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The effect of exogenous salicylic acid on the germination and seedling growth of sweet melon (*Cucumis melo* L.) seeds under NaCl stress

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Abstract: The objective of this research was to investigate the effects of different concentrations of salicylic acid (SA) on seed germination and seedling growth physiology of sweet melon under NaCl stress. Under salt stress, low concentrations of 0.25–0.5 mmol/L SA treatment can effectively alleviate plant salt damage and promote the germination rate of sweet melon seeds. Simultaneously, high concentrations of SA had a significant inhibitory effect on the root length, root fresh weight, and root : shoot ratio of sweet melon, but using medium concentrations (1.0 mmol/L) of SA can increase the root length and root : shoot ratio of seedlings. In addition, low concentration SA treatment can reduce the malondialdehyde (MDA) content of plants and increase the activity of peroxidase (POD). High concentrations will reduce POD activity and increase MDA content. Adding exogenous salicylic acid at different concentrations without NaCl stress can, to some extent, inhibit seedling growth, reduce plant root length, root fresh weight and other growth indicators, but can reduce MDA content, increase POD activity, and enhance plant defence ability against the outside world. Under NaCl stress, treatment with 0.25 mmol/L SA can reduce MDA content, increase POD activity, enhance plant salt resistance, and improve seed germination rate. Treatment with 1.0 mmol/L SA promoted seedling root elongation and increased root : shoot ratio. In the absence of NaCl stress, treated plants with different concentrations of SA can inhibit seedling growth to some extent.

Keywords: melon; SA; seed treatment; salt stress; seed germination; seedling development; growth and physiology

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Melon (*Cucumis melo* L.) is an annual creeping plant in the Cucurbitaceae family, belonging to the *Cucumis* genus (Shao et al. 2022). It is classified into two major ecological types: thick-skinned and thin-skinned melons, also known as cantaloupe, fruit, and cantaloupe (Shahwar et al. 2023). Melons are mainly native to Africa and subtropical regions. According to the Food and Agriculture Organisation of the United Nations (FAO), China's annual production of sweet melons accounts for over 45% of the global total, with a cultivation area of over 4 million hectares. Its industrial scale plays an irreplaceable role in the agricultural economy, increasing farmers' income, and developing regional characteristic agriculture (Zhang et al. 2016). However, with the rapid expansion of facility agriculture and the intensification of climate change, soil salinisation has become a key environmental stress factor restricting the high and stable yield of sweet melons (Zhou et al. 2024). According to statistics, about 20% of irrigated farmland worldwide has experienced a decline in productivity due to salinisation. The accumulation of salt, mainly NaCl, inhibits plant growth through multiple mechanisms (Bouzroud et al. 2023). On the one hand, high concentrations of Na^+ interfere with cellular ion homeostasis, causing obstruction of the absorption of essential elements such as K^+ and Ca^{2+}, damaging enzyme activity and membrane system function (Balasubramaniam et al. 2023); On the other hand, salt stress-induced osmotic imbalance and reactive oxygen species (ROS) outbreak further trigger oxidative damage, leading to delayed seed germination, seedling growth arrest, and even plant death (Munns, Tester 2008; Du et al. 2018; Liang et al. 2021). As a salt sensitive crop, sweet melon is particularly vulnerable to salt stress during its seed germination period. Salt concentrations exceeding 50 mmol/L can significantly inhibit germination rate and embryonic root elongation (Diao et al. 2018). Therefore, exploring effective strategies to alleviate salt stress, especially during the critical stages of seed germination and seedling establishment, is of urgent practical significance for ensuring the safe production of sweet melons and the efficient utilisation of saline land resources.

Salicylic acid (SA), as an endogenous phenolic signalling molecule, has attracted much attention in recent years due to its pleiotropy in plant stress regulation (Khan et al. 2015). Research has shown that SA can not only clear ROS by activating antioxidant enzyme systems such as superoxide dismutase (SOD) and peroxidase (POD), but also induce the expression of disease-related proteins (PRPs), regulate stomatal movement, and maintain cell membrane integrity, thereby enhancing plant tolerance to drought, low temperature, heavy metals, and salt stress (González-Villagra et al. 2022; Das et al. 2024). For example, exogenous SA treatment significantly increased proline accumulation and photosynthetic efficiency in cucumber seedlings under salt stress (Yang et al. 2018), and alleviated Na^+ toxicity in rice by activating the mitogen-activated protein kinase (MAPK) signalling pathway (Hua 2021). However, current research on SA mainly focuses on the nutritional or reproductive growth stages, and there is still a lack of systematic exploration of its regulatory effects and concentration dependence on seed germination stages. Especially for sweet melon, an important economic crop, the mechanism by which SA coordinates seed germination kinetics, embryonic root morphogenesis, and physiological metabolic balance under salt stress is not yet clear. In addition, previous studies have generally indicated that the biological effects of SA exhibit a typical 'double-edged sword' characteristic: low concentrations (0.1~0.5 mmol/L) can significantly promote plant growth, while high concentrations (> 1.0 mmol/L) may have inhibitory effects due to overactivation of defence responses or triggering cell toxicity (Hua 2021). The complexity of this concentration dependence requires a precise definition of the optimal threshold for SA to avoid potential risks in technology promotion.

