



# Salicylic Acid Mitigates Salt-Induced Physiological and Biochemical Stress in *Dianthus barbatus*

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## ABSTRACT

*Dianthus barbatus* is an important and widely cultivated ornamental species in temperate regions. Valued for its aesthetic appeal and use as both bedding and cut flowers, it holds a significant position in the floriculture market. Salinity is a major environmental stress that adversely affects plant growth and performance. This study investigated the effects of 1 mM salicylic acid (SA) on the growth, biochemical, and physiological characteristics of *D. barbatus* under salt stress. SA application under non-stress conditions significantly increased leaf count, leaf area, and shoot fresh and dry weight. Under salinity levels of 3, 6, and 9 dS m<sup>-1</sup>, SA partially alleviated reductions in leaf area and fresh weight, although no significant improvement was observed at the highest salinity level. Additionally, SA enhanced phenolic and flavonoid content, increased antioxidant enzyme activities (SOD and CAT), improved total antioxidant capacity, and reduced electrolyte leakage at all salinity levels, with the greatest effect at 6 dS m<sup>-1</sup>. SA also contributed to maintaining or increasing soluble protein, proline, and potassium levels while reducing sodium accumulation in leaves, indicating an ion exclusion mechanism employed by *D. barbatus* to cope with salt stress. Application of SA, a natural hormone effective at low concentrations, may serve as a cost-effective strategy to enhance growth and salt tolerance in *D. barbatus* and other ornamental species. This potentially reduces losses caused by salinity stress while increasing floral economic value.

**Abbreviations:** Catalase (CAT), Chlorophyll (Chl), Salicylic acid (SA), Superoxide dismutase (SOD)

## Introduction

The Sweet William (*Dianthus barbatus*), a popular ornamental plant in the Caryophyllaceae family, is valued for its colorful flowers and long flowering period. It is widely cultivated in gardens and for cut-flower production. Due to its aesthetic appeal and ease of propagation, it holds considerable economic importance in the ornamental plant market, although precise global production statistics are not available. Environmental stresses profoundly influence plant growth and crop productivity, with salt stress ranking among the most detrimental and widespread abiotic stresses worldwide. High salinity disrupts water uptake and ionic homeostasis, causing osmotic stress

and ion toxicity that negatively impact plant morphology and essential physiological processes, such as photosynthesis. These effects are especially pronounced in arid and semi-arid regions, where salinity significantly reduces arable land availability and crop yields (Hossain, 2019; Younessi-Hamzekhanlu et al., 2021). Moreover, salt stress stimulates the overproduction of reactive oxygen species (ROS), which induce oxidative damage to vital cellular components including membranes, proteins, and nucleic acids (Haghpahan et al., 2025). To mitigate this oxidative damage, plants activate their antioxidant defense mechanisms, enhancing the

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activities of enzymes such as superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD), which scavenge ROS and protect cells from injury (Younessi-Hamzekhanlu et al., 2021).

Previous studies have shown that salinity can alter germination, mineral composition, and ion uptake in plants. For instance, Lotfi et al. (2009) reported that salinity reduced germination and disrupted ion balance in walnut seedlings. Similarly, Rabari et al. (2023) demonstrated that exogenous calcium improved growth and physiological responses under saline conditions, highlighting the importance of nutrient management in mitigating salt stress. Salicylic acid, a low molecular weight phenolic phytohormone, plays a crucial role in regulating plant growth, development, and defense responses under both biotic and abiotic stress conditions. SA enhances plant tolerance to salinity stress by modulating antioxidant enzyme activities, maintaining ionic balance, and improving photosynthetic efficiency (Hayat et al., 2010; Khaldi et al., 2024). Foliar application of SA is considered more effective than root application due to better bioavailability and reduced degradation within the soil environment (Sultana et al., 2025). This phytohormone also participates in signal transduction pathways that assist plants in better coping with adverse environmental conditions. Exogenous salicylic acid has reportedly enhanced plant tolerance, as shown by Gharibiyani et al. (2023), and improved growth and physiological status in *Pistacia* species under salt stress.

Despite extensive research on related species such as *D. superbis* (Ma et al., 2017), the morphophysiological and biochemical responses of *D. barbatus* to salt stress remain poorly understood. This study specifically investigates the potential of salicylic acid to alleviate salt-induced damage in *D. barbatus* and elucidates the underlying physiological and biochemical mechanisms. The findings are expected to contribute to improved cultivation practices and management of this ornamental species under saline conditions. Therefore, the aim of this study was to investigate the effects of salt stress on the morphological, physiological, and biochemical traits of *D. barbatus*. The role of salicylic acid was also evaluated in mitigating the negative impacts of this stress on the ornamental plant.

