM resulted in a greater accumulation of ascorbic acid in the fruits comparison to the 1.0 mM and 2.0 mM concentrations. Therefore, the maximum concentration of both total soluble solids (TSS), and ascorbic acid content were observed in plants that were treated with 1.5 mM salicylic acid at 3500 ppm salinity levels. This shows that salicylic acid improves fruit quality even when it is exposed to high levels of salt.

Fig. 7. The effect of salinity (S) levels, salicylic acid (SA) treatments, and their combined interaction on the ascorbic acid content (mg/100 g FW), and total soluble solids (TSS %) in brinjal plants cv. Ajay was determined during two consecutive summer seasons (2024 and 2025). The significant differences ($p < 0.05$) are showed through different colours: **Dark Red** represents the effect of salinity (S) levels, **Light Green** indications the effect of salicylic acid (SA) levels, and **Purple** represents the combined interaction between salinity concentration (S) and salicylic acid (SA) levels.

Nutrient Dynamics in Brinjal Leaf

The data presented in Figure 8 show that irrigation with the control salinity level of (350 ppm) resulted in the maximum fruit N and K contents, while the augment in P content between 350 ppm and 1500 ppm salinity levels remained statistically insignificant. Among the salicylic acid (SA) treatments, the 1.5 mM concentration improved the accumulation of N, P, and K more effectively than the 1.0 mM and 2.0 mM levels. Additionally, the interaction impacts indicated that the maximum increase in N, P, and K contents were obtained when 1.5 mM salicylic acid was applied at a salinity level of 1500 ppm. This resulted in a favorable response to nutrient accumulation under this particular combination of salicylic acid (SA) with salinity levels.