Although some studies have preliminarily confirmed the positive effect of SA on salt tolerance in cantaloupe, such as Diao et al. (2018). found that SA pretreatment can alleviate membrane lipid peroxidation in cantaloupe seedlings under low temperature stress, there are still scientific questions to be solved regarding its regulatory mechanism on seed germination under salt stress: (1) How does SA alleviate the inhibition of salt stress on cantaloupe seed swelling, embryonic root breakthrough, and storage substance mobilization by regulating osmotic substance metabolism and antioxidant system dynamic balance? (2) Is there a significant difference in the regulation of morphological development (such as root:shoot ratio and biomass allocation) of sweet melon seedlings

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under salt stress and non-stress conditions at different concentrations of SA? (3) Is the salt tolerance enhancement mediated by SA related to the interaction of endogenous hormone (such as abscisic acid (ABA), gibberellic acid 3 (GA_3)) signalling? These issues have not been fully elucidated in existing literature, which hinders the precise application of SA in salt-tolerant cultivation of sweet melons.

Based on this, this study used 'Emerald' melon as the experimental material and combined exogenous SA soaking with 150 mmol/L NaCl stress treatment to systematically investigate the effects of 0–2.0 mmol/L SA gradient concentration on melon seed germination (germination potential, germination rate), seedling morphological indicators (root length, seedling height, seedling fresh weight, root fresh weight), and physiological characteristics (malondialdehyde (MDA) content, POD activity) (Li et al. 2016; Alghamdi et al. 2023). By using the membership function method and distance to ideal solution (DTOPSIS) model to comprehensively evaluate the salt tolerance effects of different treatments, the aim was to reveal the concentration threshold and action pattern of SA in alleviating salt stress (Li et al. 2020; Liang et al. 2024). Analysed the physiological mechanism of SA regulation on melon seed germination and seedling growth (Jayasinghege et al. 2023). Screened the optimal SA treatment plan to provide a theoretical basis and technical parameters for stress-resistant cultivation of sweet melons in saline alkali areas. The innovation of this study lies in the first combination of the concentration effect of SA with the salt stress response during the germination stage of melon seeds, and the comprehensive evaluation of multidimensional indicators, providing a more scientific dose reference for the agricultural application of SA.

MATERIAL AND METHODS

Plant material and treatments. The 'Emerald' melon seeds were purchased from the market, and melon seeds with plump and approximately equal particle size were selected as experimental materials. Exogenous salicylic acid, NaCl solution, and other analytical drugs are provided by the laboratory of the School of Life Sciences, Huaibei Normal University.

Prepare solution. The experiment was conducted on December 30, 2024, in the laboratory of the School of Life Sciences, Huaibei Normal University. Prepare 150 mmol/L NaCl solution and (0.25, 0.5, 1.0, 1.5, 2.0 mmol/L) salicylic acid solution.

Seed soaking. This experiment adopts a multi factor design method and consists of 12 experimental groups, including a blank control group (CK), a salicylic acid single factor treatment group (with five concentration gradients of 0.25, 0.5, 1.0, 1.5, and 2.0 mmol/L, labelled as 0.25 SA–2.0 SA), a salt stress treatment group (treated with 150 mmol/L NaCl solution, labelled as N), and a salt salicylic acid composite treatment group (treated with a mixed solution of 150 mmol/L NaCl and the above five salicylic acid concentrations, labelled as N + 0.25 SA–N + 2.0 SA) (as shown in Table 1). Each treatment was set with 3 replicates, each replicate containing 10 melon seeds, a total of 360 seeds of similar size were used.

Firstly, the seeds were surface sterilised using a 5% sodium hypochlorite solution for 20 min, followed by rinsing with deionised water and soaking for 30 minutes. Different concentrations of salicylic acid working solution and 150 mmol/L sodium chloride solution were prepared according to the experimental design. Laid a single layer of filter paper in a sterile culture dish and added 5 mL of the corresponding treatment solution to wet the filter paper. Placed the sterilised seeds evenly on the surface of the treated filter paper, and fi-

Table 1. Different treatments for sweet melon seeds

Treatment	Treatment type (mmol/L)	
	NaCl concentration	SA concentration
CK	0.00	0.00
0.25 SA	0.00	0.25
0.5 SA	0.00	0.50
1.0 SA	0.00	1.00
1.5 SA	0.00	1.50
2.0 SA	0.00	2.00
NaCl (N)	150.00	0.00
N + 0.25 SA	150.00	0.25
N + 0.5 SA	150.00	0.50
N + 1.0 SA	150.00	1.00
N + 1.5 SA	150.00	1.50
N + 2.0 SA	150.00	2.00

CK – control; SA – salicylic acid

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nally placed the culture dish in a 25 °C constant temperature incubator for dark cultivation.

Determination of seed germination index. Seed germination potential refers to the ratio of the number of seeds germinated within five days to the tested seeds. Seed germination rate refers to the ratio of the number of seeds germinated within seven days to the tested seeds.

Determination of growth indicators for seedlings. At seven days after seed germination, morphological indicators were measured on the seedlings of each treatment group. Including root length (cm), root fresh biomass (g), hypocotyl height (cm), aboveground fresh mass (g), and root:shoot ratio calculated by the ratio of root system to aboveground part.

Measurement of physiological indicators of seedlings. At seven days after seed germination, the MDA content (mmol/g) and POD activity (U/(min·g)) in the seedlings were measured according to the methods proposed by Coutts et al. (2019) and Fei and Yang (2014).

Statistical analyses. Used Microsoft Excel 2016 to perform preliminary calculations and create charts, and then annotated significant differences in the charts for comparison between groups. Performed one-way analysis of variance (ANOVA) using SPSS Statistics 27.0 to test the significance of differences between different treatment groups.

Principal component analysis (PCA) was used in the membership function method to determine the weights of indicators. Extracted the principal components of the data (linearly independent new variables) to explain most of the variance of the original data (Fei, Yang 2014). Calculated the weights of each indicator based on the variance contribution rate of the principal components and their coefficients on each indicator.

