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Original Article

Concentration-Dependent Effects of Exogenous Salicylic Acid on Germination and Seedling Growth of Lallemantia royleana Landraces

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ABSTRACT

Lallemantia royleana (Balango) is a valuable medicinal plant whose seed germination and early seedling establishment strongly influence final yield. This study evaluated the germination and early growth responses of three Balango landraces (Isfahan, Mashhad, and Shiraz) to different concentrations of salicylic acid (SA: 0, 0.3, 0.6, and 0.9 mM). A factorial experiment was conducted in a completely randomized design with three replications. Analysis of variance revealed significant effects ($P \leq 0.01$) of landrace and SA concentration on all measured traits. Among the landraces, Isfahan showed superior performance, with the highest germination percentage (86.66%), number of normal seedlings (23.33), and radicle length (5.49 cm), along with the lowest number of non-germinated seeds (1.89). The response to SA varied depending on genotype and concentration. While increasing SA concentration generally reduced seedling growth traits such as shoot length and seedling dry weight, a moderate SA level (0.6 mM) enhanced germination in the Isfahan landrace, resulting in the highest germination percentage (94.66%). This stimulatory effect at moderate SA levels may be related to the role of salicylic acid in regulating antioxidant activity and hormonal signaling during early germination. However, higher concentrations (0.9 mM) negatively affected both germination and early growth, indicating potential phytotoxic effects. Overall, the Isfahan landrace demonstrated greater tolerance to SA and superior germination performance, whereas excessive SA concentrations were detrimental to early seedling development. Therefore, selecting the Isfahan landrace and avoiding high SA concentrations during germination is recommended.

Keywords: Balango, Salicylic acid, Germination, *Lallemantia royleana*, Seedling growth

INTRODUCTION

Seed germination and successful seedling establishment represent the most sensitive stages of the plant life cycle and play a decisive role in determining final crop productivity [1]. During these early developmental phases, seeds are particularly vulnerable to environmental stresses such as temperature fluctuations, salinity, and water deficit, which can reduce seed vigor and impair field establishment [2]. Consequently, the application of plant growth regulators has been widely investigated as an effective approach to enhance germination performance and improve early seedling growth under both optimal and stress conditions [3].

Salicylic acid (SA) is an endogenous phenolic phytohormone that plays an important regulatory role in plant growth, development, and stress responses. Numerous studies have demonstrated that SA can influence seed germination by modulating multiple physiological and biochemical pathways, including reactive oxygen species (ROS) signaling, antioxidant enzyme activity, and hormonal balance [4,5]. Moderate levels of ROS act as signaling molecules that promote the transition from seed dormancy to germination, whereas excessive ROS accumulation can cause oxidative damage to cellular components. SA has been shown to regulate this balance by enhancing antioxidant defenses such as catalase, peroxidase, and superoxide dismutase, thereby maintaining cellular redox homeostasis during germination [6,7]. In addition, SA interacts with key hormonal pathways that control dormancy and germination, particularly the balance between abscisic acid (ABA) and gibberellins (GA). While ABA generally maintains seed dormancy, GA promotes embryo growth and radicle emergence; SA can influence this ABA/GA equilibrium and thereby regulate germination responses depending on its concentration and the plant genotype [8,9]. Recent studies in various medicinal and aromatic plants have reported that low concentrations of SA can enhance germination percentage, seedling vigor, and stress tolerance, whereas higher concentrations may exert inhibitory or phytotoxic effects [10–12].

Balango (*Lallemantia royleana* Benth.), a medicinal plant belonging to the Lamiaceae family, has attracted increasing attention due to its nutritional and pharmaceutical properties. Its seeds are widely used in traditional medicine and contain valuable bioactive compounds, mucilage, and essential fatty acids [13]. Despite its economic and medicinal importance, information regarding the physiological responses of Balango seeds to plant growth regulators during germination is still limited. Moreover, different landraces may exhibit considerable variability in germination capacity and stress tolerance due to their genetic background and adaptation to local environments. Evaluating the response of different Balango landraces to SA application can therefore provide valuable insights into genotype-dependent physiological responses and help identify superior germplasm for cultivation. Hence, the present study aimed to investigate the effects of different concentrations of salicylic acid on germination characteristics and early seedling growth of three Balango (*Lallemantia royleana*) landraces.