## Materials and Methods

### *Experimental location and growth conditions*

The experiment was conducted in 2024 in the greenhouse of the Department of Horticultural Sciences, Sari Agricultural Sciences and Natural Resources University, Iran. Seeds of *Dianthus barbatus* (Pakaan Seed Company, Isfahan, Iran)

were soaked in distilled water and sown in trays containing an equal mixture of cocopeat and perlite. Cocopeat was rinsed with distilled water before use to reduce residual salinity. Seedlings were irrigated with Hoagland nutrient solution every 3 d. At the four true-leaf stage, seedlings were transplanted into 12 cm diameter pots filled with a 2:1 (v/v) mixture of cocopeat and perlite. Plants were acclimated for one week under greenhouse conditions (22 °C, 60-65% RH, natural light) before treatment application.

### *Treatments and experimental design*

SA (Merck, Germany) was applied as foliar sprays at 0 and 1 mM every 5 d for four applications. The 1 mM concentration was selected based on previous studies demonstrating its effectiveness in enhancing salinity tolerance (Yang et al., 2023). Salt stress was imposed using NaCl ( $\geq 99.5\%$ , Merck, Germany) at 0, 3, 6, and 9 dS m<sup>-1</sup>, representing low, moderate, and high salinity. Salt solutions were applied as soil drench one d after the last SA spray for four weeks at 4 d intervals. EC of irrigation water and leachate was monitored using an EC meter (HC3010, Bangladesh). The experiment was a factorial arrangement in a completely randomized design with three replications. No additional nutrients were applied during the experiment.

### *Growth and biomass measurements*

Fresh weight of stems was measured immediately after separation from the crown. Samples were then oven-dried at 90 °C for 24 h to determine dry weight. Leaf area was measured by scanning leaves and analyzing the images using ImageJ software (v1.53t). Leaf count was recorded at the end of the experiment.

### *Chl, total phenolic compounds, and flavonoids content*

Chl *a*, *b*, and total Chl were extracted from 0.2 g frozen leaf tissue with 10 mL methanol and incubated in the dark for 24 h. Absorbance was measured at 665, 652, and 470 nm, and pigment content was calculated following Lichtenthaler and Buschmann (2001). Total phenolic compounds were quantified by the Folin-Ciocalteu method, with absorbance at 765 nm and gallic acid as standard (Singleton and Rossi, 1965). Total flavonoids were determined using 2% aluminum chloride, incubated for 60 min at room temperature, and absorbance measured at 420 nm (Chang et al., 2002).

### *Antioxidant activity, electrolyte leakage, and proline content*

Antioxidant activity was assessed by DPPH radical scavenging assay, measuring absorbance at 517 nm after 30 min incubation (Brand-Williams et al., 1995). Electrolyte leakage was determined by

incubating 0.1 g fresh leaf in 10 mL deionized water at 30 °C for 3 h, measuring conductivity before and after autoclaving (Dionisio-Sese and Tobita, 1998). Proline content was measured from 0.2 g leaf tissue homogenized in 3% sulfosalicylic acid, reacted with acid ninhydrin, and absorbance was read at 520 nm (Bates et al., 1973).

### ***Soluble protein content and antioxidant enzyme activity***

Protein content was measured using the Bradford method (Bradford, 1976). For enzyme assays, 0.1 g leaf tissue was homogenized in potassium phosphate buffer (pH 7.5) and centrifuged; the supernatant was used for analysis. Catalase (CAT) activity was determined via H<sub>2</sub>O<sub>2</sub> decomposition at 240 nm (Aebi, 1984), and superoxide dismutase (SOD) activity via inhibition of NBT photoreduction at 560 nm (Beauchamp and Fridovich, 1971).

### ***Leaf mineral content (Na<sup>+</sup> and K<sup>+</sup>)***

Na<sup>+</sup> and K<sup>+</sup> were measured in 0.5–1 g dried leaf tissue, turned into ash at 550 °C for 5 h. Ash was dissolved in 2 N HCl, diluted, filtered, and analyzed with a flame photometer (Williams and Twine, 1960).

### ***Statistical analysis***

Data were analyzed using SAS version 9.1, and means were compared by LSD at  $P \leq 0.05$ .

