International Journal of Horticultural Science and Technology (2027) Vol. 14, No. 2, pp. 401-420 doi.org/10.22059/10.22059/ijhst………………….

International Journal of Horticultural Science and Technology

Journal homepage: https://ijhst.ut.ac.ir

Mitigation of Salinity Stress in Roselle (*Hibiscus sabdariffa* L.) through Foliar Application of Salicylic Acid and Potassium Silicate

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ARTICLE INFO

Article history:

Received: 2 August 2025,
Received in revised form: 26 November 2025,
Accepted: 4 December 2025,

Article type:

Research paper

Keywords:

Potassium silicate,
Roselle (*Hibiscus sabdariffa* L.),
Salicylic acid,
Water saline stress

ABSTRACT

A pot experiment was conducted over two consecutive seasons (2022 and 2023) at the Experimental Farm, Faculty of Agriculture, Al-Azhar University, Assiut, Egypt, to evaluate the effects of saline irrigation water and foliar-applied stimulants on roselle (*Hibiscus sabdariffa* L., cultivar 'Sabahia 17'). The experiment included four salinity levels in irrigation water (0, 2000, 3000, and 4000 ppm) in combination with foliar applications of salicylic acid (0, 50, and 100 ppm) and potassium silicate (1 and 2 mL L^{-1}). Plant growth, yield components, and chemical traits were assessed. Increasing salinity levels significantly reduced growth, yield, fixed oil content, anthocyanin content, and acidity, whereas irrigation at 2000 ppm improved these traits. In contrast, higher salinity levels increased sodium and proline accumulation. Foliar application of stimulants, particularly salicylic acid at 100 ppm and potassium silicate at 2 mL L^{-1}, markedly enhanced growth and yield parameters and reduced the adverse accumulation of sodium and proline. The interaction between saline irrigation and stimulant application showed that the combination of low salinity stress (2000 ppm) with salicylic acid at 100 ppm was the most effective treatment for alleviating salinity stress and improving overall plant performance.

Abbreviations: Salicylic acid (SA), Potassium silicate (PS)

Introduction

Roselle (*Hibiscus sabdariffa* L.) is a summer annual herbaceous plant belonging to the Malvaceae family. It is native to tropical and subtropical regions, including Africa, India, and Malaysia, and is cultivated worldwide for its diverse applications. Roselle is widely recognized for its high medicinal and nutritional value, which has contributed to its importance in international markets (Sanders et al., 2020). The sepals, which represent the primary commercial component of the plant, are commonly used to prepare beverages consumed either hot or cold and are valued in traditional medicine for their ability to lower blood pressure without adverse side effects (Mohamed et al., 2012). The calyces are rich in anthocyanin pigments and contain considerable amounts of organic acids, including ascorbic, malic, oxalic, and tartaric acids, as well as essential minerals such as iron and calcium, while maintaining low glucose levels (Jung et al., 2013). In addition, roselle calyces are used as natural food colorants, providing vivid coloration for a wide range of products (Maganha et al., 2010). The anthocyanins in roselle also exhibit therapeutic potential, contributing to the management of inflammatory disorders, liver diseases, and cancer (Kong et al., 2003). Beyond the calyces, roselle seeds constitute a valuable source of fixed oil and proteins, further enhancing the plant's nutritional significance (Al-Wandawi et al., 1984). Moreover, roselle exhibits notable antibacterial, antifungal, and diuretic

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properties, which further underscore its medicinal importance (Guerin and Reveillere, 1984; Caceres et al., 1987).

Plants are exposed to a wide range of environmental stresses throughout their life cycles, among which soil salinity is a significant factor limiting agricultural productivity worldwide (Bulgari et al., 2019). These stresses stimulate the generation of reactive oxygen species (ROS), including superoxide radicals, hydrogen peroxide, hydroxyl anions, and singlet oxygen, which cause damage to essential cellular components such as lipids, proteins, and DNA (Bulgari et al., 2019; Khan and Duke, 2001). Salinity stress, in particular, poses a major threat to global agriculture, especially in arid and semi-arid regions, thereby endangering food security. It is estimated that approximately 40% of the world's arable land is affected by salinity, resulting in substantial yield losses (Jadhav et al., 2010; Tester and Davenport, 2003). Salinity induces osmotic, ionic, nutritional, and hormonal imbalances, enhances oxidative stress, and increases susceptibility to diseases, collectively leading to severe constraints on plant growth and development (Nadeem et al., 2016; Bhise and Dandge, 2019). In irrigated agricultural systems, elevated concentrations of sodium (Na^+) and chloride (Cl^-) ions impair water uptake, disrupt nutrient homeostasis, and cause ion toxicity (Hu and Schmidhalter, 2005; Munns, 2005; Roussos et al., 2007). Consequently, salinity stress reduces root and shoot length, thickness, and both fresh and dry biomass, with shoot growth often being more severely affected than root growth (Naser et al., 2009). Such adverse effects have been documented in numerous plant species, including *Atriplex halimus* (Darwish and Reda, 2000), *Hibiscus rosa-sinensis*, *Adhatoda vasica*, and *Phyllanthus emblica* (Abd El-Fattah, 2001), *Ambrosia maritima* (Kotb et al., 2001), Bougainvillea cultivars (Habib, 2002), *Salicornia europaea* and *Suaeda maritima* (Moghaieb et al., 2004), *Pittosporum tobira* (Nasr, 2005), and *Acokanthera spectabilis* (Nasr, 2009). In agricultural crops, salinity stress similarly results in pronounced yield reductions, such as decreased shoot and root biomass in cucumber irrigated with 5% NaCl (Nadeem et al., 2016), reduced yield components in hot pepper under saline irrigation at 30 and 60 mM (Ibrahim and Abd El-Raheem, 2021), and comparable declines in tomato productivity (Parvin et al., 2015). Plants subjected to salinity stress also exhibit elevated sodium and proline contents, as reported in hot pepper (Ibrahim and Abd El-Raheem, 2021), *Atriplex halimus* (Darwish and Reda, 2000), and jojoba seedlings (Salem, 2018; Abdou et al., 2010), reflecting physiological stress responses that often occur at the expense of growth and yield.

To address these challenges, recent research has increasingly focused on the use of stimulant substances, such as salicylic acid (SA) and silicon-based compounds, including potassium silicate (PS), to mitigate salinity stress and enhance plant resilience. Salicylic acid (SA), a key phenolic compound and endogenous plant hormone regulator, plays a pivotal role in improving tolerance to both abiotic and biotic stresses by modulating physiological and biochemical processes, particularly antioxidant enzyme activity (Senaratna et al., 2000; Hayat et al., 2010; Horváth et al., 2007; Harfouche et al., 2008; Yalpani et al., 1994; Durner and Klessing, 1996; Szalai et al., 2000). Numerous studies have demonstrated the effectiveness of SA in alleviating salinity stress across different plant species, although its impact varies depending on NaCl concentration and plant type. For example, Parisa et al. (2023) reported that irrigation with 100 mM NaCl caused substantial damage to *Pistacia* species, whereas SA application significantly improved salinity tolerance. Salicylic acid has also been shown to enhance growth and seed yield in several crops, including fennel (Tanious, 2008; Ali et al., 2017), coriander (Rekaby, 2013), black cumin (Helmy, 2008; Abd El-Khalek et al., 2023), guar (Kamel, 2009), and *Tagetes minuta* (Ali, 2004). In addition, SA application increased fixed oil content in black cumin (Helmy, 2008; Abd El-Khalek et al., 2023) and reduced sodium and proline accumulation in certain species, such as jojoba (Salem, 2018) and *Khaya senegalensis* (Ibrahim, 2013), although contrasting responses, including increased proline accumulation, have been reported in *Satureja hortensis* (Yazdanpanah et al., 2011).

