

Salicylic acid enhances growth and ionic balance of shallots (*Allium ascalonicum* L.) grown from true seeds under saline conditions

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Abstract: Salinity stress is a significant limiting factor in shallot (*Allium ascalonicum* L.) production, affecting ion homeostasis and plant growth. This study aimed to evaluate the role of salicylic acid (SA) in enhancing salt tolerance in shallots grown from true shallot seeds (TSS) under medium saline conditions maintained at ± 5.8 dS/m. A factorial experiment was conducted using a randomized block design with four SA concentrations (0, 1, 1.5, and 2 mM) and three transplanting ages (28, 35, and 42 days after sowing). Saline conditions were induced by applying 2,922 ppm NaCl (equivalent to 5.8 dS/m) to the growing medium every five days, starting at 10 days after planting (DAP). SA was administered by spraying it onto the leaves at 14, 17, 20, and 23 DAP. The results of the study show that the SA application significantly influences Na⁺ and K⁺ uptake of shallot plants grown in saline conditions of 5.8dS/m, reducing Na⁺ accumulation while increasing K⁺ content in plant tissues. The Na⁺/K⁺ selective absorption index (SAI) also decreased below 1.0 in the 1–1.5 mM SA treatments, indicating improved ionic balance and stress tolerance. The 1.5 mM SA concentration resulted in the highest bulb dry weight (12.07 g), stover dry weight (25.92 g), and bulb number per plant (3.89). Moreover, it produced the highest proportion of Grade 1 bulbs (78.17%) as per the Indonesian National Standard (SNI 3159:2013). Early transplanting at 28 DAS further improved yield parameters. These findings suggest that moderate SA application, particularly at 1.5 mM, can mitigate salinity stress and enhance productivity in shallot cultivation by improving ion regulation and physiological performance.

Keywords: Salicylic acid, ion balance, Na⁺/K⁺ ratio, TSS, salinity stress, shallot, bulb quality.

Abbreviations: CoE_centre of excellence; DAP_days after planting; DAS_days after sowing; RBD_randomized block design; SA_salicylic acid; SAI_selective absorption index; TSS_true shallot seeds.

Introduction

Soil salinity poses a serious threat to agricultural productivity by impairing key physiological processes in plants. Elevated salt concentrations, particularly sodium ions (Na⁺), disrupt nutrient uptake and osmotic balance, making most crop species highly susceptible. The adverse effects of salinity manifest throughout the plant life cycle, from germination and early seedling stages to vegetative growth and reproductive development. Saline soils with high concentrations of dissolved salts, particularly sodium (Na⁺) ions, can significantly reduce the availability of essential nutrients such as calcium (Ca²⁺), magnesium (Mg²⁺), and potassium (K⁺). This nutrient imbalance, along with the osmotic and toxic effects of excessive salt accumulation, inhibits plant growth and development (Jon & Busyra, 2020). One major contributor to soil salinization is the prolonged use of irrigation water with high salinity, which leads to salt buildup in the plant root zone, further impairing growth. Additionally, climate change has accelerated sea level rise, contributing to increased salinity in both groundwater and soils (Vicca and Wahida, 2020).

Shallots are a strategic horticultural commodity in Indonesia but are classified as sensitive to salinity stress. Bulb production, both quantitatively and qualitatively, decreases significantly when plants are exposed to high salinity. One important parameter that reflects the physiological response of plants to salinity stress is tuber dry weight, as it illustrates the efficiency of photosynthate allocation to storage organs.

Excessive Na⁺ causes ion toxicity that disrupts the ion balance in plant cells. Na⁺ ions are physico-chemically similar to K⁺ so that they compete in the active transport process, resulting in the removal of K⁺ from cells and disruption of plant metabolic functions such as photosynthesis (Hussain et al., 2022; Maathuis, 2023). In addition, accumulation of excess Na⁺