## **Results**

### ***Changes in leaf characteristics and shoot biomass***

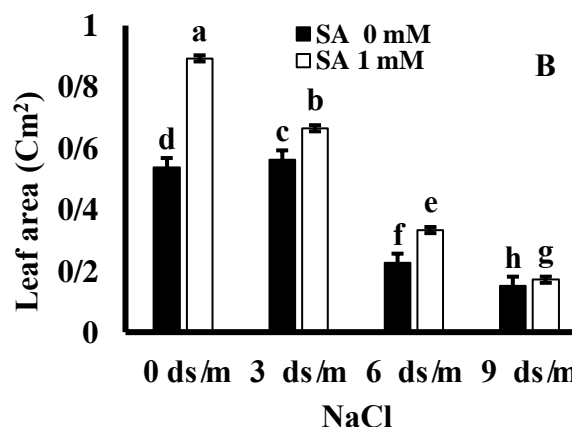
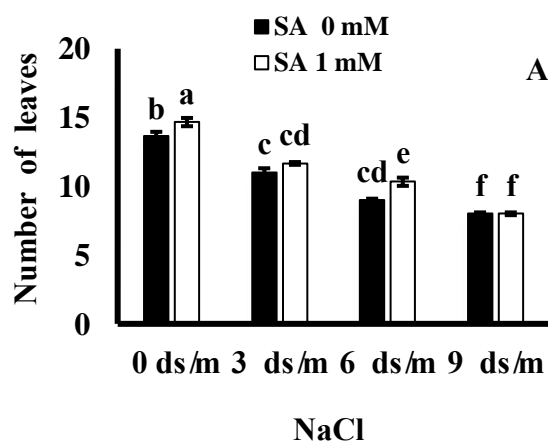
The application of 1 mM SA significantly affected leaf traits and shoot biomass under different salinity

levels. Under non-saline conditions, SA treatment increased both leaf count and leaf area compared to the control. At 3 and 6 dS m<sup>-1</sup> salinity, both parameters decreased in all plants; however, SA-treated plants maintained higher leaf count and area than untreated ones. At 9 dS m<sup>-1</sup>, no significant difference was observed between treatments (Figs. 1A and B).

Shoot fresh weight was also influenced by SA. Under non-saline conditions, SA significantly increased shoot fresh weight compared with the control. At 3 dS m<sup>-1</sup> salinity, SA-treated plants retained higher fresh weight than the control. At 6 and 9 dS m<sup>-1</sup>, differences between treatments were not significant (Fig. 1C).

Shoot dry weight followed a similar pattern. SA significantly increased dry weight under non-saline conditions, while all plants showed a marked reduction under 3, 6, and 9 dS m<sup>-1</sup> salinity. At 9 dS m<sup>-1</sup>, no significant difference was detected between treatments (Fig. 1D).

Phenolic and flavonoid contents were also significantly influenced by SA and salinity (Fig. 3A and B). Under non-stress conditions, SA increased both compounds relative to the control. At 3 dS m<sup>-1</sup> salinity, phenolic content increased in control plants, but the increase was greater in SA-treated plants. At higher salinity levels (6 and 9 dS m<sup>-1</sup>), both phenolic compounds and flavonoids decreased across treatments, and yet the reductions were less severe in SA-treated plants.



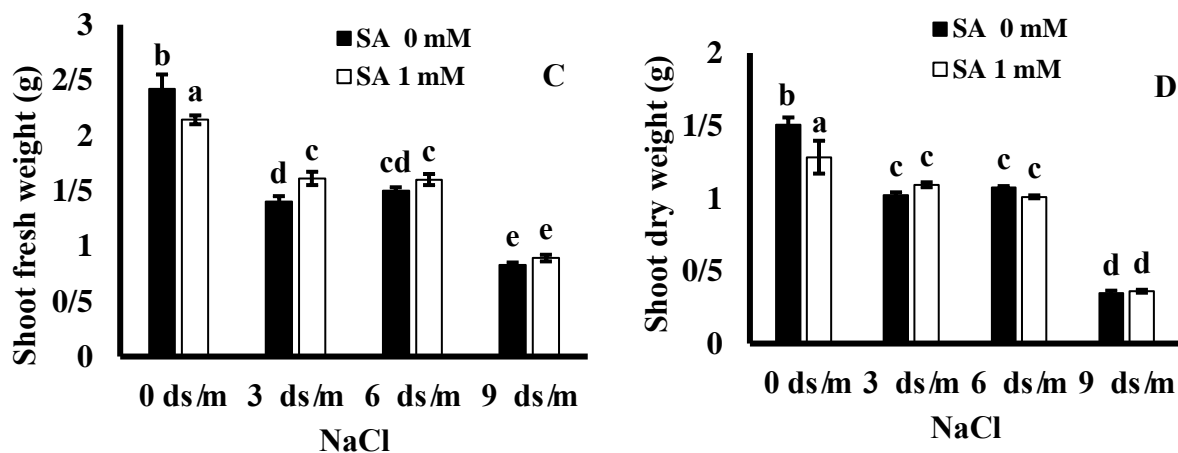


Fig. 1. Effect of salicylic acid (0, 1 mM) on (A) number of leaves, (B) leaf area, (C) shoot fresh weight, and (D) shoot dry weight in *D. barbatus* under salt stress (0, 3, 6, and 9 ds m<sup>-1</sup>) conditions. Different letters indicate significance according to LSD test at  $P < 0.05$ .