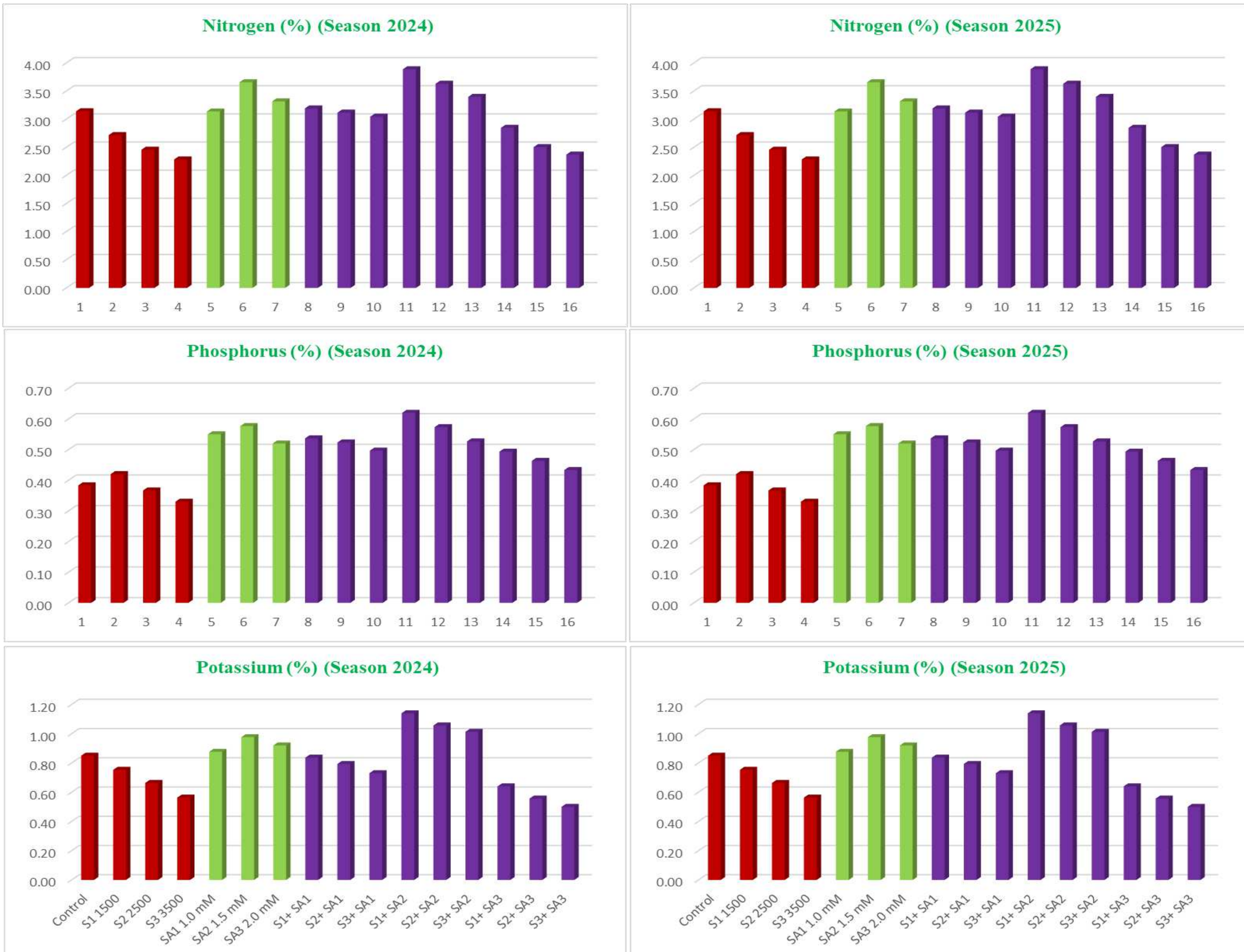

Fig. 8. The impact of salinity (S) levels, salicylic acid (SA) treatments and their combined interaction on fruit N, P, and K contents (%) in brinjal plants cv. Ajay was estimated during two consecutive summer seasons (2024 and 2025). The significant differences ($p < 0.05$) are exhibited through various colours: **Dark Red** represents the impact of salinity (S) levels, **Light Green** indicates the impacts of salicylic acid (SA) concentration and **Purple** represents the combined interaction between salinity (S) and salicylic acid (SA) levels.

Yield Characteristics

The data showed in Figure 9 shows that the yield per plant (g) did not fluctuate significantly between the control 350 ppm, and 1500 ppm salinity concentration, despite the fact a significant decrease was observed at greater salinity levels. The yield per plant remained constant across all concentrations during the first season in the context of salicylic acid (SA) treatments. Nevertheless, in the second season, plants treated with 1.5 mM salicylic acid (SA) exhibited higher yield as compared those treated with 1.0 mM and 2.0 mM salicylic acid. Additionally, the maximum yield per plant was documented under the 1500 ppm salinity level combined with foliar application of 1.5 mM salicylic acid, whereas the lowest yield was obtained from plants exposed to 3500 ppm salinity level along with a foliar spray of 2.0 mM salicylic acid.

Fig. 9. The effect of salinity (S) levels, salicylic acid (SA) treatments, and their combined interaction on the yield per plant (g) in brinjal cv. Ajay was assessed during two consecutive summer seasons (2024 and 2025). Significant differences ($p < 0.05$) are exhibited by different colours: **Dark Red** represents the influence of salinity (S) levels, **Light Green** indicates the influence of salicylic acid (SA) levels, and **Purple** represents the combined interaction between salinity (S) and salicylic acid (SA) levels.

Discussion

Plant Physical Characteristics

Any kind of abiotic stress makes vegetable crops much less likely to produce because most vegetables are either very sensitive to these stresses or can only handle them to a moderate degree. Salinity stress is acknowledged as the most detrimental of all abiotic stresses, significantly hindering the growth and productivity of numerous crops. Plant growth is also significantly impacted by salinity stress, which adversely affects both osmotic stress and ion toxicity, which result in secondary oxidative stress. The previous research indicates that brinjal has a moderate tolerance to salinity, indicating that it can tolerate a certain amount of abiotic stress (Chartzoulakis et al. 1997, Assaha et al. 2013). In this context, an important objective of the current investigation was to evaluate the efficacy of salicylic acid (SA) foliar application in improving tolerance to salinity stress.