interferes with the uptake of K^+ and Ca^{2+} , which play a role in stomatal opening. Stomatal closure due to K^+ deficiency and ion disturbance cause a decrease in CO_2 assimilation and photosynthesis, thus suppressing plant growth (Widhodho et al., 2022). Conversely, high concentrations of Na^+ at the root surface hinder K^+ uptake, rendering root-applied potassium fertilizers ineffective and limiting K availability to plants. This is critical, as potassium plays an essential role in maintaining cell turgor, regulating enzyme activity, and supporting the uptake of key macronutrients such as phosphorus (Jon, 2020). As salinity levels increase, Na^+ content in plant tissues increases significantly, while K^+ content decreases due to competition for K^+ absorption and removal from cells. This led to a significant increase in the Na^+/K^+ ratio, which was inversely proportional to the level of salinity stress. As in the 50, 100, and 200 mM NaCl treatments, the Na^+/K^+ ratio increased to 13%, 21%, and 33% of the control, indicating increasingly severe ion balance disturbances with increasing salinity (Purwanto, 2019). The high Na^+/K^+ ratio, due to high Na^+ and low K^+ , interferes with potassium uptake by shallot plants. Potassium plays an important role in sugar transportation from leaves to bulbs, enzyme activity, protein synthesis, and cell enlargement that determine the dry weight and quality of bulbs. Therefore, an unbalanced Na^+/K^+ ratio reduces these metabolic processes and has a negative impact on bulb dry weight (Ernawati, 2015).

Salicylic acid (SA) has been widely reported to enhance plant tolerance to salinity through multiple physiological and biochemical mechanisms. One of its primary roles is improving ionic homeostasis by reducing sodium (Na^+) accumulation and promoting potassium (K^+) uptake, which helps restore the Na^+/K^+ balance critical for maintaining cellular function under salt stress (Hussain et al., 2022; Maathuis, 2023). SA also enhances antioxidant defense systems by upregulating the activities of enzymes such as superoxide dismutase (SOD), peroxidase (POD), and catalase (CAT), thereby reducing oxidative damage induced by reactive oxygen species in saline environments (Arif et al., 2021; Hassan et al., 2021). Moreover, SA contributes to osmotic regulation by stimulating the accumulation of osmoprotectants like proline and soluble sugars, which support cell turgor and metabolic stability under salt-induced dehydration (Arif et al., 2021). In onion plants specifically, SA application has been shown to improve photosynthetic efficiency, pigment retention, and bulb yield even under drought and salinity stress, indicating its effectiveness in *Allium* species (Hassan et al., 2021). Additionally, the use of SA has been linked to improved nutrient selectivity and absorption efficiency, as evidenced by reductions in the Na^+/K^+ absorption sensitivity index (SAI), further supporting its role in salinity tolerance (Ma et al., 2025). Understanding the relationship between the Na^+/K^+ ratio with bulb dry weight and other production parameters can be the basis for adaptation strategies for shallot cultivation in saline land. Therefore, this study aims to evaluate the relationship between Na^+/K^+ selective absorption index in plant tissues with bulb dry weight and other production components in shallot plants under saline conditions.

Results and discussion

Effect of salicylic acid on the Na and K absorption

The findings of this study emphasize the crucial role of salicylic acid (SA) in modulating plant responses to salinity stress in shallot cultivation. Salinity stress, which increases sodium (Na^+) accumulation while inhibiting potassium (K^+) uptake, disrupts ionic homeostasis and affects plant physiological functions such as photosynthesis, enzyme activity, and turgor maintenance (Widhodho et al., 2022). In the recent study, the salicylic acid application notably alters sodium (Na^+) and potassium (K^+) content in both plant leaves and growth media (Table 1). Without SA treatment (0 mM), Na^+ accumulation in leaves is high (0.62), while K^+ is low (0.12), indicating ionic imbalance of sodium, key indicator of salt stress. As SA concentration increases up to 1.5 mM, Na^+ content in leaves significantly decreases while K^+ content increases, showing improved ionic homeostasis (Fairoj et al., 2023). The trend is also reflected in soil ion contents. This shift suggests that SA enhances selective ion uptake, promoting K^+ over Na^+ , which is crucial for osmotic balance and enzyme activation under salt stress.

The application of SA at optimal concentrations (particularly 1.5 mM) significantly reduced Na^+ accumulation and enhanced K^+ uptake, thereby improving the Na^+/K^+ ratio in both plant tissues and soil. This indicates an enhanced ionic balance which is a critical factor for maintaining metabolic stability and stress resilience under saline conditions (Cheng et al., 2021).

Table 1. Na and K content in plant tissue and soil.

Salicylic Acid (mM)	Na and K Content (%)			
	Leaves		Soil	
	Na	K	Na	K
0	0.62	0.12	0.12	0.18
1	0.18	0.24	0.32	0.29
1.5	0.34	0.48	0.52	0.41
2	0.35	0.29	0.49	0.58

Na^+/K^+ Absorption Sensitivity Index

Table 2 presents data on the Na^+/K^+ absorption sensitivity index (SAI), which is the ratio between the Na^+/K^+ in plant tissues and the growing medium. A SAI value > 1 indicates that the plant absorbs Na^+ higher than the condition in the media (sensitive), while $SAI < 1$ indicates Na^+ exclusion ability or K^+ absorption efficiency (tolerant).