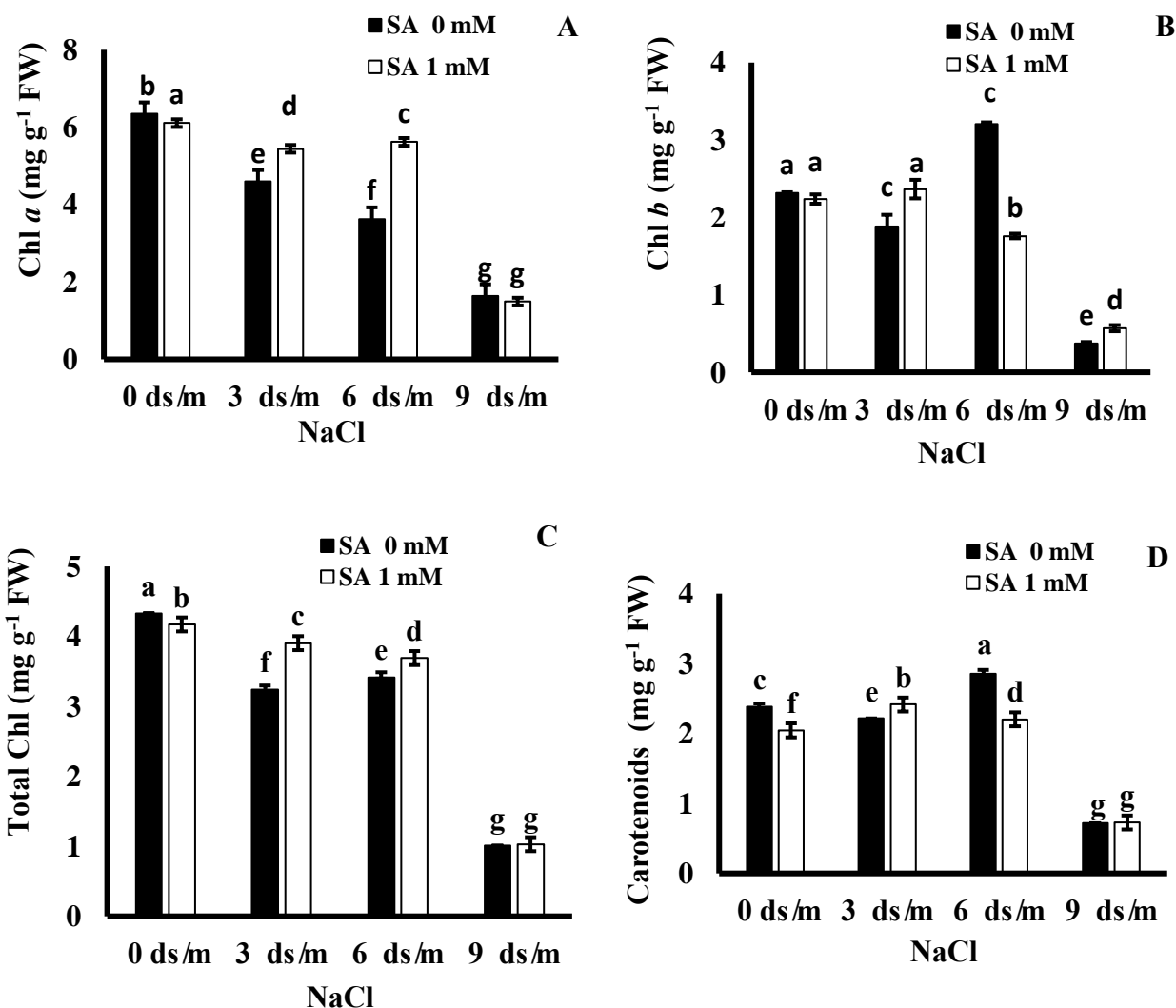