Silicon represents another important element in plant stress management, contributing to improved growth by supplying essential mineral and micronutrients and enhancing crop yield and quality (Liang et al., 2006; Chen et al., 2010; Regina and Katarzyna, 2011; Liang et al., 2015). Silicon alleviates salinity stress by regulating Na^+ and K^+ uptake, transport, and accumulation (Zhu and Gong, 2014; Rizwan et al., 2015), enhancing antioxidant enzyme activity (Liang et al., 2007), and improving nitrogen use efficiency and ionic balance within plant tissues (Jugal and Ramani, 2017). Moreover, silicon strengthens plant resistance to pathogens and lodging (Deren et al., 1994). The beneficial effects of silicon on growth and productivity have been documented in roselle (Abdelkader et al., 2016; Mahmoud et al., 2021), *Salvia splendens* (Soundararajan et al., 2014), pot marigold (Attia and Elbohy, 2019), zinnia (Abd El-Gayed, 2019), and *Tagetes patula* (Ahmed and Abdel-Mola, 2020).

Accordingly, the present study provides a comprehensive evaluation of the interactive effects of saline irrigation and foliar application of salicylic acid and/or potassium silicate on roselle (*Hibiscus* *sabdariffa* L., cv. ‘Sabahia 17’). The study specifically examines plant morphological traits, fruit and fixed oil productivity, and anthocyanin content to elucidate the potential of these treatments to mitigate salinity-induced stress and improve physiological, agronomic, and biochemical performance.

Materials and Methods

During the 2022 and 2023 growing seasons, a pot experiment was conducted at the Experimental Farm, Faculty of Agriculture, Al-Azhar University, Assiut, Egypt, to evaluate the effects of salinity and foliar-applied stimulants on roselle (*Hibiscus sabdariffa* L.), cv. ‘Sabahia 17’ (dark line). The experiment included irrigation with saline water at concentrations of 2000, 3000, and 4000 ppm, with tap water used as the control, in combination with foliar applications of salicylic acid at 50 and 100 ppm and potassium silicate at 1 and 2 mL L^{-1}. Roselle seeds were obtained from the Medicinal and Aromatic Plants Department, Horticulture Research Institute, Agricultural Research Center, Giza, Egypt, and were sown on 15 March in each growing season. The study was conducted under controlled environmental conditions, with an average temperature of 35.5 °C, relative humidity of 65.7%, and a photoperiod of 13.5 h light and 10.5 h dark. Seedlings were transplanted 45 days after sowing into polyethylene bags (25 × 30 cm) containing 10 kg of sandy soil. The physical and chemical properties of the soil were determined according to Jackson (1973) and are presented in Table 1.

Table 1. Measured soil properties, averaged over the two seasons of the study.

Particle size distribution			**Texture class**	**$CaCO_3$ %**	**EC (dS m^{-1}) 1:2.5**	**pH**
Sand %	**Silt %**	**Clay %**				
81.3	12.5	6.2	Sandy	11.41	3.02	8.00
	N %	P %	K %	Cl %	Mg %	
	0.041	0.027	0.09	3.91	0.14	

Compost was mixed with the soil in all pots at the recommended rate of 72 g bag^{-1}, equivalent to 24 m^3 fed^{-1}, at the time of seedling transplanting. The experiment was arranged in a split-plot design with three replicates, each replicate consisting of five seedlings (one seedling per pot). Salinity levels were assigned to the main plots (A) and comprised four treatments: 0 ppm (tap water), 2000 ppm (3.125 dS m^{-1}; 2 g NaCl L^{-1} water), 3000 ppm (4.688 dS m^{-1}; 3 g NaCl L^{-1} water), and 4000 ppm (6.250 dS m^{-1}; 4 g NaCl L^{-1} water). A portable electrical conductivity (EC) meter was used to determine the electrical conductivity of the irrigation water (ECiw). The sub-plots (B) were assigned five stimulant treatments: control (0), salicylic acid at 50 and 100 ppm, and potassium silicate at 1 and 2 mL L^{-1}, resulting in a total of 20 treatment combinations (A × B).

One month after transplanting, seedlings were irrigated once weekly with 500 mL per pot, corresponding to 75% of field capacity, using either the designated saline solutions or tap water for the control treatment. To avoid nutrient deficiencies, all pots were irrigated with groundwater once every two weeks. During both growing seasons, foliar applications of salicylic acid and potassium silicate were applied four times at two-week intervals, beginning on 15 May, and were sprayed onto the leaves in the early morning. A surfactant (Tween 20 at 0.01%) was added to the spray solution to enhance the penetration of salicylic acid and potassium silicate into leaf tissues.

At the end of the experiment, during the second week of October, data were recorded for growth, yield, and chemical parameters, including number of branches per plant, herb dry weight (g $plant^{-1}$), root length, root dry weight (g $plant^{-1}$), sepals dry weight (g $plant^{-1}$), seed yield (g $plant^{-1}$), and fixed oil percentage in dried seeds. Fixed oil was extracted using a Soxhlet apparatus with hexane (boiling point 60–80 °C) according to A.O.A.C. (1980), and fixed oil yield (mL $plant^{-1}$) was calculated by multiplying the fixed oil percentage by seed yield (g $plant^{-1}$). Total anthocyanin percentage in air-dried sepal extracts was determined following the method of Fulcki and Francis (1968), as modified by Du and Francis (1973). Titratable acidity, expressed as citric acid percentage, was measured in air-dried sepals by alkali titration according to A.O.A.C. (1970). Sodium percentage (Na%) in dried leaves was estimated following Jackson (1962), while free proline content (µmol g^{-1} DW) was determined according to Bates et al. (1973). The collected data were tabulated and statistically analyzed using MSTAT-C software (1986). Differences among treatment means were evaluated using the least significant difference (LSD) test at the 5% probability level, following the procedure described by Mead et al. (1993).

Results

Plant growth traits

The data presented in Table 2 show that increasing irrigation water salinity levels significantly reduced the number of branches per plant, herb dry weight per plant, root length, and root dry weight per plant in both growing seasons. In contrast, the application of low saline water stress (2000 ppm) resulted in measurable improvements compared to the unsalinized control. Under this treatment, branch number increased by 6.3 and 6.5%, herb dry weight per plant by 3.9 and 3.7%, root length by 4.6 and 5.4%, and root dry weight per plant by 5.2% in the first and second seasons, respectively.

Table 2. Mean plant growth traits per roselle plant as influenced by saline water levels and foliar treatments with salicylic acid (SA), potassium silicate (PS), and their interactions during the 2022 and 2023 growing seasons.