The purpose of the membership function method is to integrate multiple indicators into one evaluation score, overcoming the limitations of a single indicator. The calculation formula was:

$$\text{Positive membership function value} = (X_i - X_{\min})/(X_{\max} - X_{\min})$$

$$\text{Negative membership function value} = 1 - (X_i - X_{\min})/(X_{\max} - X_{\min})$$

where: X_i – the actual measured value of a certain evaluation indicator requires calculating the original value of the indicator for a single sample of membership degree; $X_{\min}$ – the minimum value of the corresponding indicator among all the samples participating in the evaluation; $X_{\max}$ – the maximum value of the corresponding indicator among all the samples participating in the evaluation.

The weight calculation was to determine the weights of each indicator through principal component analysis. The calculation method for the comprehensive score was:

$$\text{Comprehensive score} = \sum (\text{membership value} \times \text{weight})$$

The DTOPSIS method was a multi-criteria ranking method that calculated the closeness of each treatment to the 'ideal solution'. First, standardise the multi index data of each process, then determined the positive ideal solution ($S+$) and negative ideal solution ($S-$), and used the Euclidean distance method to calculate the distance between each process and the positive ideal solution (S_i+) and the distance between each process and the negative ideal solution (S_i-), and finally calculated the relative proximity (C_i) (Shu et al. 2024). The closer the C_i value was to 1, the better the overall performance of the treatment. The calculation formula for C_i was:

$$C_i = S_i-/(S_i+ + S_i-)$$

RESULTS

The effect of exogenous salicylic acid at different concentrations on the germination of sweet melon seeds under salt stress

Table 2 showed that the germination potential of melon seeds under 150 mmol/L NaCl treatment was 60.0%, lower than that under CK treatment (73.3%). When the SA concentration was 0.5–2.0 mmol/L, the germination potential of seeds was significantly lower than that of the control group (CK), with the 2.0 mmol/L SA treatment group having the lowest germination potential (53.3%). Under salt stress (150 mmol/L NaCl), the effect of exogenous SA addition on seed germination potential showed that as SA concentration increased, germination potential first increased, then decreased, and then slightly rebounded. Among them, the N + 1.5 SA combi-

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Table 2. The effect of adding exogenous salicylic acid on the germination potential and germination rate of sweet melon seeds with or without NaCl coercion

Treatment	Germination potential (%)	Germination rate (%)
CK	73.3^{e}	86.7^{e}
0.25 SA	76.7^{f}	93.3^{g}
0.5 SA	70.0^{d}	90.0^{f}
1.0 SA	63.3^{c}	76.7^{c}
1.5 SA	60.0^{b}	73.3^{b}
2.0 SA	53.3^{a}	66.7^{a}
NaCl (N)	60.0^{b}	73.3^{b}
N + 0.25 SA	83.3^{g}	90.0^{f}
N + 0.5 SA	73.3^{e}	86.7^{e}
N + 1.0 SA	66.7^{d}	80.0^{d}
N + 1.5 SA	60.0^{b}	73.3^{b}
N + 2.0 SA	63.3^{c}	76.7^{c}

CK – control; SA – salicylic acid; different letters mean a significant difference among different treatments at the 0.05 level

nation treatment had the lowest germination potential (60.0%).

Salt stress significantly inhibited the germination of melon seeds, and the germination rate (73.3%) of the 150 mmol/L NaCl treatment group was significantly lower than that of the CK group (86.7%). The effect of SA single-factor treatment on seed germination rate showed a concentration-dependent change, with low promotion and high inhibition. Under salt stress, 0.25~0.5 mmol/L SA can effectively alleviate salt damage and significantly increase germination rate compared to the NaCl salt stress group, the germination rates of N + 0.25 SA and N + 0.5 SA treatment groups were 90.0% and 86.7%, respectively, which were 22.78% and 18.28% higher than those of the NaCl salt stress group. Under salt stress indicating that SA in this concentration range had a significant salt stress resistance effect.

The effect of exogenous salicylic acid at different concentrations on the growth indicators of sweet melon seeds under salt stress

As shown in Figure 1A, B, SA treatment significantly inhibited the root growth of sweet melon seedlings. The experimental data showed that the root elongation and fresh matter accumulation of each treatment group with 0.25~2.0 mmol/L SA were significantly reduced compared to the control (CK) ($P < 0.05$). 150 mmol/L NaCl stress also significantly inhibited the growth and development of seedling roots ($P < 0.05$), compared with the blank control group, the seed germination potential decreased by 22.22%, the seed germination rate decreased by 18.19%, the seedling root length decreased by 39.89%, the seedling height decreased by 13.49%, the seedling fresh weight decreased by 106.67%, and the seedling root shoot ratio decreased by 39.66%. Under salt stress treatment, the addition of different concentrations of SA showed concentration dependence: the change in root length showed an increase-decrease rebound trend, with the 1.0 mmol/L SA treatment group showing the most significant growth-promoting effect ($P < 0.05$). The accumulation of root biomass is initially inhibited and then promoted.

As shown in Figures 1C, D, both single SA treatment and NaCl stress had significant inhibitory effects on the aboveground growth of seedlings, resulting in a significant decrease in plant height and fresh weight indicators compared to the control ($P < 0.05$). After adding 0.25–2.0 mmol/L SA under NaCl stress, the seedling height and fresh weight of the seedlings first decreased and then increased, then sharply decreased and then increased. Under NaCl stress, the height (0.22 cm) and fresh weight (0.18 g) of seedlings treated with 1.5 mmol/L SA were significantly lower than those of all other treatments.

As shown in Figure 1E, salt stress treatment resulted in a decrease in the root cap of sweet melon seedlings compared to the CK group, but the difference did not reach a significant level. Under salt stress conditions, different concentrations of SA treatment have differential effects on root : shoot ratio: when 1.0 mmol/L SA was added, the root : shoot ratio reached its maximum value (0.76). The root : shoot ratio of the 1.5 mmol/L SA treatment group was the lowest among all treatments (0.42).