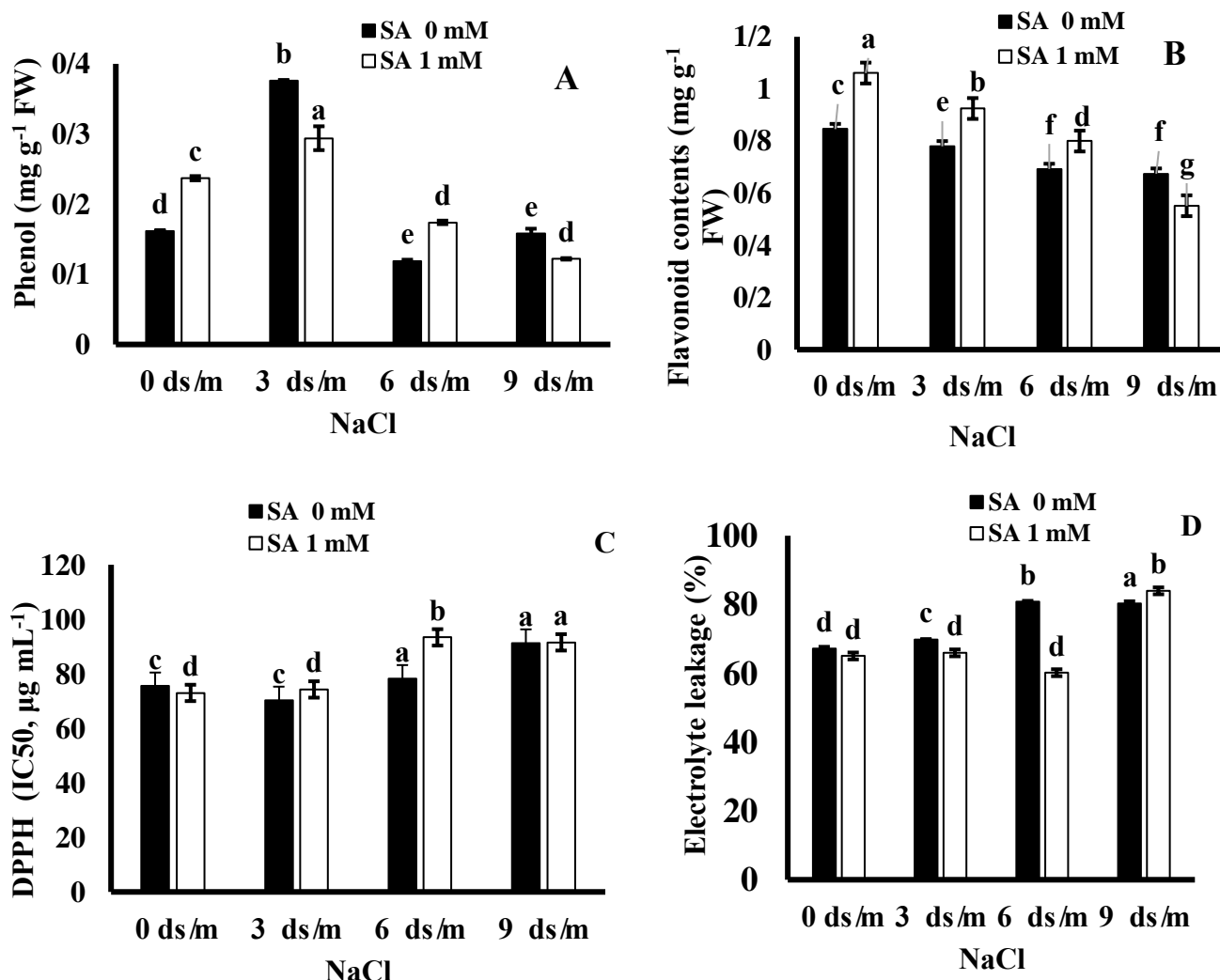