Stimulant substance treatments (ST)	**Saline water levels (SW) (ppm)**									
	First season					**Second season**				
	Control	**2000**	**3000**	**4000**	**Mean (ST)**	**Control**	**2000**	**3000**	**4000**	**Mean (ST)**
Branch number plant^{-1}										
Control	8.8	8.6	7.6	6.0	7.7	10.0	10.0	7.9	6.1	8.5
SA (50 ppm)	9.4	10.1	8.4	6.6	8.6	10.9	11.6	9.0	6.7	9.6
SA (100 ppm)	10.5	11.2	8.9	7.0	9.4	11.9	13.2	9.7	7.2	10.5
PS (1 mL L^{-1})	9.1	9.8	8.1	6.5	8.4	10.2	10.8	8.4	6.4	8.9
PS (2 mL L^{-1})	9.8	10.8	8.8	6.8	9.0	11.1	12.1	9.2	7.0	9.9
Mean (SW)	9.5	10.1	8.4	6.6		10.8	11.5	8.8	6.7	
LSD$_{0.05}$	SW: 0.2	ST: 0.3	SWxST: N.S			SW: 0.3	ST: 0.5	SWxST: 0.7		
Weight of herb dry (g) plant^{-1}										
Control	112.5	115.7	102.5	88.5	104.8	118.8	123.2	109.9	92.2	111.0
SA (50 ppm)	117.3	121.0	105.8	92.6	109.2	123.1	125.8	112.0	95.4	114.1
SA (100 ppm)	118.7	127.7	107.5	95.9	112.5	125.4	133.0	115.8	100.0	118.6
PS (1 mL L^{-1})	116.2	119.7	105.7	90.6	108.0	121.8	124.9	110.1	94.6	112.9
PS (2 mL L^{-1})	118.3	122.0	105.8	92.8	109.7	123.3	128.0	112.4	97.0	115.2
Mean (SW)	116.6	121.2	105.5	92.1		122.5	127.0	112.1	95.8	
L.S.D for 0.05	SW: 2.6	ST: 2.0	SWxST: 4.0			SW: 3.0	ST: 2.4	SWxST: N.S		
Root length (cm) plant^{-1}										
Control	16.4	16.0	14.2	12.6	14.8	17.2	17.1	15.3	13.1	15.7
SA (50 ppm)	17.3	17.8	15.5	13.9	16.1	18.5	19.6	16.7	14.8	17.4
SA (100 ppm)	18.3	20.9	15.8	14.9	17.5	19.9	22.3	17.3	15.6	18.8
PS (1 mL L^{-1})	17.1	17.5	15.2	13.5	15.9	18.2	18.9	16.2	14.4	16.9
PS (2 mL L^{-1})	17.5	18.2	15.7	13.8	16.3	19.0	19.9	17.0	14.8	17.7
Mean (SW)	17.3	18.1	15.3	13.7		18.6	19.6	16.5	14.6	
LSD$_{0.05}$	SW: 0.4	ST: 0.6	SWxST: 2.2			SW: 0.3	ST: 0.4	SWxST: 0.8		
Root dry weight (g) plant^{-1}										
Control	9.2	9.1	7.5	6.3	8.0	9.7	9.5	7.9	6.6	8.4
SA (50 ppm)	9.5	9.7	7.7	6.5	8.4	9.8	10.2	8.1	6.9	8.8
SA (100 ppm)	9.9	10.2	8.6	7.3	9.0	10.1	10.9	8.9	7.5	9.3
PS (1 mL L^{-1})	9.3	9.4	8.1	6.6	8.4	9.4	9.9	8.1	6.7	8.5
PS (2 mL L^{-1})	9.5	9.8	8.5	7.1	8.7	9.7	10.4	8.4	7.0	8.9
Mean (SW)	9.5	9.6	8.1	6.8		9.7	10.2	8.3	7.0	
LSD$_{0.05}$	SW: 0.2	ST: 0.2	SWxST: 0.3			SW: 0.3	ST: 0.2	SWxST: N.S		

The results presented in Table 2 indicated that foliar application of salicylic acid (SA) and potassium silicate (PS) significantly increased the number of branches per plant in roselle during both growing seasons compared to the unsprayed control. All tested concentrations of these biostimulants enhanced branch number per plant, herb dry weight per plant, root length, and root dry weight per plant, except for PS at 1 mL L^{-1} in the second season, which did not result in a significant increase in branch number, herb dry weight, or root dry weight per plant. Among the treatments, salicylic acid at 100 ppm was the most effective, increasing branch number by 22.1 and 23.5%, herb dry weight per plant by 7.3 and 6.8%, root length by 18.2 and 19.7%, and root dry weight per plant by 12.5 and 10.7% in the first and second seasons, respectively, compared to the control.

Interaction analysis showed that branch number per plant was significantly affected by the combined treatments, particularly during the second season. The interaction between saline water and stimulant treatments significantly influenced herb dry weight per plant in the first season only. Root length was significantly affected by the interaction effects in both seasons, whereas root dry weight per plant was significantly influenced by the interaction between salinity and stimulant treatments in the first season only. Overall, the most effective strategy for improving these growth traits was irrigation with low-salinity water (2000 ppm) combined with foliar application of either salicylic acid or potassium silicate, irrespective of concentration. This combination consistently produced higher branch numbers than other treatments across both seasons.

In contrast, irrigation with higher salinity levels (3000 or 4000 ppm), even when combined with foliar spraying, resulted in the lowest values for branch number, herb dry weight, root length, and root dry weight per plant. Notably, the most pronounced improvement was obtained by combining 2000 ppm saline water with foliar application of salicylic acid at 100 ppm, followed by potassium silicate at 2 mL L^{-1}, which significantly outperformed the other treatment combinations. Furthermore, irrigation with 3000 ppm saline water combined with foliar application of salicylic acid at 100 ppm produced branch number per plant, herb dry weight per plant, root length, and root dry weight per plant values that were statistically comparable to those of the control treatment (unsalinized and unsprayed) in most cases, as shown in Table 2.

Yield and its components

The data in Table 3 demonstrated that increasing saline water levels led to a progressive and significant reduction in the sepal dry weight and seed weight per roselle plant across both growing seasons. In contrast, plants irrigated with a low salinity level (2000 ppm) exhibited a notable increase in sepal dry weight and seed weight, with values rising by 5.9 and 4.0% and 7.4 and 6.6%, respectively, compared to unsalinized plants in the first and second seasons, respectively.

Table 3. Mean yield and its components per roselle plant as influenced by saline water levels and foliar treatments with salicylic acid (SA), potassium silicate (PS), and their interactions during the 2022 and 2023 growing seasons.

Stimulant substance treatments (ST)	Saline water levels (SW) (ppm)									
	First season					Second season				
	Control	2000	3000	4000	Mean (ST)	Control	2000	3000	4000	Mean (ST)
Sepals dry weight (g) plant^{-1}										
Control	17.2	18.0	15.0	11.7	15.5	19.4	20.1	17.2	13.9	17.6
SA (50 ppm)	20.7	22.2	18.0	14.2	18.8	23.2	24.4	20.2	16.3	21.0
SA (100 ppm)	22.2	24.0	19.1	14.9	20.0	24.3	25.5	21.2	17.1	22.0
PS (1 mL L^{-1})	19.9	20.9	16.7	13.5	17.7	22.4	22.8	18.8	15.6	19.9
PS (2 mL L^{-1})	21.4	22.5	17.6	13.7	18.8	23.5	24.5	19.8	15.9	20.9
Mean (SW)	20.3	21.5	17.3	13.6		22.5	23.4	19.5	15.8	
LSD$_{0.05}$	SW: 0.4		ST: 0.4	SWxST: 0.8		SW: 0.6		ST: 0.5	SWxST: 0.9	
Seeds weight (g) plant^{-1}										
Control	20.7	21.6	20.4	16.0	19.7	21.8	22.1	21.5	18.2	20.9
SA (50 ppm)	22.8	25.0	22.7	17.5	22.0	24.1	26.1	23.8	19.6	23.4
SA (100 ppm)	25.1	26.8	24.7	19.4	24.0	26.2	28.0	25.8	21.5	25.4
PS (1 mL L^{-1})	22.0	24.7	21.3	16.8	21.2	23.1	25.8	22.5	19.0	22.6
PS (2 mL L^{-1})	24.3	25.6	22.1	17.6	22.4	25.4	26.6	23.2	19.8	23.7
Mean (SW)	23.0	24.7	22.2	17.5		24.1	25.7	23.3	19.6	
LSD$_{0.05}$	SW: 0.9		ST: 0.5	SWxST: 1.1		SW: 0.8		ST: 0.6	SWxST: 1.2	

It is noteworthy that foliar application of both stimulant substances at all tested concentrations significantly increased sepal dry weight and seed weight per plant in roselle compared to the untreated control in both growing seasons. Among the treatments, salicylic acid at 100 ppm produced the highest sepal dry weight per plant, resulting in increases of 29 and 25%, as well as increases of 21.8 and 21.5% in seed weight per plant, compared to the control in the first and second seasons, respectively, as shown in Table 3.