In the present investigation, all vegetative growth characteristics of brinjal cv. Ajay plants were adversely affected by irrigation with augmenting salinity levels up to 3500 ppm. On the other hand, the number of leaves per plant, and leaf area (cm^2) showed no significant variances between the control 350 ppm and 1500 ppm salinity levels, except for number of leaves per plant during the second season.

Plant Chemical Components

Related to the chemical alterations, the salinity levels of 350 and 1500 ppm had an insignificant impact on the total chlorophyll content (mg/100g FW). The control treatment (350 ppm) demonstrated that the maximum carotenoid content (mg/100g FW), whereas the augmenting salinity levels up to (2500 and 3500 ppm) resulted in a considerable decrease, which may be attributed to increased chlorophyllase activity. The growth is obstructed by salt stress in one of two ways: either through damages meristematic tissues or through restricting the availability of necessary metabolites (Hussein et al. 2012). Moreover, the accumulation of Na+ and Cl+ ions can lead to ionic toxicity, which damages the synthesis of chlorophyll and interrupt leaf function of plants (Salima et al. 2019). The partial stomatal closure in response to salinity stress results in a declined in light-use efficiency and CO_2 assimilation, consequently inhibiting photosynthesis and vegetative growth (Schwarz et al. 2002, Foyer and Shigeoka, 2011).

The acid salicylic acid (SA) may help protect the chloroplast pigments from the salinity-induced toxicity (Foyer and Shigeoka, 2011). The exogenous application of salicylic acid (SA) induces a pre-adoptive response to saline stress condition, consequently improving the protective mechanisms of photosynthetic pigments and maintaining of membrane integrity which continuously contributes to enhanced plant growth under salinity conditions (Alsahli et al. 2019, Mady et al. 2023). Therefore, the salicylic acid (SA) also acts as a significant antioxidant, augmentations the production of chlorophyll biosynthesis through augmenting the activation of antioxidants enzymes, comprising catalase, peroxidase, and superoxide dismutase, which effectively neutralize reactive oxygen species (Szepesi, 2008, Aires et al. 2022). Furthermore, several investigators have recorded a considerable augmentation in chlorophyll content in various plant species in response to salicylic acid (SA) application (Suhaib et al. 2018, Loutfy et al. 2020).

In the present investigation, proline and total sugars were identified as the primary osmolytes in brinjal plant leaves under salinity concentration up to 3500 ppm compared with the control treatment (350 ppm). Moreover, the electrolyte leakage was also higher in brinjal plant leaves at the 3500 ppm salinity, indicating membrane damage under salt stress conditions. These consequences show that the osmoregulation in brinjal plants under saline irrigation greatly depends on the accumulation of total sugars and proline. Concurrently, enhanced electrolyte leakage indicates structural and functional damage to cell membranes caused by excessive accumulations of Na^+ and Cl^- ions in the leaf tissue of brinjal plants under salinity stress conditions. Therefore, plants exposed to salinity stress without salicylic acid treatment (control) demonstrated the maximum electrolyte leakage (EL), whereas foliar application of 1.5 mM salicylic acid (SA) resulted in the lowest electrolyte leakage in brinjal leaves, indicating enhanced membrane stability under the salinity stress conditions (Jaleel et al. 2008). This protective impacts may be responsible to the capability of salicylic acid (SA) to mitigate salinity –induced membrane degradation and decreased cellular damage (Senaratna et al. 2000).