Analysis of phenotypic differences in melon growth

Growth differences under non salt stress with different concentrations of SA treatment. As shown in Figure 2, the germination vigour and germination rate of melon seeds with 0.25 mmol/L SA (76.67%)

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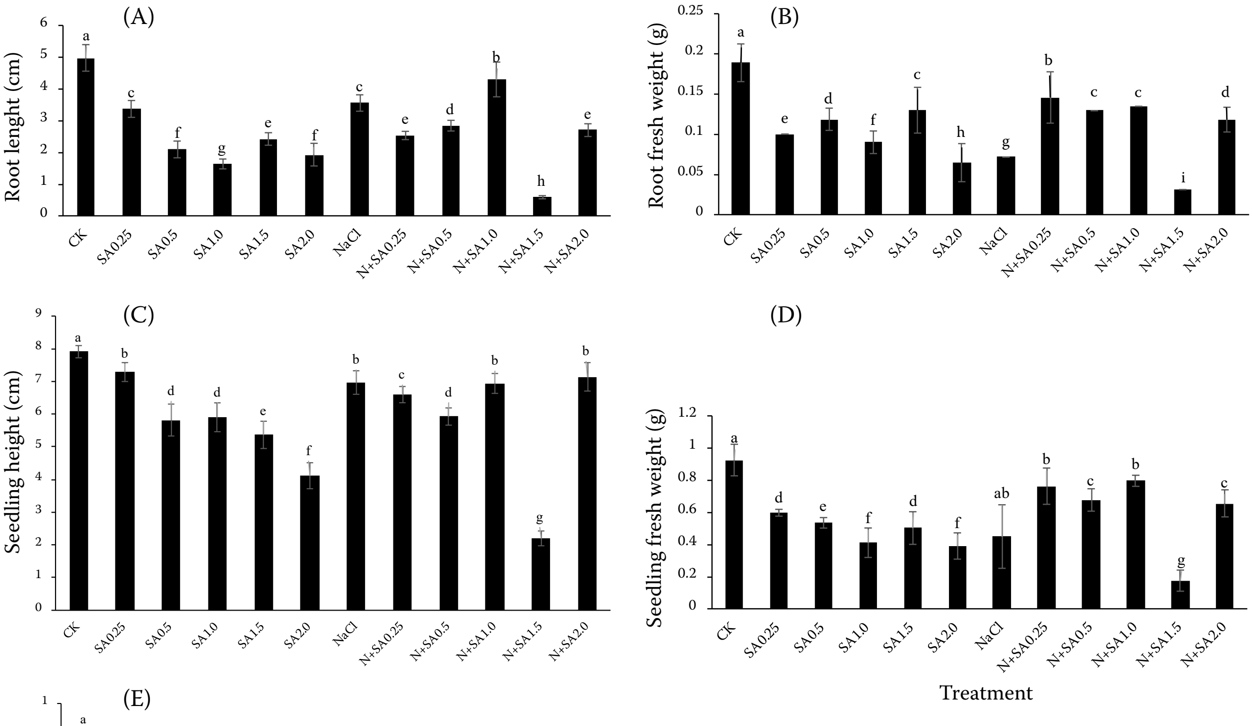
added alone were higher than those of CK (73.33%), indicating that low concentration SA promotes seed swelling and embryonic root breakthrough. Its root length (3.37 cm) was lower than CK (4.98 cm), indicating that low concentration SA slightly inhibits morphological growth. The germination potential and germination rate of sweet melon seeds separately added with 0.5–2.0 mmol/L SA decreased with increasing concentration, and the morphological indicators of seedling root length and height significantly decreased. From this, it can be seen that when there is no stress, the morphological growth of melon seeds with 0.25 mmol/L SA added is slightly inhibited. Adding 0.5–2.0 mmol/L SA significantly inhibited germination and growth of melon seeds.

Growth differences under different concentrations of SA treatment under NaCl stress. As shown in Figure 3, when 0.25 mmol/L SA was added under NaCl stress, the germination potential (83.33%) and germination rate (90.00%) of melon seeds were significantly higher than those under NaCl treatment (60.00%, 73.33%), approaching the CK treatment, indicating that SA effectively alleviated the inhibition of salt stress on germination. The root length of the seedlings was higher than that of the 150 mmol/L NaCl treatment. The germination rate and partial recovery of root length in the N + 1.0 SA treatment group. The root length of the N + 1.5 SA treatment group was severely restricted, the value was 0.59 cm, possibly due to excessive SA concentration leading to abnormal root development. The germination potential (63.33%) and germination rate (76.67%) of the N + 2.0 SA treatment group were slightly higher than those of the NaCl treatment (60.00%, 73.33%).



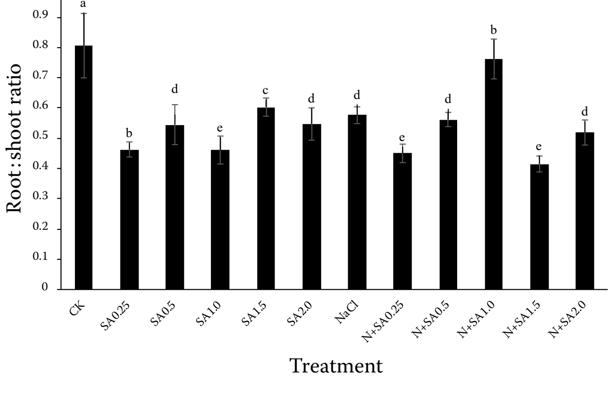


Figure 1. The effect of exogenous salicylic acid on (A) root length, (B) root fresh weight, (C) seedling height, (D) seedling fresh weight, and (E) root : shoot ratio of sweet melon seedlings under NaCl stress