Regarding the interaction effects, Table 3 demonstrates that the combined influence of saline irrigation levels and foliar application of stimulant substances significantly affected both sepal dry weight and seed weight per plant in roselle during the two seasons. Plants irrigated with low-salinity water (2000 ppm) and treated with any of the stimulant substances exhibited a marked increase in these parameters compared to other treatment combinations. In contrast, the application of higher salinity levels (3000 or 4000 ppm), even when combined with foliar stimulants, resulted in lower sepal dry weight and seed weight per plant. The most effective treatment was the combination of 2000 ppm saline water with foliar application of salicylic acid at 100 ppm, which produced the highest sepal dry weight and seed weight.

Furthermore, irrigation with 3000 ppm saline water combined with foliar application of salicylic acid at 50 or 100 ppm in the first season, and at 100 ppm in the second season, resulted in significantly higher sepal dry weight compared to the control (unsalinized and unsprayed) plants. Similarly, irrigation with 3000 ppm saline water combined with foliar application of salicylic acid at 50 or 100 ppm, or potassium silicate at 2 mL L^{-1}, significantly enhanced seed weight per plant compared to the control in both seasons.

Chemical constituent traits

Fixed oil productivity

Data in Table 4 and Figure 1 indicate that fixed oil percentage fixed oil yield per plant of roselle seeds significantly decreased as saline water levels increased over both seasons. In contrast, irrigation with low-salinity water (2000 ppm) led to a notable increase in fixed oil percentage and yield per plant, with a 1.1 and 3.0% and 8.6 and 9.6%, respectively, elevation over unsalinized conditions in the first and second season, respectively.

Regarding the stimulant treatments, foliar spraying with both salicylic acid and potassium silicate at all concentrations resulted in a significant enhancement of fixed oil percentage and yield in roselle seeds compared to unsprayed plants across the two seasons (Table 4 and Fig. 2). Notably, treatment with 100 ppm salicylic acid produced the highest fixed oil, increasing these parameters by 18.3% in the first season and 18.2% in the second season (fixed oil %, Table 4) and by 44.6% in the first season and 43.8% in the second season for fixed oil yield, as clearly shown in Figure 2, compared to the control.

Table 4. Mean fixed oil % in roselle plant as influenced by saline water levels and foliar treatments with salicylic acid (SA), potassium silicate (PS), and their interactions during the 2022 and 2023 growing seasons.

Stimulant substance	Saline water levels (SW) (ppm)				
	Control	2000	3000	4000	Mean (ST)
First season					
Control	15.56	16.04	14.48	12.82	14.73
SA (50 ppm)	17.55	18.06	16.34	14.59	16.64
SA (100 ppm)	18.69	18.73	17.57	14.74	17.43
PS (1 mL L^{-1})	17.38	17.55	16.25	14.49	16.42
PS (2 mL L^{-1})	18.61	18.38	16.59	14.66	17.06
Mean (SW)	17.56	17.75	16.25	14.26	
$LSD_{0.05}$	SW: 0.20 ST: 0.37 SWxST: 0.73				
Second season					
Control	15.97	16.74	15.05	12.32	15.02
SA (50 ppm)	18.03	19.16	16.83	14.13	17.04
SA (100 ppm)	19.22	19.43	18.06	14.28	17.75
PS (1 mL L^{-1})	17.87	18.37	16.74	14.00	16.75
PS (2 mL L^{-1})	19.13	19.23	17.09	14.03	17.37
Mean (SW)	18.04	18.59	16.76	13.75	
$LSD_{0.05}$	SW: 0.36 ST: 0.39 SWxST: 0.79				

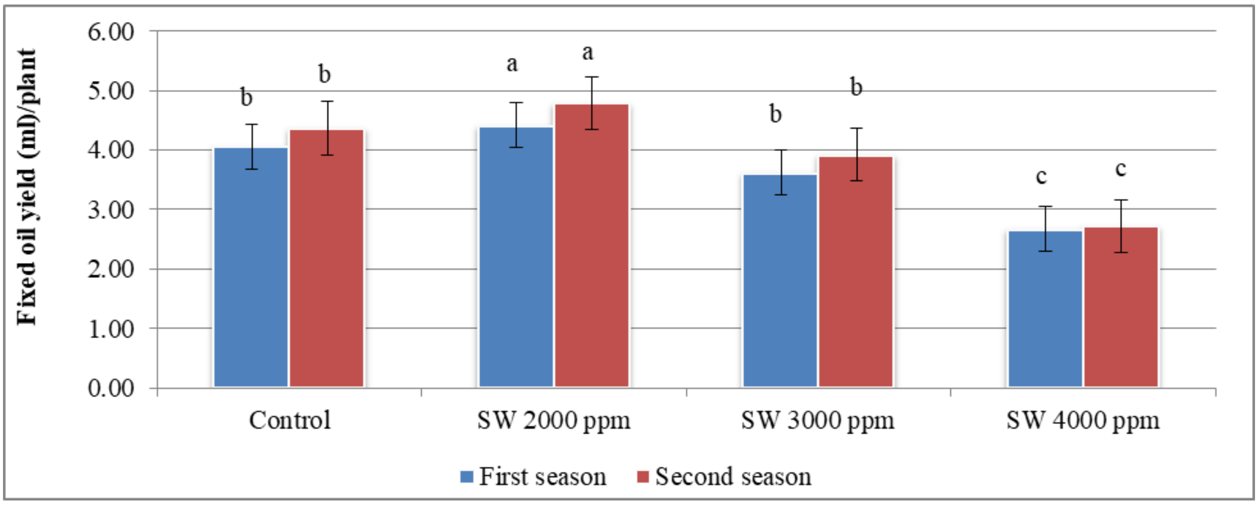

Fig. 1. Mean fixed oil yield (mL) plant^{-1} of roselle as influenced by saline water (SW) levels during the 2022 and 2023 growing seasons.

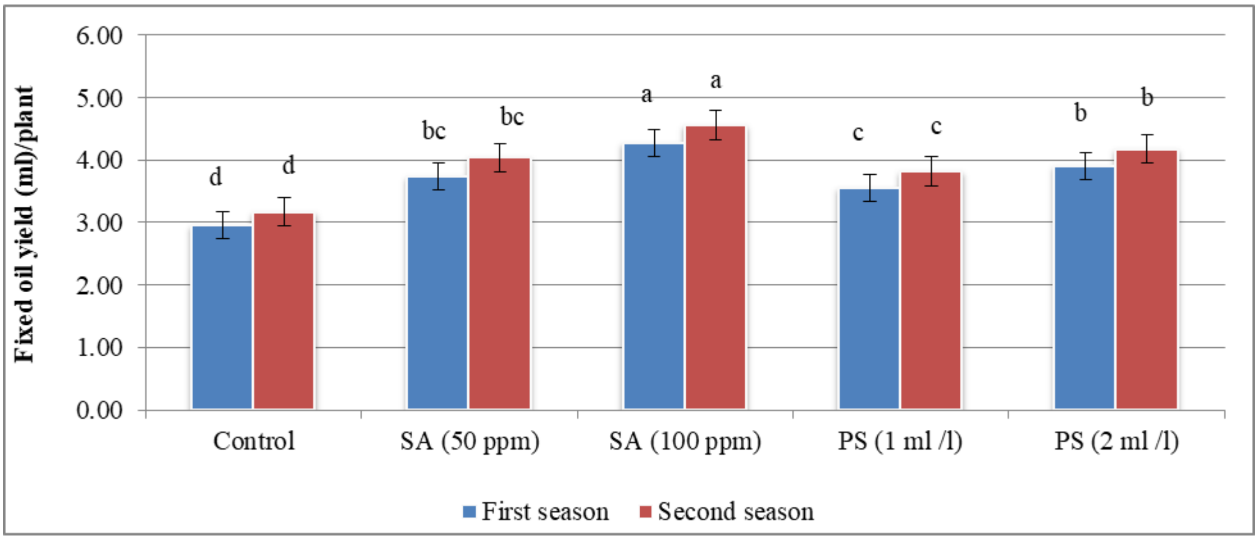

Fig. 2. Mean fixed oil yield (mL) plant^{-1} of roselle as influenced by salicylic acid (SA) and potassium silicate (PS) during the 2022 and 2023 growing seasons.