According to an investigation on brinjal plants cv. Ajay, the salinity stress altered the structure of the leaf cell membrane and greater salinity levels intensified membrane impairment. However, the application of salicylic acid (SA) decreased the adverse influence of salinity stress in comparison with the untreated (control) (Pirasteh-Anosheh et al. 2016). Furthermore, investigation reported that the foliar application of 1.5 mM salicylic acid (SA) at salinity levels of 350 and 1500 ppm, results in a more pronounced the enhance leaf relative water content. They attributed this impacts to the role of salicylic acid in enhancing the accumulation of compatible osmolytes in plants exposed to salinity stress, consequently helping to maintain turgor in the leaf cells of brinjal plants (Amirinejad et al. 2017). Furthermore, augmenting salinity concentrations up to 3500 ppm resulted in a noticeable decreases in relative water content. Subsequently, the leaf relative water content (RWC) is an essential parameter reflecting plant water status, its decrease shows decreased water balance under high salinity stress conditions. Additionally, decreased water availability under saline conditions caused by an excess of salts in the rhizosphere, may lead the reduced relative water content (Ferraz et al. 2015). Furthermore, the degeneration in relative water content may be attributed to a compromised root system that decreases the capability for water uptake, predominantly following water loss connected with lessened absorbing surfaces (Acosta-motos et al. 2017).

Fruit Physical Characteristics

With regard to fruit physical characteristics comprising fresh fruit weight, fruit length and fruit diameter, indicated a substantial enhancement at 1500 ppm salinity levels, even though the enhancement in the fruit length was not statistically significant. In contrast, the substantial reduction observed at higher salinity levels of 2500 ppm and 3500 ppm may be attributed to osmotic and ionic stress conditions, which inhibits fruit development through restricting impaired water uptake, lessening turgor pressure, and controlling cell expansion (Ferraz et al. 2015). The greater response observed with application of 1.5 mM salicylic acid (SA) may be attributed to its capability to facilitated nutrient transport under salt stress conditions, sustaining membrane stability, decrease oxidative injury and augmenting antioxidant activity (Gadallah et al. 2000). These impacts contributes to the maintenance of photosynthesis activity and effective assimilate translocation. The optimum fruit physical characteristics documented at 1500 ppm salinity in combination with 1.5 mM salicylic acid (SA) recommend an advantageous interaction whereby moderate stress signals are modulated through salicylic acid (SA), consequently augmenting metabolic activity and enhanced water relations (Ali and Ismail, 2014). This saline stress condition augmented respiration rates, abnormal cell enlargement and decreased meristematic activity, predominantly because of the increased energy demand required to maintain cellular homeostasis under the saline environment (Kaydan and Okut 2007).

Fruit Chemical Characteristics

The results demonstrated that a gradually increase in fruit ascorbic acid content with an enhancing the salinity levels of irrigation water. This response could be associated with the antioxidative role of ascorbic acid in mitigating detrimental effects of salinity-induced oxidative stress in the plants (Gadallah et al. 2000). Moreover, the progressive increase in saline irrigation levels resulted in insignificant increases in total soluble solid (TSS) content in brinjal fruits. These slightly enhancement may be indicate that under salinity stress conditions, plants regulate the activity of specific metabolic processes through converting polysaccharides into simple sugars, consequently augmenting the TSS accumulation in the brinjal fruit (Ali and Ismail, 2014). Moreover, the exogenous application of 1.5 mM salicylic acid (SA) demonstrated to be the most effective treatment over rest of the treatments, leading to augmented levels of ascorbic acid content and total soluble solids (TSS) in brinjal fruits across various salinity levels of irrigation water. These results confirm the essential role of salicylic acid (SA) in augmenting salinity stress tolerance, as it stimulates the activity of antioxidant enzymes that defend plants against salinity-induced oxidative injury (Farhangi-Abriz and Ghassemi-Golezani et al. 2018).