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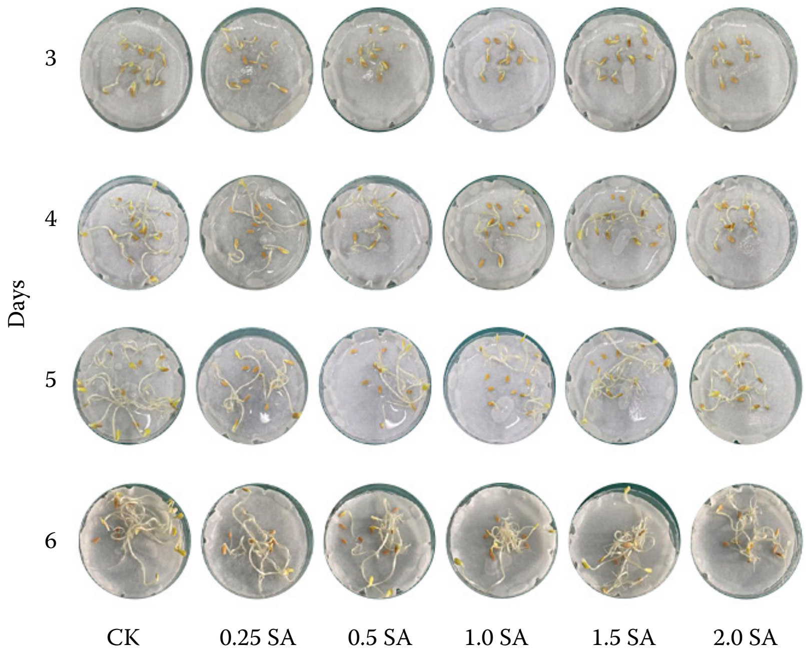

Figure 2. The effect of different concentrations of salicylic acid on the sprout growth of sweet melon
CK – control; SA – salicylic acid

Effects of exogenous salicylic acid at different concentrations on POD activity and MDA content in sweet melon seedlings under salt stress

Under the stress condition of 150 mmol/L NaCl, there was no significant difference in MDA content between melon seedlings treated with 0.5–2.0 mmol/L SA and those without SA. However, the MDA content of melon seedlings treated with 0.25 mmol/L SA (5.47 mmol/g) decreased compared to 150 mmol/L NaCl (14.78 mmol/g) treatment. Under CK conditions, the MDA content was the lowest, with a value of 2.82 mmol/g (Figure 4A). Under the same conditions, there was no significant difference in POD activity compared to CK treatment and 150 mmol/L NaCl treatment. However, the POD activity of seedlings treated with N + 2.0 mmol/L SA (3 747.20 U/(min·g)) decreased significantly compared to CK (3 891.20 U/(min·g)) treatment and 150 mmol/L NaCl (3 856.00 U/(min·g)) treatment (Figure 4B).

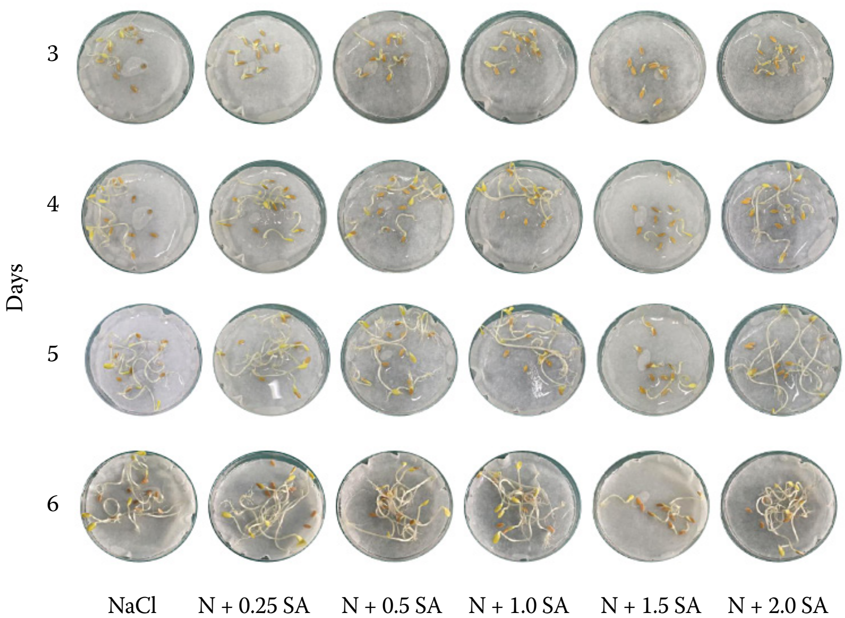

Figure 3. The effect of different concentrations of salicylic acid on the growth of sweet melon sprouts under NaCl stress
N – NaCl; SA – salicylic acid

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Comprehensive evaluation

As shown in Table 3, under normal growth conditions (without NaCl stress), different concentrations of SA treatment showed a concentration gradient effect on the germination and seedling growth of sweet melon seeds. The intensity of the effect was in the following order: 0.25 mmol/L SA > 0.5 mmol/L SA > 1.0 mmol/L SA > 1.5 mmol/L SA > 2.0 mmol/L. The 0.25 mmol/L SA treatment group showed the best physiological effects: it not only significantly improved the germination indicators of seeds (germination rate 93.33% and germination potential 76.67%), but also enhanced the antioxidant capacity of seedlings (increased POD activity, 3 896.00 U/(g·min)) and reduced the degree of membrane lipid peroxidation (decreased MDA content, 5.47 mmol/g), thus comprehensively promoting the germination process of melon seeds and the growth and development of seedlings.