Furthermore, the interaction treatments significantly affected the fixed oil production in roselle seeds (Table 4 and Fig. 3). Plants irrigated with low-salinity water (2000 ppm) combined with any stimulant consistently exhibited higher fixed oil percentage and yield than those under other treatments. Conversely, using moderate (3000 ppm) or high (4000 ppm) saline water with stimulants generally resulted in lower fixed oil. Overall, the most effective combinations for enhancing fixed oil were 2000 ppm saline water with either 100 ppm salicylic acid or 2 mL L^{-1} potassium silicate, as observed over two growing seasons.

Total anthocyanin and total acidity percentages

According to the data presented in Table 5, the total anthocyanin and total acidity percentages of roselle sepals was progressively and significantly reduced with increasing saline water levels over the two consecutive seasons. It is obvious that a low level of saline water (2000 ppm) caused a significant increase in total anthocyanin percentage (3.0 and 2.9%) and acidity percentage (3.0 and 2.5%) over untreated ones, during both seasons, respectively.

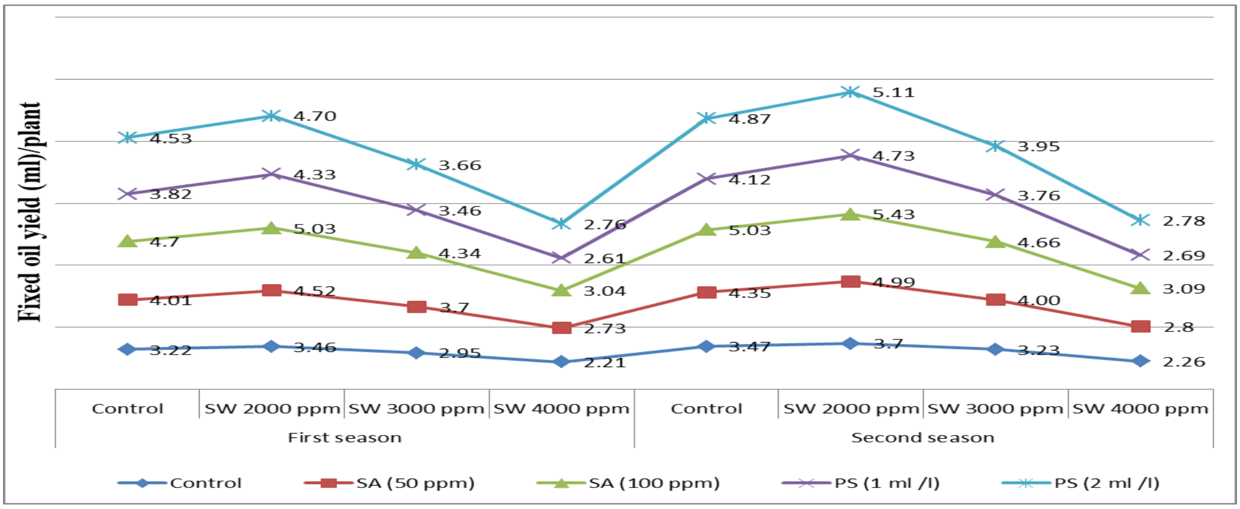

Fig. 3. Impact of interaction between saline water levels and salicylic acid (SA) and potassium silicate (PS) on fixed oil yield per plant (mL) of roselle on the mean basis of the two seasons.

Table 5. Mean total anthocyanin and total acidity percentages in dry sepals of roselle as influenced by saline water levels and foliar treatments with salicylic acid (SA), potassium silicate (PS), and their interactions during the 2022 and 2023 growing seasons.

Stimulant substance treatments (ST)	**Saline water levels (SW) (ppm)**									
	First season					**Second season**				
	Control	**2000**	**3000**	**4000**	**Mean (ST)**	**Control**	**2000**	**3000**	**4000**	**Mean (ST)**
Total anthocyanin percentage										
Control	1.88	1.90	1.83	1.11	1.68	1.95	1.97	1.92	1.19	1.76
SA (50 ppm)	1.94	2.05	1.90	1.18	1.77	2.01	2.07	1.98	1.26	1.83
SA (100 ppm)	2.11	2.18	1.97	1.25	1.88	2.13	2.27	2.05	1.33	1.95
PS (1 mL L^{-1})	1.94	1.97	1.88	1.17	1.74	2.03	2.04	1.96	1.25	1.82
PS (2 mL L^{-1})	2.00	2.09	1.92	1.23	1.81	2.06	2.16	2.00	1.30	1.88
Mean (SW)	1.97	2.03	1.90	1.19		2.04	2.10	1.99	1.27	
$LSD_{0.05}$	SW: 0.03		ST: 0.02	SWxST: 0.04		SW: 0.02		ST: 0.02	SWxST: 0.04	
Total acidity percentage										
Control	7.90	7.88	7.72	7.49	7.75	8.19	8.17	7.96	7.73	8.01
SA (50 ppm)	8.06	8.54	8.01	7.75	8.09	8.35	8.78	8.25	8.00	8.35
SA (100 ppm)	8.72	8.98	8.37	8.10	8.54	9.01	9.22	8.61	8.34	8.80
PS (1 mL L^{-1})	7.95	8.34	7.80	7.71	7.95	8.24	8.61	8.04	7.97	8.22
PS (2 mL L^{-1})	8.53	8.65	7.99	7.90	8.27	8.82	8.89	8.22	8.10	8.51
Mean (SW)	8.23	8.48	7.98	7.79		8.52	8.73	8.22	8.03	
$LSD_{0.05}$	SW: 0.11		ST: 0.06	SWxST: 0.12		SW: 0.12		ST: 0.13	SWxST: 0.25	

With respect to stimulant substances, the data presented in Table 5 indicate that total anthocyanin percentage in roselle was significantly increased by foliar application of these substances at all tested concentrations compared to unsprayed plants during both growing seasons. Among the treatments, foliar spraying with salicylic acid at 100 ppm was the most effective, resulting in increases of 11.9 and 10.8% in total anthocyanin percentage and 10.2 and 9.9% in acidity percentage compared to the control in the first and second seasons, respectively.

The interaction between saline irrigation levels and foliar application of stimulant substances had a statistically significant effect on both total anthocyanin and acidity percentages in roselle over the two seasons. Irrigation with low-salinity water

(2000 ppm) combined with any stimulant treatment consistently produced higher anthocyanin and acidity percentages compared to other treatment combinations. Notably, irrigation with 3000 ppm saline water combined with foliar application of salicylic acid at 100 ppm or potassium silicate at 2 mL L^{-1} significantly enhanced total anthocyanin percentage compared to the control treatment. In addition, treatments involving 3000 ppm saline water combined with salicylic acid at 100 ppm in both seasons, as well as 4000 ppm saline water combined with salicylic acid at 100 ppm in the first season, resulted in significantly higher acidity percentages than those of the control (unsalinized and unsprayed) plants. Overall, the highest values of total anthocyanin and acidity percentages were obtained when roselle plants were irrigated with 2000 ppm saline water and sprayed with salicylic acid at 100 ppm, which outperformed all other treatment combinations, as shown in Table 5.