Nutrient dynamics in brinjal leaf

The irrigation under the control treatment significantly augmented fruit N and K contents, even though P content did not demonstration a significant response at 350 and 1500 ppm salinity levels. Under salt stress conditions, the uptake of essential nutrients is often restricted because of competitive interactions between Na^+ and other nutrients, resulting in nutrient imbalances, deficiencies, and consequently decreased plant growth (Assaha et al. 2013). The exogenous application of salicylic acid (SA) at concentrations of 1.0, 1.5 and 2.0 mM significantly increased nitrogen (N) and potassium (K) concentrations under the control salinity levels (350 ppm). Additionally, among the treatments, 1.5 mM salicylic acid (SA) was the most effective in increasing the P content in both the control 350 ppm and 1500 ppm salinity conditions. This enhancement in nutrient accumulation may be attributed to the role of salicylic acid in lessening of electrolyte leakage and the augmentation of critical physiological processes comprising chlorophyll synthesis, photosynthetic efficiency, and increased dry matter production. The collectively, these physiological processes augment the effective uptake and ensuing translocation of macro- and micronutrients all over plant tissues (Rajeshwari and Bhuvaneshwari, 2017).

Yield Characteristics

The findings revealed that the total yield augmented a substantial at a salinity level of 1.5 dS m^{-1}, followed by a noticeable decline at higher salinity concentrations. This improvement in total yield may be attributed to the non-significant decreases in leaf number, leaf area, total chlorophyll content, and fruit fresh weight at 350 and 1500 ppm salinity, which collectively contributes in improved yields and productivity. Moreover, the application of 1.5 mM salicylic acid (SA) under the control treatment (350 ppm) resulted in significantly increase plant height, further supporting improved plant growth performance. On the other hand, plants irrigated with 350 and 1500 ppm saline water demonstrated a higher leaf number and leaf area when treated with 1.5 mM salicylic acid. The physical characteristics of the fruit followed similar trend to that of the vegetative characters. These results recommend that salicylic acid functions as an endogenous plant growth regulator that improves tolerance to salt stress (Horváth et al. 2007, Sousa et al. 2021).

Conclusions

The findings indicate that the most analyzed characteristics of brinjal plants, comprising leaf, and fruit characteristics are reduced as salinity levels increased up to 3500 ppm. Nevertheless, the brinjal plants treated with 1.5 mM salicylic acid (SA) indicated that greater tolerance in salinity stress, particularly at 1500 ppm salinity level in agricultural drainage saline water. They were also capable tolerate irrigation at salinity level up to 3500 ppm through enhancing the physical characteristics of the brinjal plant and fruit, as well as the biochemical characteristics of the leaves and fruits. These improvements comprises higher leaf chlorophyll, carotenoid contents, proline, total sugars accumulation , relative water content, fruit total soluble solids (TSS), ascorbic acid content and improved nitrogen, phosphorus, and potassium concentrations. Furthermore, the application of salicylic acid (SA) lessened the detrimental influence of salinity on the degradation of cell membranes through decreasing the electrolyte leakage percentage in leaves. Overall, these results suggest that the application of salicylic acid (SA) at a concentration of 1.5 mM may alleviate the detrimental effects of salinity stress on brinjal plant, consequently promoting improved plant growth and overall yield.

Acknowledgements

The authors express their sincere gratitude to School of Agriculture, Sanjeev Agrawal Global Educational University, Bhopal for providing the necessary facilities and support for this investigation. I am deeply grateful to my colleagues and students for their invaluable support and contributions, which facilitated the successful conclusion of this investigation.

Authors' contributions

The authors would like to thank Govind Gupta, Yogendra Singh and Ujwal Virkhare for their valuable contributions to the implementation two-year research trial, data analysis, and preparation of the initial manuscript draft. Moreover, Mukul Kumar, Ranjeet Singh Raghav and Amar Bahadur Singh provided technical supports and guidance on research methodology. Yogita Chouhan, Subham Pareek, and Harshit Jangid performed the statistical analysis. The manuscript was drafted by Govind Gupta, Yogendra Singh, Mukul Kumar, Amar Bahadur Singh and Ujwal Virkhare. All listed contributors have reviewed and approved the final version of the manuscript, confirm their agreement with its content and findings.

Declarations

Conflict of the interest: The authors state they have no conflicts of interest related to this work.

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