Fig. 2. Effect of salicylic acid (0, 1 mM) on (A) chlorophyll a, (B) b, (C) total chlorophyll, and (D) carotenoids in *D. barbatus* under salt stress (0, 3, 6, and 9 ds m<sup>-1</sup>) conditions. Different letters indicate significance according to LSD test at  $P < 0.05$ .



**Fig. 3.** Effect of salicylic acid (0, 1 mM) on (A) phenol content, (B) flavonoid content, (C) DPPH, and (D) electrolyte leakage in *D. barbatus* under salt stress (0, 3, 6, and 9 dS m<sup>-1</sup>) conditions. Different letters indicate significance according to LSD test at  $P < 0.05$ .

### ***Oxidative stress markers and antioxidant defense***

Antioxidant activity, based on the DPPH assay, was influenced by SA and salinity levels (Fig. 3C). Under non-stress conditions, SA enhanced antioxidant capacity. At moderate salinity (3 dS m<sup>-1</sup>), antioxidant activity in SA-treated plants was higher than in the control, while at higher salinity levels (6 and 9 dS m<sup>-1</sup>), antioxidant activity decreased in all plants, with the effect of SA being limited.

Electrolyte leakage increased significantly with salinity (Fig. 3D). At 3 and 6 dS m<sup>-1</sup>, SA reduced electrolyte leakage compared with the control. Under severe salinity (9 dS m<sup>-1</sup>), leakage increased in both treatments, but SA still slightly mitigated this effect. Activities of antioxidant enzymes were affected by salinity and SA (Fig. 4). Superoxide dismutase

activity peaked at moderate salinity with SA treatment and decreased at higher salinity, although SA partially alleviated this decline (Fig. 4A). Catalase activity increased with salinity and reached maximum values under non-stress and moderate salinity with SA, declining under severe salinity (Fig. 4B).

Soluble protein content changed in response to salinity and SA (Fig. 4C). The highest values were observed at moderate salinity with SA, while increases were smaller at higher salinity levels. Under severe salinity, differences between treatments were not significant.

Proline content increased under all salinity levels (Fig. 4D). SA enhanced proline accumulation across all salinity levels, although differences at moderate salinity were not significant, and only a slight increase was observed under severe salinity.

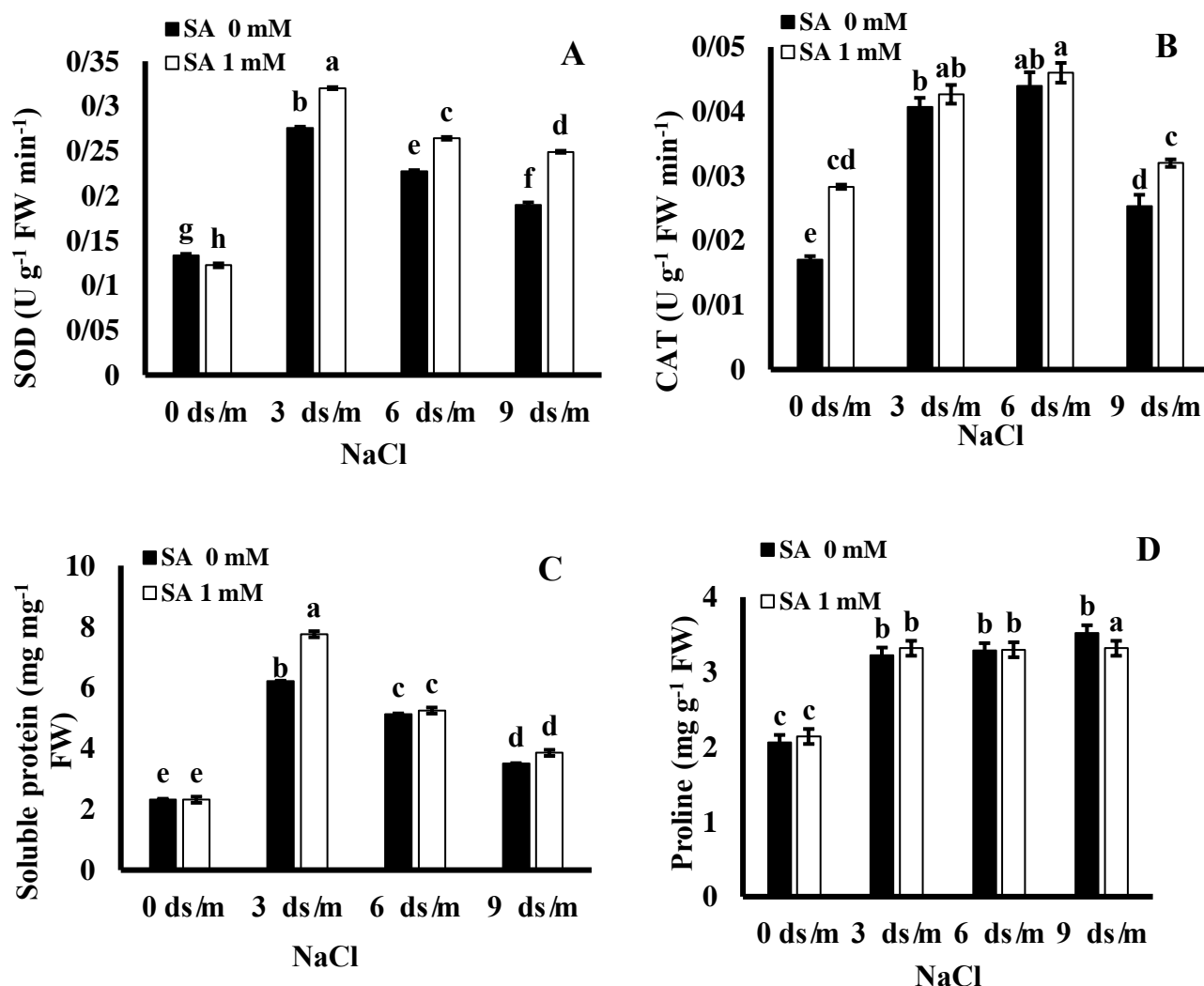


Fig. 4. Effect of salicylic acid (0, 1 mM) on (A) SOD, (B) CAT, (C) soluble protein, and (D) proline in *D. barbatus* under salt stress (0, 3, 6, and 9 dS m<sup>-1</sup>) conditions. Different letters indicate significance according to LSD test at  $P < 0.05$ .