Sodium percentage

Table 6 reveals that the Na% in roselle leaves increased significantly and progressively with rising saline water levels across both seasons. The lowest Na% values were recorded in plants irrigated with 2000 ppm saline water, which showed increases of 29.9% in the first season and 34.8% in the second season compared to unsalinized plants.

Table 6. Mean Na % in roselle dry leaves as influenced by saline water levels and foliar treatments with salicylic acid (SA), potassium silicate (PS), and their interactions during the 2022 and 2023 growing seasons.

Stimulant substance	Saline water levels (SW) (ppm)				
	Control	2000	3000	4000	Mean (ST)
First season					
Control	0.92	1.27	1.71	2.16	1.52
SA (50 ppm)	0.88	1.15	1.60	2.07	1.43
SA (100 ppm)	0.84	1.03	1.49	2.01	1.34
PS (1 mL L^{-1})	0.89	1.12	1.65	2.10	1.44
PS (2 mL L^{-1})	0.84	1.09	1.60	2.03	1.39
Mean (SW)	0.87	1.13	1.61	2.07	
$LSD_{0.05}$		SW: 0.04	ST: 0.02	SWxST: 0.05	
Second season					
Control	0.95	1.32	1.70	2.24	1.55
SA (50 ppm)	0.92	1.22	1.57	2.06	1.44
SA (100 ppm)	0.85	1.09	1.53	2.02	1.37
PS (1 mL L^{-1})	0.88	1.20	1.59	2.09	1.44
PS (2 mL L^{-1})	0.84	1.17	1.58	2.07	1.42
Mean (SW)	0.89	1.20	1.59	2.10	
$LSD_{0.05}$		SW: 0.05	ST: 0.03	SWxST: 0.06	

According to Table 6, foliar applications of the two tested stimulant substances, at all concentrations, significantly lowered the Na% in roselle leaves compared to unsprayed plants during both experimental seasons. In particular, spraying with 100 ppm salicylic acid produced the most substantial decrease in Na%, with reductions of 11.8 and 13.1% in the first and second seasons, respectively.

Obviously, in both seasons, the Na% in roselle leaves was significantly influenced by the interaction treatments (Table 6). Lower Na% values were observed when 2000 ppm saline water was used in combination with any stimulant, compared to higher salinity levels (3000 or 4000 ppm) with similar treatments. Furthermore, plants irrigated under non-saline conditions with any stimulant exhibited the lowest Na% overall. Notably, the combination of 2000 ppm saline water with 100 ppm salicylic acid was the most effective in reducing Na% across both seasons.

Free proline content (μ mole g^{-1} DW)

The results depicted in Figure 4 emphasized that free proline content in roselle leaves increased significantly and gradually with rising saline water levels across both experimental seasons. Specifically, the lowest free proline values were observed in plants irrigated with a low level of saline water (2000 ppm), which exhibited increases of 5.2 and 7.8% over unsalinized plants in the two seasons, respectively.

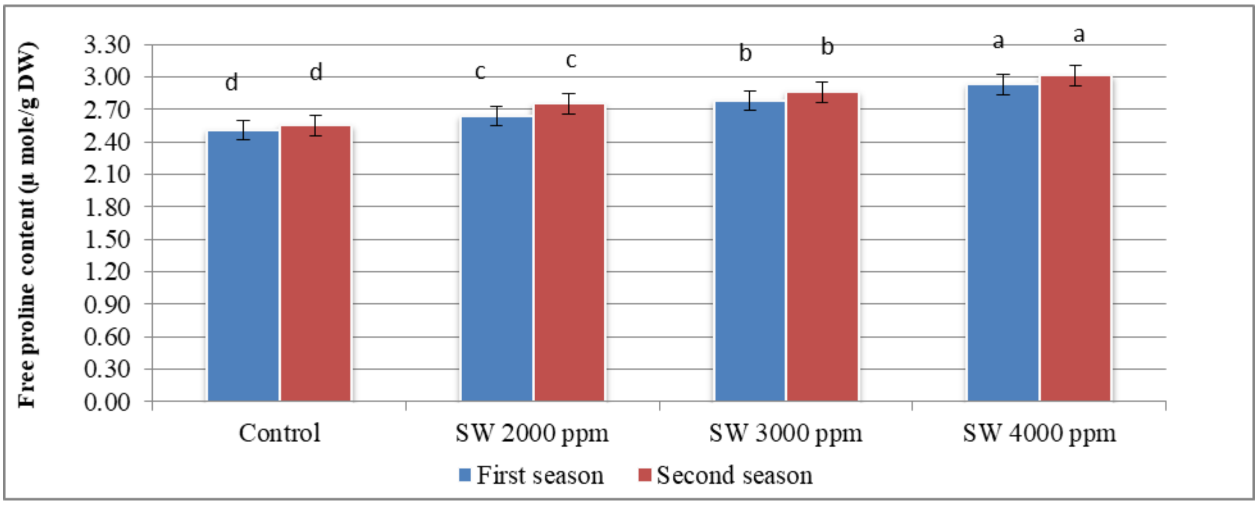

Fig. 4. Content of free proline (µ mole g^{-1} DW) in roselle dry leaves, showing the influence of different saline water (SW) levels over the 2022 and 2023 growing seasons.

According to the data in Figure 5, foliar spraying roselle plants with both stimulant substances at all tested concentrations significantly decreased the free proline content in the leaves compared to unsprayed plants, in both seasons. Notably, the foliar spray with 100 ppm salicylic acid was the most effective, reducing free proline content by 6% in one season and 6.2% in the other compared to the control.

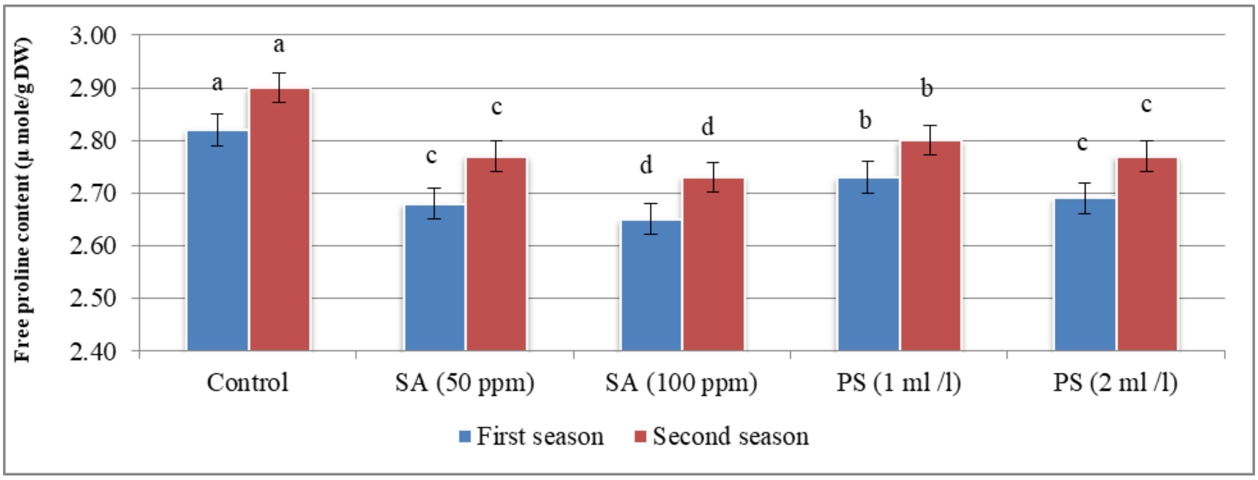

Fig. 5. Content of free proline (µmole g^{-1} DW) in roselle dry leaves in response to foliar applications of salicylic acid (SA) and potassium silicate (PS) during the 2022 and 2023 seasons.