Table 2. Na/K absorption sensitivity index (SAI).

Salicylic Acid (mM)	Na/K (%) (Plant tissue)	Na/K (%) (Growth Media)	Index
0	5.26	0.67	7.89 > 1
1	0.76	1.10	0.68 < 1
1.5	0.71	1.27	0.55 < 1
2	1.20	0.84	1.41 > 1

SAI > 1 = sensitive; SAI < 1 = tolerant

The Na⁺/K⁺ ratio serves as a crucial physiological indicator for assessing plant tolerance to salinity stress. A high Na⁺/K⁺ ratio (index > 1) typically reflects greater sensitivity to salt stress, whereas a lower ratio (index < 1) indicates enhanced tolerance. In this study, the control group without salicylic acid (SA) treatment (0 mM) exhibited a high sensitivity index of 7.89, signifying substantial ionic imbalance under salinity. However, SA application at 1 mM and 1.5 mM markedly reduced the sensitivity index to 0.68 and 0.55, respectively, both below the critical threshold of 1.0, demonstrating improved salt tolerance. Interestingly, at 2 mM SA, the index increased again to 1.41, suggesting that excessive SA may diminish its positive effects. These findings confirm that SA at optimal concentrations, particularly between 1–1.5 mM, plays a pivotal role in alleviating salinity stress by maintaining ionic homeostasis, especially the Na⁺/K⁺ balance in plant tissues.

The reduced Na⁺/K⁺ selective absorption index (SAI < 1) observed in treatments with 1–1.5 mM SA demonstrates a physiological tolerance mechanism, potentially linked to enhanced selective ion transport and reduced Na⁺ influx. Similar responses have been reported in other crops, where SA modulated ion channel activity and stress-related signaling pathways to improve salinity tolerance (Tarigan & Febriyana, 2022). Notably, the increase in SAI at 2 mM SA suggests a threshold beyond which the compound may lose its effectiveness or even exert inhibitory effects, corroborating findings that excessive biostimulant application may disrupt hormonal balance and physiological processes (Andriani et al., 2015). Treatments with a low Na⁺/K⁺ ratio produced the highest dry stover weight, indicating that the plants were able to maintain optimal vegetative growth. Conversely, the higher the Na⁺/K⁺ ratio (meaning Na⁺ was dominant), the dry stalk weight decreased significantly. This indicates that excess Na⁺ inhibits vegetative growth due to physiological disorders and ionic stress. In accordance with the opinion of Dinarti et al. (2019), that an optimal K⁺ ratio supports the growth of branches, leaves, and total plant dry weight, as found in citrus plants with low N and K ratios, resulting in higher plant dry weight. The enhanced productivity at optimal SA levels may also reflect increased antioxidant capacity and osmotic adjustment, as SA is known to induce stress-responsive pathways and promote the expression of protective genes under abiotic stress (Cheng et al., 2021).

Effect of transplanting age and salicylic acid on the production of shallots

The positive effect of salicylic acid extends beyond physiological improvements, as evidenced by its influence on growth and yield traits in shallot plants. Both transplanting age and SA treatment significantly affected plant productivity (Table 3). Earlier transplanting ages (28–35 days after sowing) were associated with greater biomass accumulation and higher bulb yields. Notably, SA application enhanced all yield parameters, with the most pronounced effects observed at 1.5 mM. This concentration led to the highest stover dry weight (25.92 g), bulb dry weight (12.07 g), and number of bulbs per plant (3.89), indicating optimal plant performance. The enhancement in growth and yield at this concentration suggests that SA may activate key physiological and metabolic processes, including improved nutrient uptake, enhanced antioxidant defense, and modulation of stress-responsive pathways, thereby contributing to increased plant resilience and productivity under salinity stress conditions.

Table 3. Effect of transplanting age and salicylic acid on the production of Shallots.

Treatments	Parameter		
	Stover Dry Weight (g)	Bulbs Dry Weight (g)	Bulbs number
Transplanting Age			
42 DAS	15.39 ^b	7.23 ^b	2.67 ^b
35 DAS	21.93 ^a	8.77 ^a	3.08 ^a
28 DAS	23.76 ^a	9.73 ^a	3.04 ^a
LSD0.05	3.99	1.31	0.36
Salicylic Acid			
0 mM	14.54 ^c	5.69 ^d	1.94 ^d
1 mM	19.31 ^b	7.31 ^c	2.72 ^c
1.5 mM	25.92 ^a	12.07 ^a	3.89 ^a
2 mM	21.68 ^{ab}	9.24 ^b	3.17 ^b
LSD0.05	4.61	1.51	0.31

Numbers followed by the same letter in the column (a, b, c, d) for each treatment indicate that the means are not significantly different at the LSD0.05 level. DAS: Days after sowing.