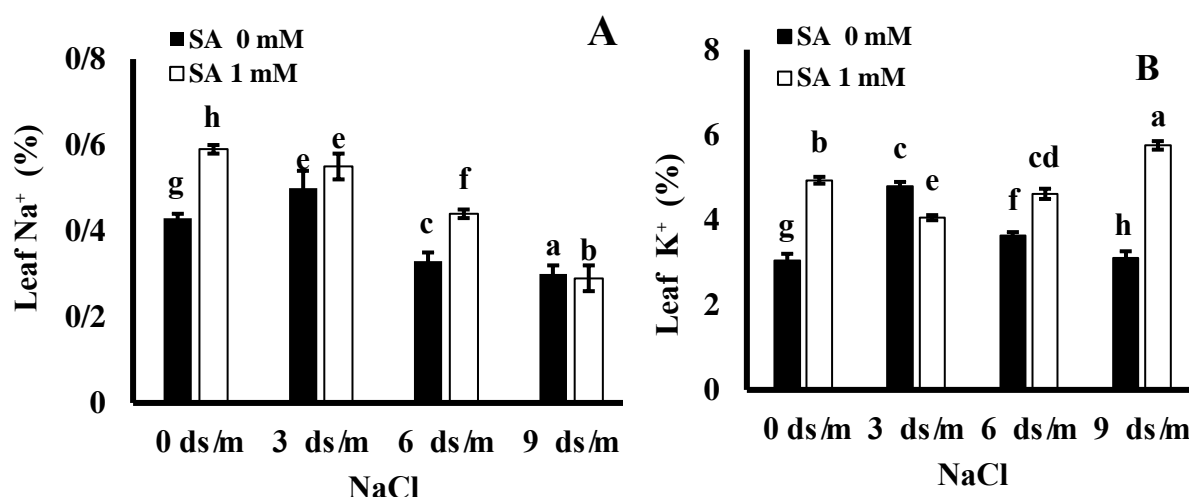
#### Leaf sodium and potassium content

Leaf sodium (Na<sup>+</sup>) and potassium (K<sup>+</sup>) contents were significantly affected by salinity and SA treatment (Fig. 5A and B). Under 0 dS m<sup>-1</sup> salinity, K<sup>+</sup> content was higher in SA-treated plants compared with the control, while Na<sup>+</sup> remained low and similar in both treatments. At 3 dS m<sup>-1</sup> salinity, K<sup>+</sup> decreased in control plants but was maintained at a higher level in SA-treated plants, whereas Na<sup>+</sup> content remained similar in both treatments. At 6 dS m<sup>-1</sup> salinity, SA helped sustain higher K<sup>+</sup> levels and reduced Na<sup>+</sup> accumulation compared with the control. At 9 dS m<sup>-1</sup> salinity, K<sup>+</sup> content remained higher in SA-treated plants, while Na<sup>+</sup> was slightly reduced by SA and reached its maximum in control plants.

#### Discussion

Salinity is among the most detrimental abiotic stresses limiting plant growth and development, as it

induces ionic imbalance, osmotic stress, and excessive production of reactive oxygen species (ROS) (Zhu, 2016). In *D. barbatus*, increasing salinity resulted in reductions in leaf number, leaf area, and shoot biomass, reflecting the inhibitory effects of ionic and osmotic stress on cell division and elongation processes (Akbari et al., 2018). Under these conditions, foliar application of salicylic acid (SA) improved growth traits under mild and moderate salinity levels, in agreement with reports in *Rosa damascena*, *Calendula officinalis*, and *Helianthus annuus* (Noreen et al., 2017; El-Nashar, 2022; Omidi et al., 2022). This growth-promoting effect is likely mediated through enhanced osmotic regulation and sustained meristematic activity, which support cell expansion and increase cell volume (Ahanger et al., 2019; Sultana et al., 2025).



**Fig. 5.** Effect of salicylic acid (0.5, 1 mM) on Na<sup>+</sup> and K<sup>+</sup> in *D. barbatus* under salt stress (0, 3, 6, and 9 dS m<sup>-1</sup>) conditions. Different letters indicate significance according to LSD test at  $P < 0.05$ .