The data in Figure 6 demonstrates that the combined treatments significantly affected free proline content in roselle leaves over both growing seasons. Lower free proline levels were observed with 2000 ppm saline water combined with any stimulant compared to higher salinity levels (3000 or 4000 ppm) paired with stimulants. Non-saline conditions with any stimulant also resulted in lower free proline values compared to the higher salinity treatments. Notably, the combination of 2000 ppm saline water with 100 ppm salicylic acid proved to be the most effective in reducing free proline content consistently across both seasons.

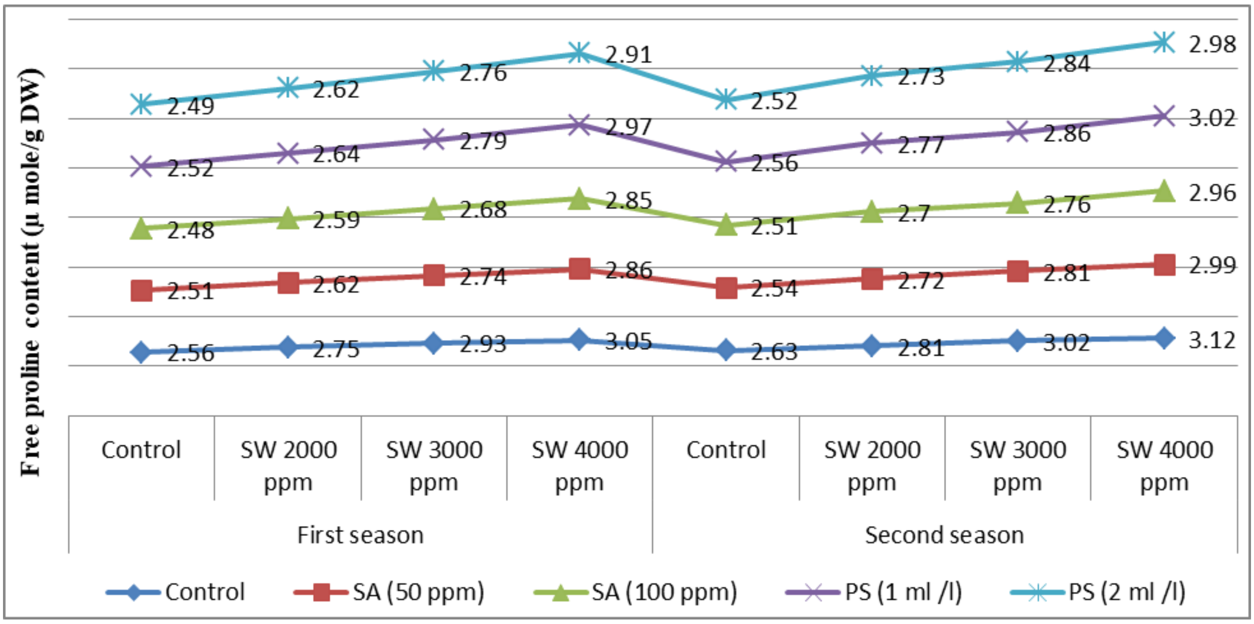

Fig. 6. Effect of the interaction of saline water levels with salicylic acid (SA) and potassium silicate (PS) on content of free proline (μmol g^{-1} DW) in roselle dry leaves, presented as a mean across the two growing seasons.

Discussion

The results of the present study demonstrated the significant role of foliar application of salicylic acid (SA) and potassium silicate (PS) in alleviating the adverse effects of saline irrigation water (2000, 3000, and 4000 ppm) on roselle (*Hibiscus sabdariffa* L.), cv. 'Sabahia 17'. These treatments markedly improved plant growth and productivity, as reflected by increases in plant height, sepal and seed weights, fixed oil content, total anthocyanin percentage, and acidity, while simultaneously reducing sodium (Na^+) accumulation and proline content, which are widely recognized indicators of salinity-induced stress. The present discussion places these findings within the context of plant stress physiology and previous research, highlighting the underlying mechanisms responsible for the observed improvements and their relevance to sustainable crop production under saline conditions.

Salinity stress imposes complex constraints on plant growth and development, primarily through ionic imbalance, osmotic stress, and impaired nutrient uptake (Alzahrani et al., 2019; Abrar et al., 2020). Elevated salinity levels, such as those applied in this study (2000, 3000, and 4000 ppm), disrupt root system architecture by reducing root hair density and length, thereby limiting water and nutrient absorption (Robin et al., 2016; Arif et al., 2019). The consequent reduction in root surface area restricts the uptake of essential minerals, negatively affecting cellular metabolism and overall plant performance. In addition, salinity-induced osmotic stress increases abscisic acid (ABA) accumulation in stomatal guard cells, promoting stomatal closure and leading to reduced CO_2 assimilation and lower photosynthetic efficiency (Sarker and Oba, 2020). Similar responses have been reported in *Salvadora persica*, where increasing salinity and osmotic pressure significantly altered growth traits (Patel and Parida, 2022).

At the cellular level, salinity stress causes dehydration by lowering cellular water potential, thereby impairing cell expansion and cell wall synthesis and ultimately inhibiting cell division and elongation (Kumar et al., 2021). This effect is further exacerbated by the suppression of cell cycle–related genes, including cyclins and cyclin-dependent kinases, which reduces meristematic activity and limits overall plant vigor (Balasubramaniam et al., 2023). Moreover, plants exposed to saline conditions reallocate metabolic energy from growth-related processes toward maintaining ionic homeostasis and carbon balance, resulting in decreased carbon assimilation and biomass accumulation (Pompeiano et al., 2017; Kumar et al., 2021). The present results corroborate these mechanisms, as increasing salinity levels led to a reduction in root length, consistent with earlier reports (Shahid et al., 2011). High salinity induced dehydration, Na^+ and Cl^- ion toxicity in root tissues, and reduced stomatal conductance, collectively contributing to declines in both shoot and root dry weights (Abbruzzese et al., 2009; Shahid et al., 2011).

These growth reductions can be attributed to impaired photosynthetic activity, decreased stomatal conductance, and limited carbon dioxide uptake under saline conditions, which collectively restrict carbon assimilation and root biomass production (Hayat et al., 2009; Karlidag et al., 2011). Salinity stress also suppresses cell division and cell expansion, further constraining root development (Pitann et al., 2009). The observed decline in root dry weight is therefore closely associated with reduced root length, a common morphological response to salt stress (Vasquez et al., 2006; Keutgen and Pawelzik, 2008). The reduced growth and biomass accumulation at higher salinity levels in this research are consistent with previous reports documenting significant decreases in root dry weight under NaCl stress (Rahneshan et al., 2018).

In roselle specifically, salinity stress has been widely reported to impair growth and physiological performance. Moosavi et al. (2013) demonstrated that increasing salinity significantly reduced developmental parameters in roselle seedlings, while Mohamed et al. (2013) reported pronounced negative effects on physiological and biochemical traits in roselle plants. Similarly, Ghabour et al. (2020) observed substantial declines in roselle growth and yield under elevated soil salinity. Comparable salinity-induced growth inhibition has been reported in other species, such as Bruguiera parviflora, where salinity impaired overall growth (Parida et al., 2004), and sunflower, in which exposure to 150 mM NaCl reduced the maximum quantum efficiency of photosystem II (Fv/Fm) (Akram et al., 2009). Nevertheless, plant responses to salinity are species- and dose-dependent; for instance, Wang et al. (2023) reported increased biomass in certain species under moderate salinity, highlighting the complexity and variability of salinity tolerance mechanisms.