Tuber dry weight also decreased as the Na^+/K^+ ratio increased. At the lowest Na^+/K^+ ratio treatment, tuber dry weight reached the maximum value, while at the highest ratio, tuber dry weight decreased significantly. This indicates that K^+ is very important in the process of tuber formation and filling, as well as in the transportation of photosynthetic products to the tubers. The number of tubers per plant also tended to decrease in treatments with high Na^+/K^+ ratio. This is in line with the decrease in dry weight, because salinity stress and ion imbalance inhibit the process of tuber formation and development.

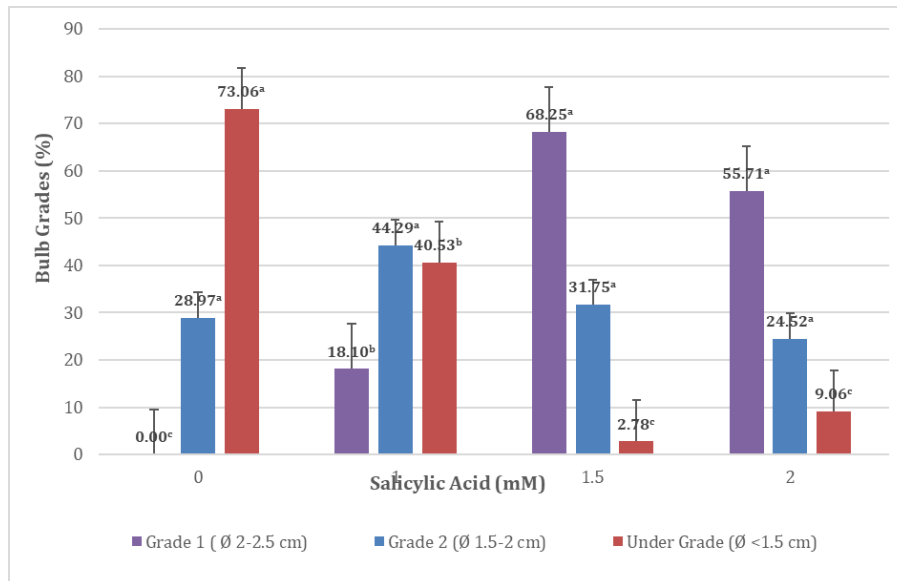


Figure 1. Effect of Salicylic Acid on the Bulb Grading based on Indonesian Nasional Standard (SNI) Number SNI: 3159:2013, Grade A or Super Class (diameter >2.5), Grade B or Class 1 (diameter 2–2.5 cm), and Grade C or Class 2 (diameter = 1.5-2 cm); Under Grade (diameter <1.5 cm) (Ministry of Agriculture, 2013). Numbers followed by the same letter for each grade category indicate that the means are not significantly different at the LSD0.05 level.

Figure 1 illustrates the impact of different concentrations of salicylic acid (0, 1, 1.5, and 2 mM) on the distribution of bulb grades according to the Indonesian National Standard (SNI) Number 3159:2013. The application of salicylic acid significantly improved bulb quality by reducing under grade bulbs and increasing the proportion of Grade 1 and 2 bulbs, with 1.5 mM emerging as the most effective concentration. Shallot bulbs produced in the control treatment were predominantly classified as under grade (66%), with only 34% falling into grade 2 and none reaching Grade 1, indicating poor bulb development under untreated conditions. The application of 1 mM salicylic acid improved bulb quality, increasing Grade 2 bulbs to 50.64% and introducing Grade 1 bulbs (13.74%), while reducing Under Grade bulbs to 35.62%. A more pronounced effect was observed at 1.5 mM, where Grade 1 bulbs dominated at 78.17%, Grade 2 dropped to 21.83%, and Under Grade bulbs were eliminated. This suggests that 1.5 mM is the optimal concentration for enhancing bulb diameter within the 2–2.5 cm range. At 2 mM, the proportion of Grade 1 bulbs slightly declined to 44.21%, with Grade 2 increasing to 54.13%, and Under Grade remaining minimal at 1.67%. Overall, the data indicate that salicylic acid application effectively enhances bulb grading, especially at 1.5 mM, by reducing the number of undersized bulbs and promoting the development of bulbs within the desired commercial size range.