As shown in Table 4, under the stress condition of 150 mmol/L NaCl, exogenous SA showed a significant concentration effect on the regulation of salt tolerance in cantaloupe. The ranking of the alleviating effects of each treatment group on salt stress is: 0.25 mmol/L SA > 1.0 mmol/L SA > 0.5 mmol/L SA > 2.0 mmol/L SA > 1.5 mmol/L. The 0.25 mmol/L SA treatment showed the best salt stress relief effect, which significantly improved the germination performance of melon seeds and enhanced the antioxidant enzyme activity of seedlings, effectively reducing oxidative damage caused by salt stress and significantly improving the salt tolerance of melon plants.

The experimental results indicate that SA has a significant concentration-dependent effect on the germination of melon seeds and the growth of seedlings (Wang et al. 2015). Under salt-free stress conditions, low concentrations of SA (0.25–0.5 mmol/L) significantly increased the germination rate of seeds, while high concentrations (SA ≥ 1.0 mmol/L) showed inhibitory effects (germination rate decreased to 66.7%). This phenomenon may be related to the dual mechanism of action of SA: low concentrations of SA activate the antioxidant system (such as increased POD activity) to alleviate oxidative damage (decreased MDA content), thereby promoting germination. High concentrations of SA may cause excessive oxidative stress or disrupt the endogenous hormone balance in seeds, leading to metabolic disorders.

Under salt stress conditions, the alleviating effect of SA is more significant. After adding 0.25 mmol/L SA, the germination potential and germination rate of melon seeds increased from 60.0% and 73.3% to 83.3% and 90.0%, respectively. The morphologi-

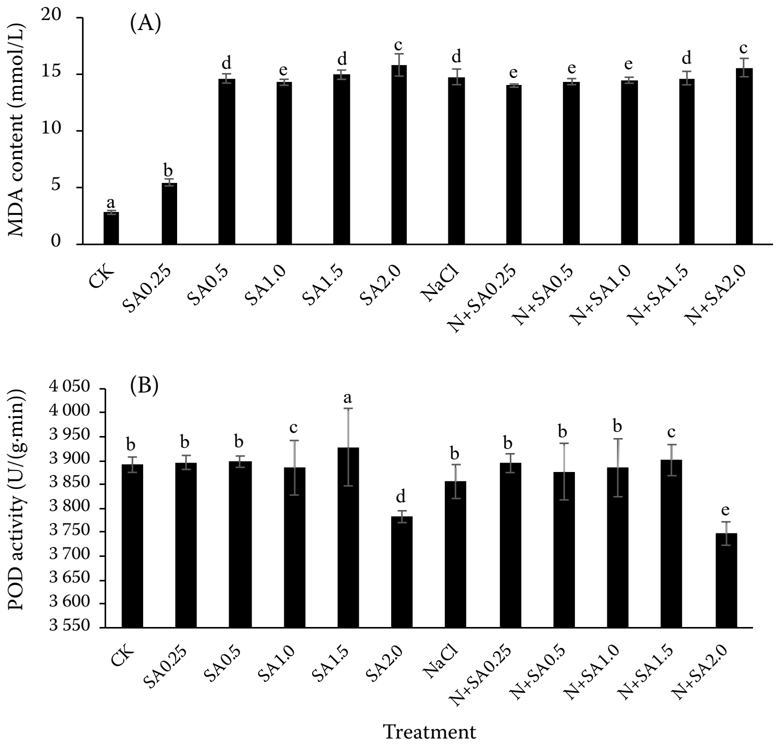

Figure 4. The effect of different concentrations of salicylic acid treatment on enzyme activity in sweet melon seedlings under salt stress

MDA – malondialdehyde; POD – peroxidase; CK – control; SA – salicylic acid; N – NaCl

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Table 3. Comprehensive analysis of the impact of different treatments on various indicators under no salt stress conditions

Treatment	Germination potential (%)	Germination rate (%)	Root length (cm)	Root fresh weight (g)	Seedling height (cm)	Seedling fresh weight (g)	Root : shoot ratio	POD activity (U/(min·g))	MDA content (mmol/g)	Weight score	Rank
CK	73.33^{c}	86.67^{c}	4.98^{e}	0.19^{c}	7.91^{c}	0.93^{d}	0.81^{d}	3 891.20^{c}	2.82^{a}	0.86	1
0.25 SA	76.67^{d}	93.33^{d}	3.37^{d}	0.10^{b}	7.29^{c}	0.60^{c}	0.46^{a}	3 896.00^{c}	5.47^{b}	0.75	2
0.5 SA	70.00^{c}	90.00^{d}	2.09^{b}	0.12^{b}	5.82^{b}	0.54^{b}	0.55^{b}	3 897.60^{c}	14.64^{c}	0.60	3
1.0 SA	63.33^{b}	76.67^{b}	1.64^{a}	0.09^{a}	5.90^{b}	0.41^{a}	0.46^{a}	3 884.80^{b}	14.30^{c}	0.50	4
1.5 SA	60.00^{b}	73.33^{b}	2.42^{c}	0.13^{b}	5.37^{b}	0.50^{b}	0.60^{c}	3 928.00^{d}	14.97^{c}	0.43	5
2.0 SA	53.33^{a}	66.67^{a}	1.93^{a}	0.06^{a}	4.12^{a}	0.39^{a}	0.55^{b}	3 782.40^{a}	15.83^{d}	0.39	6
Weight score	0.10	0.14	0.12	0.08	0.10	0.10	0.15	0.10	0.11		

POD – peroxidase; MDA – malondialdehyde; CK – control; SA – salicylic acid; different letters mean a significant difference among different treatments at the 0.05 level

Table 4. Comprehensive analysis of the effects of different treatments on various indicators under NaCl stress