Under salinity stress, plants commonly exhibit increased proline accumulation, which results from enhanced proline biosynthesis and/or inhibition of proline catabolism (Sellami et al., 2019). Proline functions as a key osmoprotectant by stabilizing cellular membranes and proteins, scavenging reactive oxygen species, and contributing to osmotic adjustment under conditions of reduced water potential induced by high salt concentrations. This adaptive response has been well documented in several species, including *Salvadora persica*, in which Tounekti et al. (2018) reported elevated proline levels as an important component of salinity tolerance. These observations align with broader evidence underscoring the central role of proline accumulation in enhancing plant resilience to salinity stress across diverse species.

Salicylic acid (SA) plays a pivotal role in enhancing plant resilience to salinity stress through its regulation of hormonal balance, photosynthetic efficiency, and stress defense mechanisms. Metwally et al. (2003) emphasized that maintaining optimal endogenous SA levels is essential for the synthesis and regulation of auxin and cytokinin, two hormones that govern cell division, elongation, and overall plant development. In the present study, the observed increases in branch number, sepal dry weight, and seed yield in SA-treated roselle plants can be attributed to enhanced auxin and cytokinin activity, which promoted root differentiation and shoot growth under saline conditions (Singh, 1993). In addition, SA-induced stimulation of anthocyanin accumulation likely contributed to improved photosynthetic performance, facilitating greater carbon assimilation and biomass production despite the presence of salinity stress.

Salicylic acid is also known to regulate nitrogen metabolism, water use efficiency, and antioxidant defense systems (Khan et al., 2015), processes that are particularly crucial under saline conditions where ionic imbalance and oxidative damage limit plant productivity. By enhancing antioxidant enzyme activity, SA mitigates the accumulation of reactive oxygen species (ROS) generated under high salinity, thereby protecting cellular membranes, proteins, and metabolic processes (Hayat et al., 2008). Furthermore, Jayakannan et al. (2013) demonstrated that SA application increases endogenous SA and potassium (K^+) concentrations while restricting sodium (Na^+) uptake in salt-stressed plants. This mechanism provides a plausible explanation for the reduced Na^+ accumulation observed in SA-treated roselle plants in the present study, which likely alleviated ionic toxicity and supported improved growth and yield.

The growth-promoting effects of SA observed in this study further support its role as an effective plant growth regulator, owing to its capacity to enhance nutrient uptake, enzymatic activity, protein synthesis, photosynthetic efficiency, and antioxidant capacity, while conferring protection against both biotic and abiotic stresses (Blokhina et al., 2003; Sahu, 2013; Aliniaeifard et al., 2016). The enhancement of carbon dioxide assimilation, photosynthetic rate, mineral uptake, and nutrient translocation following SA application has been linked to improved nutrient status in leaf tissues (Szepesi et al., 2005; Magda et al., 2013). However, the effects of SA are highly context-dependent; for example, Xiaohua et al. (2017) reported inhibitory effects of SA on Dianthus superbus under moderate salinity, indicating that the optimal concentration and efficacy of SA may vary with species, cultivar, and stress intensity. In contrast, the present results clearly demonstrate that SA application, particularly at appropriate concentrations, substantially enhanced the growth and productivity of roselle under saline irrigation. These findings are in good agreement with earlier reports documenting the beneficial role of SA in improving plant performance under stress conditions (El-Khallal et al., 2009; Delavari et al., 2010; Abd El-Hameid Asmaa et al., 2017).

In contrast to the inhibitory effects of salinity stress, the application of potassium silicate (KSi) at 1 or 2 mL L^{-1} markedly improved growth, yield, and biochemical attributes of roselle plants under saline irrigation. Silicon is known to enhance net photosynthetic rate, chlorophyll concentration, and Rubisco activity (Hadi et al., 2016; Ahmad et al., 2013), which likely explains the observed increases in sepal and seed weights as well as anthocyanin accumulation in KSi-treated plants by supporting greater biomass production and secondary metabolite synthesis (Dawood et al., 2014). In addition, silicon improves plant water relations by reducing transpiration losses and enhancing root water uptake, as demonstrated in *Cucumis sativus* (Zhu et al., 2015). This mechanism enables KSi-treated roselle plants to maintain better hydration status, alleviate osmotic stress, and sustain cell expansion and vegetative growth under saline conditions.

Silicon also promotes root development, thereby improving nutrient uptake efficiency and counteracting ionic imbalances caused by excessive Na^+ and Cl^- accumulation (Ma and Yamaji, 2006; Abo-Baker et al., 2011; Shaaban and Abou El-Nour, 2014), a response consistent with the increased root length and dry weight observed in this study. Furthermore, silica deposition within plant tissues enhances cell wall strength, conferring mechanical protection against salinity-induced cellular damage and contributing to improved plant vigor (Romero-Aranda et al., 2006; Lopes et al., 2014). Potassium silicate has also been reported to improve membrane integrity and stability under stress conditions (Maghsoudi et al., 2016; Zhu and Gong, 2014), preserve leaf water potential, and enhance stomatal conductance and light interception under high evaporative demand (Crusciol et al., 2009; Das et al., 2017; Marschner, 2011).

At the metabolic level, silicon stimulates cell division and carbohydrate biosynthesis and strengthens antioxidant defense systems by activating enzymes such as glutathione peroxidase, thereby reducing reactive oxygen species (ROS) accumulation and delaying stress-induced senescence (Ma and Takahashi, 2005). The potassium component of KSi further contributes to stress tolerance by enhancing assimilate translocation, protein synthesis, and key metabolic processes that support cell enlargement, division, and overall growth under salinity stress (Bidari and Hebsur, 2011; Abd El-Gawad et al., 2017). Notably, KSi application at 2 mL L^{-1} significantly reduced proline concentration relative to the elevated levels observed in untreated control plants, indicating a lower degree of stress perception. This reduction may be attributed to the formation of a silicated layer on leaf surfaces, which decreases cuticular transpiration through silica deposition beneath the cuticle and within epidermal cell walls (Meena et al., 2014). An additional protective mechanism involves enhanced synthesis of phenolic compounds, which promotes lignification and strengthens cell walls, thereby improving resistance to salinity stress (Lopes et al., 2014).

Collectively, these physiological, biochemical, and structural adjustments were supported by improved water and nutrient uptake through well-developed root hairs (Shaaban and Abou El-Nour, 2014). These adjustments contributed to the partial alleviation of salt stress by limiting oxidative damage and facilitating osmotic adjustment (Ahmad and Haddad, 2011). Taken together with the effects of salicylic acid, these findings highlight the combined potential of SA and KSi as sustainable agronomic tools for enhancing roselle productivity and stress resilience under saline conditions, with important implications for cultivation in salt-affected regions such as Egypt.

Conclusion

Salinity stress exerted a profound negative impact on plant growth, yield components, and various chemical attributes in the present research. The findings revealed that the foliar application of salicylic acid (SA) or potassium silicate (PS) on roselle plants (*Hibiscus sabdariffa* L. cv. ‘Sabahia 17’) effectively alleviated the deleterious effects induced by NaCl stress. Specifically, SA at 100 ppm and PS at 2 mL L^{-1} demonstrated remarkable efficiency in enhancing plant growth and physiological responses under NaCl-induced salinity conditions. This combined strategy offers a promising and environmentally friendly framework for improving both the quantity and quality of medicinal and aromatic plant yields under practical field conditions, making it a sustainable option for farmers aiming to maximize productivity while minimizing the impact of salinity.

Acknowledgments

The authors express sincere gratitude for the essential logistical and technical support from the faculties of agriculture at the participating universities and the Horticulture Research Institute, which made this work possible.

Author Contributions

All authors equally participated in drafting, editing, and finalizing the manuscript, and they collectively agreed to its submission to the journal. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Conflict of Interest

The authors indicate no conflict of interest in this work.

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