In terms of agronomic performance, the increase in bulb and stover dry weight and bulb number under 1.5 mM SA and early transplanting age (28 DAS) treatments indicate enhanced resource allocation and developmental synchrony under salinity stress. Early transplanting may have allowed for better root establishment and nutrient absorption during early growth stages, which is essential under adverse conditions. This is in line with research by Kurniasari & Adi (2018), who noted that younger TSS transplants often exhibit superior adaptability and faster growth recovery.

Better adaptability of younger seeds that resulted in higher plant performances is in line with the opinion of Kurniasari & Adi (2018) that seeds with a younger age have several advantages including reducing seed damage, plants do not experience stagnation, and plant growth is faster. In addition, salicylic acid application is able to improve plant physiological performance, possibly by increasing tolerance to environmental stress including salinity. Andriani et al. (2015) stated that the application of salicylic acid at the appropriate concentration can increase the wet weight of plants, this is because there is an increase in cell division in the apical meristem of shoots and roots of plants which causes growth to increase so that the dry weight of plants also increases. Vice versa, Tarigan & Febriyana (2018) added that if the concentration of salicylic acid is excessive from the required levels it will reduce plant biomass such as fresh biomass and dry biomass of plants.

The optimum concentration of 1.5 mM SA also applied on highest percentage of the observed Grade 1 bulbs produced that sharply increased to 78.17%. This suggests that 1.5 mM is the most effective concentration for improving bulb quality and increasing SA concentration beyond 1.5 mM does not linearly improve quality and may even reduce effectiveness, possibly due to stress caused by excessive SA (Hayat et al., 2019; Hassan et al., 2021). SA is known to enhance plant growth and development by influencing physiological processes such as improved photosynthesis, biomass accumulation, and nutrient use efficiency (Khan et al., 2020). SA also contributes to plant tolerance under environmental stress, which may indirectly improve yield and bulb size (Singh et al., 2020). These findings are in line with previous studies that demonstrate the

positive role of SA at optimal concentrations in improving horticultural crop yields, including bulb size and weight (Arif et al., 2021). However, plant response to SA is species-specific and depends on the dosage and environmental conditions. Overall, these results suggest that salicylic acid, when applied at moderate concentrations, can serve as an effective agronomic tool to mitigate the negative impacts of salinity on shallot cultivation. However, its efficacy is dose-dependent and may be influenced by factors such as plant age at transplanting, environmental conditions, and varietal characteristics. The findings from this study provide practical insights for improving shallot cultivation under saline conditions, an increasingly critical issue due to rising sea levels, unsustainable irrigation, and climate-induced soil degradation (Vicca & Wahida, 2020). The demonstrated effectiveness of SA, particularly at 1.5 mM, in reducing the Na^+/K^+ ratio and improving plant tolerance to salinity offers a low-cost and accessible strategy for smallholder farmers and commercial producers facing soil salinization challenges. From a sustainability perspective, using SA is environmentally benign compared to chemical leaching or salt flushing practices. It reduces the need for excessive K fertilizers, whose overuse contributes to soil degradation and nutrient runoff. As a natural plant hormone derivative, SA enhances endogenous stress response pathways rather than replacing them, aligning with ecological agriculture and integrated soil fertility management strategies (Cheng et al., 2021). While this study focused on shallots, the mechanisms described, particularly SA's effect on Na^+ exclusion and K^+ uptake, are conserved across many crops. Therefore, similar protocols could be adapted for other horticultural or high-value crops grown in saline-affected areas, including tomatoes, chili, or leafy greens. Extension programs could pilot cross-crop trials using SA to validate its versatility under local conditions.

Despite providing valuable insights into the role of salicylic acid (SA) in enhancing salinity tolerance in shallot plants, this study presents several limitations that warrant consideration. Firstly, the experiment was conducted under controlled greenhouse conditions, which may not fully replicate the variability and complexity of field environments, particularly with respect to fluctuating salinity levels, microbial interactions, and climatic conditions (Cheng et al., 2021). Additionally, the study focused solely on one variety of shallot (Sanren) and used a fixed salinity level (5.8 dS/m), limiting the generalizability of the findings across diverse genotypes and salinity intensities. Another limitation lies in the relatively short duration of the study, which may not capture long-term physiological and agronomic responses, including potential cumulative effects of SA applications or seasonal changes in salinity stress. Furthermore, while the Na^+/K^+ ratio was a central parameter, the study did not explore related physiological traits such as proline accumulation, antioxidant enzyme activities, or gene expression profiles that underpin SA-mediated stress tolerance (Tarigan & Febriyana, 2022; Widhodho et al., 2022). Lastly, the interaction of SA with other biostimulants or nutrient amendments was not assessed, yet such combinations might offer synergistic benefits under saline conditions (Vicca & Wahida, 2020). Future research should address these limitations by incorporating multi-location field trials, additional physiological markers, and diverse genotypes to better understand the broader applicability and mechanisms of SA in salinity stress mitigation.