Treatment	Germination potential (%)	Germination rate (%)	Root length (cm)	Root fresh weight (g)	Seedling height (cm)	Seedling fresh weight (g)	Root : shoot ratio	POD activity (U/(min·g))	MDA content (mmol/g)	Weight score	Rank
NaCl (N)	60.00^{a}	73.33^{a}	3.56^{c}	0.07^{b}	6.97^{c}	0.45^{b}	0.58^{c}	3 856.00^{b}	14.78^{c}	0.44^{b}	4
N + 0.25 SA	83.33^{d}	90.00^{e}	2.53^{b}	0.15^{c}	6.60^{c}	0.76^{d}	0.45^{a}	3 894.40^{d}	14.01^{a}	0.83^{d}	1
N + 0.5 SA	73.33^{c}	86.67^{d}	2.84^{b}	0.13^{c}	5.93^{b}	0.68^{c}	0.56^{c}	3 876.80^{c}	14.36^{b}	0.64^{c}	3
N + 1.0 SA	66.67^{b}	80.00^{c}	4.30^{d}	0.13^{c}	6.94^{c}	0.80^{e}	0.76^{d}	3 884.80^{d}	14.48^{b}	0.66^{c}	2
N + 1.5 SA	60.00^{a}	73.33^{a}	0.59^{a}	0.03^{a}	0.22^{a}	0.18^{a}	0.42^{a}	3 900.80^{e}	14.67^{c}	0.30^{a}	6
N + 2.0 SA	63.33^{a}	76.67^{b}	2.70^{b}	0.12^{c}	7.14^{d}	0.66^{c}	0.52^{b}	3 747.20^{a}	15.60^{d}	0.34^{a}	5
Weight score	0.10	0.14	0.12	0.08	0.10	0.10	0.15	0.10	0.11		

POD – peroxidase; MDA – malondialdehyde; SA – salicylic acid; different letters mean a significant difference among different treatments at the 0.05 level

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Table 5. Distance to ideal solution (DTOPSIS) analysis of each indicator with different treatments without NaCl treatment

Treatment	Positive ideal weighted distance S_i+	Negative ideal weighted distance S_i–	Relative proximity C_i	Rank
CK	0.0438	0.0397	0.4760	2
0.25 SA	0.0356	0.0498	0.5830	1
0.5 SA	0.0489	0.0331	0.4040	3
1.0 SA	0.0502	0.0308	0.3800	5
1.5 SA	0.0498	0.0319	0.3900	4
2.0 SA	0.1580	0.0251	0.3190	6

CK – control; SA – salicylic acid

cal indicators of seedling root length, fresh weight, and height were also significantly improved. This indicates that low concentrations of SA can alleviate the negative effects of salt stress by enhancing antioxidant capacity and reducing membrane lipid peroxidation. However, when the concentration of SA exceeds 1.0 mmol/L, its alleviating effect gradually weakens and even turns into inhibition. The existence of this concentration threshold suggests the need for strict control of SA application concentration in practical applications.

The experimental results showed that 0.25 mmol/L exogenous salicylic acid (SA) can effectively alleviate the inhibitory effect of 150 mmol/L NaCl stress on the growth of cantaloupe. This concentration treatment showed the best salt stress relief effect and can be recommended as a concentration for improving salt tolerance in sweet melons. Exogenous salicylic acid effectively alleviates the inhibition of salt stress on melon seed germination and seedling growth through concentration dependent antioxidant and osmotic regulation effects, with 0.25 mmol/L SA being the optimal treatment concentration.

DTOPSIS comprehensive analysis and evaluation

The comprehensive evaluation results based on DTOPSIS method showed that under normal growth conditions (without NaCl stress), there were significant differences in the effects of different concentrations of salicylic acid (SA) treatment on physiological indicators of cantaloupe (Table 5). The comprehensive evaluation values (C_i) of each treatment group are ranked as follows: 0.25 mmol/L SA > 0.5 mmol/L SA > 1.5 mmol/L SA > 1.0 mmol/L SA > 2.0 mmol/L SA. Among them, the C_i value of the 0.25 mmol/L SA treatment group was not only significantly higher than other treatment groups ($P < 0.05$), but also increased compared to the control group (CK), indicating that this concentration treatment can optimally promote the growth and development of sweet melons. Under NaCl stress, the C_i values of melons treated with different concentrations of SA decreased from high to low: N + SA 0.25 > N + SA 0.5 > N + SA 2.0 > N + SA 1.0 > N + SA 1.5, The comprehensive indicators of sweet melon under N + SA 0.25 treatment are the best, and adding 0.25 mmol/L SA under NaCl stress can

Table 6. Distance to ideal solution (DTOPSIS) analysis of each indicator with different treatments under NaCl treatment

Treatment	Positive ideal weighted distance S_i+	Negative ideal weighted distance S_i–	Relative proximity C_i	Rank
NaCl (N)	0.0475	0.0349	0.4240	5
N + 0.25 SA	0.0271	0.0583	0.6820	1
N + 0.5 SA	0.0412	0.0451	0.5230	2
N + 1.0 SA	0.0461	0.0364	0.4410	4
N + 1.5 SA	0.0516	0.0284	0.3550	6
N + 2.0 SA	0.0453	0.0372	0.4510	3

SA – salicylic acid

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effectively alleviate the inhibitory effect caused by salt stress (Table 6).