SA also has a crucial role in maintaining photosynthetic pigments. In the present study, chlorophyll a (Chl a) and carotenoid contents declined progressively with increasing salinity, particularly at 6 and 9 dS m<sup>-1</sup>, likely due to stomatal closure, reduced RuBisCO activity, and ROS-induced pigment degradation (Gill and Tuteja, 2010; Ma et al., 2017). However, SA application partially mitigated these declines, possibly through activation of chlorophyll biosynthesis pathways and stabilization of chloroplast membranes. This response is consistent with observations reported for *Dianthus superbis* and other plant species (Ma et al., 2017; Moustakas et al., 2022).

The accumulation of secondary metabolites, including total phenolic compounds and flavonoids, increased under moderate salinity, with SA treatment further enhancing their levels. These compounds function as non-enzymatic antioxidants, contributing to ROS scavenging and osmotic adjustment under stress conditions (Kováčik and Klejduš, 2008; Yin et al., 2024). As a phenolic compound itself, SA stimulates the phenylpropanoid pathway and enhances the activity of key enzymes such as phenylalanine ammonia-lyase (PAL) and peroxidases, leading to increased synthesis of protective metabolites (Daghaghian et al., 2017; Linić et al., 2021). Together, these responses support the existence of a conserved SA-mediated protective mechanism across diverse plant species (Ma et al., 2017; Linić et al., 2021).

In addition to non-enzymatic defenses, SA enhanced the enzymatic antioxidant system. Activities of superoxide dismutase and catalase increased under 3–6 dS m<sup>-1</sup> salinity, contributing to reduced lipid peroxidation and improved membrane stability (Ahanger et al., 2019). Correspondingly, electrolyte leakage declined following SA application,

particularly at 6 dS m<sup>-1</sup>, indicating effective protection of cellular membranes, as previously reported in *Rosa hybrida* and mung bean (Nazar et al., 2011; Omidi et al., 2022). However, under severe salinity stress (9 dS m<sup>-1</sup>), enzymatic antioxidant responses were insufficient to fully counteract oxidative damage, highlighting the limited efficacy of SA under extreme stress conditions.

Osmotic adjustment and the accumulation of proline and soluble proteins were positively influenced by SA application. Proline functioned as an effective osmoprotectant and ROS scavenger, contributing to the stabilization of cellular structures under saline conditions (Hayat et al., 2012; El Moukhtari et al., 2020). Soluble protein content increased under mild salinity in SA-treated plants, likely due to protection of ribosomal integrity and enhanced enzymatic activity. In contrast, under severe salinity, protein levels declined, probably as a consequence of ionic toxicity and K<sup>+</sup> depletion disrupting protein synthesis and stability (Chen et al., 2007). Ion homeostasis was also markedly improved by SA treatment. Treated plants maintained higher K<sup>+</sup> concentrations and lower Na<sup>+</sup> accumulation, resulting in a reduced Na<sup>+</sup>/K<sup>+</sup> ratio and improved metabolic functioning under saline conditions (Kumar et al., 2022; Yang et al., 2023). Comparable SA-mediated regulation of ion balance has been reported in pepper, pea, and sunflower, indicating a common protective response across species (Noreen et al., 2017; Naz et al., 2022). Overall, these results highlighted the multifaceted role of SA in enhancing salinity tolerance in *D. barbatus*. By stimulating antioxidant defenses, maintaining ion balance, and improving osmotic adjustment, SA effectively mitigated salt-induced damage. However, its protective effects were most pronounced under moderate salinity, whereas extreme ionic and osmotic stress partially limited its

efficacy. From an applied perspective, SA represents a cost-effective strategy to enhance the resilience of ornamental plants under saline conditions, although combinatorial approaches involving other phytohormones or soil amendments may be required to achieve adequate protection under severe salinity. These findings were consistent with recent reports by Gharibiyani et al. (2023), Sultana et al. (2025), and Rabari et al. (2023), supporting the general applicability of SA-mediated stress mitigation across diverse plant species.

## Conclusion

The present study demonstrated that the foliar application of 1 mM salicylic acid improved the tolerance of *D. barbatus* to salinity levels at 3, 6, and 9 dS m<sup>-1</sup>. SA mitigated the negative effects of salinity on growth, photosynthetic pigment content, membrane integrity, and antioxidant defense systems. It enhanced osmotic adjustment and maintained ionic balance, contributing to stronger physiological and biochemical responses under salt stress. Although the protective effects of SA were less pronounced at 9 dS m<sup>-1</sup>, the findings highlight its practical potential as a cost-effective approach to enhance salt tolerance in ornamental plants. Future studies could focus on optimizing application timing and concentration, as well as combining SA with other growth regulators or biostimulants to further improve resilience under high salinity conditions.

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## Author Contributions

Designed and supervised the research as the project principal investigator, MK; Performed the greenhouse and laboratory experiments, ME, FGS, and NHR. All authors have read and agreed to the published version of the manuscript.

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## Conflict of Interest

The authors indicate no conflict of interest in this work.

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