Materials and Methods

Experimental design

The experiment was conducted under controlled conditions in the greenhouse of the Centre of Excellence (CoE), Faculty of Agriculture, Hasanuddin University, Indonesia. A randomized block design (RBD) was used, consisting of four levels of salicylic acid (0, 1, 1.5, and 2 mM) and three transplanting ages (28, 35, and 42 DAS), with three replications. Each experimental unit comprised five planter bags, each containing one plant, resulting in a total of 180 experimental units.

Plant materials

The materials used were True Shallot Seeds (TSS) variety Sanren, previously germinated and sown in a seedling tray, then transplanted to a 5-liter planter bag. Transplanting was carried out at 28, 35, and 42 days after sowing (DAS), according to the respective treatments.

Preparation of growing media

The planting medium consisted of soil, sand, and compost at a ratio of 2:1:1 and was placed into planter bags. Prior to transplanting, the planter bags were watered to field capacity, indicated by the absence of further drainage. Salinity stress was induced by applying a NaCl solution at a concentration of 2,922 ppm (equivalent to 5.8 dS/m), beginning at 10 days after planting (DAP) and subsequently every 5 days, and maintained throughout the growth period.

To ensure that the saline conditions were maintained, the electrical conductivity (EC) of the growing medium was measured periodically using an EC meter. Samples (10 g) were homogenized with 10 mL of distilled water and measured at 15, 30, 45, and 60 DAP. When deviations from the target EC were detected, additional NaCl solution was applied based on the difference between the measured and target EC values.

Application of SA treatment

Salicylic acid treatment was applied by spraying on plant leaves at 14, 17, 20, and 23 DAP. The spray volume given was 25 ml per plant (Khandaker et al., 2011).

Parameter observation

Measurement of the selective absorption index (SAI) of Na/K was carried out after harvest by taking soil samples representing the experimental unit and plant leaves to be analysed at the Laboratory of Soil Chemistry and Physics, Faculty of Agriculture, Hasanuddin University. The SAI was calculated using the formula by Laurenson et al. (2011):

$$\text{SAI Na/K} = \frac{\frac{\text{Na}}{\text{K}} \text{ in plant tissues}}{\frac{\text{Na}}{\text{K}} \text{ in planting medium}} \quad [1]$$

A selectivity index value greater than 1 indicates that the plant is more selective in absorbing sodium (salinity-sensitive plants). Conversely, a selectivity index value less than 1 indicates that the plant is more selective in absorbing potassium (salinity-tolerant plants).

Statistical analysis

Data was subjected to analysis of variance (ANOVA), and when significant or highly significant effects were detected, a Least Significant Difference (LSD) test at the 95% confidence level was used to compare the means.

Conclusion

This study demonstrates that salicylic acid (SA) plays a significant role in enhancing plant tolerance to salinity stress through multiple physiological and agronomic mechanisms. Application of SA at optimal concentrations, particularly 1.5 mM, effectively reduced the Na⁺/K⁺ ratio in both plant tissues and soil, indicating improved ion homeostasis—a key factor in salinity tolerance. The Na⁺/K⁺ absorption sensitivity index further confirmed that plants treated with 1–1.5 mM SA exhibited significantly enhanced tolerance compared to untreated controls. Moreover, SA application markedly improved growth and yield performance in shallot plants, with 1.5 mM SA yielding the highest biomass and bulb production. These findings suggest that moderate SA supplementation can serve as an effective agronomic strategy to mitigate the adverse effects of salinity, contributing to more resilient crop systems and sustainable agricultural practices under stress-prone environments.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used ChatGPT in order to refine arguments, looking for matched references, and revising the English language. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Statement of contributions: **AF** was responsible for investigation, data curation, data analysis, methodology, and writing the original draft. **IR** was responsible for methodology, data analysis, methodology, and writing the original draft, review, and revision. **FU** was responsible for supervision and methodology.

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