DISCUSSION

Salinity is one of the abiotic stress factors limiting crop growth and yield formation. At present, soil salinisation is increasing and has become a major global environmental and agricultural problem (Ogunsiji et al. 2023). The main harmful factor of soil salinisation, NaCl, affects plant growth through a dual mechanism: on the one hand, it causes an imbalance in cell permeability, leading to hindered water absorption. On the other hand, it interferes with ion homeostasis and inhibits the absorption of essential elements such as K^+ and Ca^{2+}. During the seed germination stage, salt stress mainly inhibits the germination process by disrupting cell membrane integrity and interfering with osmotic regulation. Salicylic acid, whose chemical name is o-hydroxybenzoic acid, is a small molecule phenolic substance widely distributed in higher plants. In addition, SA is also an important plant hormone, which can participate in the response process of plants to stress through a complex signal transduction network (Ma et al. 2017; Cao et al. 2020). Studies have shown that exogenous application of a certain concentration of salicylic acid can improve the salt tolerance of many plants (Cao et al. 2020; Hayat et al. 2010). Studies on the model plant *Arabidopsis thaliana* mutant showed that salicylic acid played a role in enhancing plant salt resistance (Hao et al. 2012). Related studies have shown that exogenous SA at appropriate concentrations can enhance plant salt tolerance by regulating the antioxidant system and ion balance (Liu et al. 2022; Song et al. 2025).

The results showed that the germination potential, germination rate and seedling growth of melon seeds were significantly reduced under 150 mmol/L NaCl stress. Consistent with this result, Sha et al. (2017) and Guo et al. (2018) showed that salt stress significantly inhibited the germination process of rice (*Oryza sativa*) and kale (*Brassica oleracea* var. acephala) seeds. The main reason is that salt stress forces seeds to suffer dehydration stress and ion toxicity, and salt stress induced hypertonic conditions inhibit seed water absorption, thus affecting the activation of various physiological metabolism during germination (Cao et al. 2020).

The experimental results showed that salicylic acid (SA) exhibited a significant concentration effect on the growth and development regulation of sweet melon during the germination stage. Under normal conditions, the promotion effect of 0.25 ~ 2.0 mmol/L SA treatment on melon seed germination and seedling growth gradually weakened (0.25 > 0.5 > 1.0 > 1.5 > 2.0 mmol/L). 0.25 mmol/L SA treatment significantly improved seed germination indicators (germination rate increased by 18.7%, germination potential increased by 22.3%), while enhancing seedling antioxidant capacity (POD activity increased by 35.2%) and reducing oxidative damage (MDA content decreased by 27.5%). Under the stress condition of 150 mmol/L NaCl, there was also a concentration difference in the improvement effect of SA on salt tolerance in sweet melon. 0.25 mmol/L SA showed the best salt stress relief effect, increasing various physiological indicators by more than 20% compared to the salt stress control. Some scholars have shown that salt stress can significantly reduce the water absorption rate of seeds at all stages, and the appropriate concentration of exogenous SA treatment can significantly improve the water absorption rate during imbibition and germination, thus improving the germination rate of seeds. The high concentration of SA treatment will further reduce the water absorption of seeds, thus reducing the germination potential and germination rate of seeds (Cao et al. 2020).

Under salt stress, the balance of ROS metabolic system in plants was affected, and ROS content increased sharply, leading to membrane lipid peroxidation (Nazar et al. 2015).This study showed that 0.25 mmol/L SA significantly alleviated the inhibitory effect of salt stress on cantaloupe, which is consistent with the research results of Jiang (2015) in patchouli. They found that 0.1–0.5 mmol/L SA can improve the germination rate and antioxidant enzyme activity of seeds under salt stress. Low concentrations of SA may alleviate ROS damage by activating antioxidant systems (such as POD, SOD) and accumulating osmoregulatory substances (such as proline), a mechanism reported in both *Achnatherum inebrians* (Lian, Li 2022) and *Scutellaria baicalensis* (Hua 2021).

In this study, 1.5–2.0 mmol/L SA inhibited the growth of cantaloupe, while high concentrations of SA (> 1.0 mmol/L) disrupted membrane system integrity, leading to MDA accumulation and de-

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creased enzyme activity. Excessive SA may cause cellular metabolic disorders by inhibiting mitochondrial electron transport chains or interfering with hormone balance (such as antagonising ethylene signalling). Studies have shown that salicylic acid at high concentrations can destroy the redox balance in cells, trigger reactive oxygen species (ROS) bursts, attack cell membranes, and cause lipid peroxidation. Although appropriate salicylic acid can activate plant defence, it can become a 'source of pressure' at high concentrations, inhibiting melon seed germination and seedling growth (Khan et al. 2015).

In addition, it was found that low concentrations of SA (0.25–1.0 mmol/L) could reduce the MDA content of plants under salt stress conditions, which is consistent with the results reported by Liang et al. (2021) that SA treatment significantly reduced MDA content in alfalfa (*Medicago sativa* L.). MDA, as a marker of membrane lipid peroxidation, may reflect the difference between short-term stress and long-term adaptation in its content changes (Torun et al. 2022). Low concentration SA may temporarily induce ROS signalling but maintain oxidative homeostasis in the long term. However, high concentrations of SA directly damage the membrane system, leading to sustained accumulation of MDA. SA may upregulate the transcription of POD genes through the Non Expressor of PR Genes 1 (*NPR1*) dependent pathway (Zhang et al.2021). SA may enhance the accessibility of the POD promoter region and promote its expression through histone acetylation or DNA methylation modification.

The sample size of this study was relatively small (3 replicates per treatment), which may result in insufficient influence of the experimental results. In the future, we can conduct experiments in regional fields, and carry out multi-variety melon planting experiments in typical saline areas (such as the Yellow River Delta, coastal mudflat) to evaluate the actual yield increase effect of SA treatment. This study revealed the uniqueness and commonality of SA regulation of salt tolerance in sweet melons through systematic comparison, providing a new perspective for understanding the plant SA salt stress interaction. In the future, it is necessary to combine molecular mechanisms, multi-environmental interactions, and technological transformation research to promote the theoretical application of SA and provide solutions for the sustainable use of saline land in agriculture worldwide.

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