Intraspecific genetic diversity allows for the selection of superior genotypes with higher seed vigor and growth potential [8]. Although many studies have examined SA effects on various plants, little information is available on the response of different Balango landraces to SA. Therefore, this study aimed to evaluate the germination and early growth responses of three Balango landraces to different SA concentrations, to identify superior landraces and optimal SA levels for improving field establishment.

MATERIALS AND METHODS

A factorial experiment was conducted in the Seed Technology Laboratory, Faculty of Agriculture, Shahed University, using a completely randomized design with three replications. The experimental factors consisted of three Balango (*Lallemantia royleana* Benth.) landraces (Shiraz, Mashhad, and Isfahan) and four concentrations of salicylic acid (SA) (0, 0.3, 0.6, and 0.9 mM).

Seeds were obtained from the medicinal plant collection of Shahed University and the Jihad Research Center. Prior to the experiment, seeds were stored in paper bags under dry and cool laboratory conditions (approximately 20–22 °C and 40–50% relative humidity) until use. To prevent fungal contamination, seeds were surface-sterilized with carboxin-thiram fungicide solution and then rinsed with distilled water.

For each treatment, twenty seeds were placed in 9 cm diameter Petri dishes lined with two layers of Whatman filter paper moistened with 5 mL of the respective SA solution. Petri dishes were incubated in a germination chamber at 30 °C under a 16 h light / 8 h dark photoperiod with approximately 60–70% relative humidity. The selected concentrations of salicylic acid (0.3–0.9 mM) were based on previous studies reporting stimulatory effects of low SA concentrations on seed germination and early seedling growth, whereas higher concentrations may have inhibitory effects.

Germination was recorded daily for seven days, and a seed was considered germinated when the radicle protrusion reached at least 3 mm. From each Petri dish, ten randomly selected seedlings were used to measure radicle length and shoot length using a ruler. Seedling dry weight was determined after oven-drying the samples at 70 °C for 48 h.

The following germination indices were calculated:

Mean germination time (MGT) = $\Sigma (N_i \times D_i) / \Sigma N_i$

Germination coefficient (GC) = $(\Sigma N_i / T) \times 100$

Variance of mean germination time (VMGT) = $\Sigma [N_i (D_i - MGT)^2] / (\Sigma N_i - 1)$

Uniformity of germination (UG) = 1 / VMGT

Seed vigor index (SV) = Germination percentage × Seedling length

where N_i is the number of seeds germinated on day i, D_i is the number of days from the beginning of the test, and T is the total duration of the germination test.

Data were analyzed using SAS software (version 9.1). Analysis of variance (ANOVA) was performed for the factorial experiment, and mean comparisons were conducted using Duncan's multiple range test at $P \leq 0.05$. Duncan's test was used because of its suitability for comparing treatment means in agricultural experiments involving multiple factor levels. Graphs were prepared using Microsoft Excel.

RESULTS AND DISCUTION

The analysis of variance showed that landrace, salicylic acid (SA) concentration, and their interaction had significant effects ($P \leq 0.01$) on all measured traits. These results indicate that the three *Balango landraces* differed in their response to exogenous SA application. The main effects of landrace and SA concentration on germination traits are summarized in Table 1. Among the landraces, Isfahan exhibited the highest germination percentage (86.66%), number of normal seedlings (23.33), and radicle length (5.49 cm), together with the lowest number of ungerminated seeds (1.89), indicating a superior intrinsic germination capacity under control conditions. In contrast, Shiraz and Mashhad showed lower values for these traits. Such differences among populations are consistent with previous reports of genetic variability within *Lallemantia* species and may reflect long-term adaptation to different environmental conditions.

Table 1 Main effects of population and SA concentration on germination parameters

Treatment	Germ.(%)	Nor. seedl.	Abn. seedl.	Root (cm)	Shoot (cm)	Fr. seedl. (g)	Dry seedl. (g)	Fr. shoot (g)	Ungerm. seeds
Shiraz (pop.)	77.63 c	21.963 b	2.555 a	4.693 b	8.154 a	1.258 a	0.023 a	0.041 a	3.037 a
Isfahan (pop.)	83.40 a	23.111 a	2.259 b	5.496 a	8.940 a	1.118 b	0.023 a	0.040 a	1.889 b
Mashhad (pop.)	80.59 b	22.185 b	2.037 b	5.347 a	8.282 a	1.072 b	0.022 a	0.038 a	2.814 a
0 mM SA	86.66 a	23.333 a	1.667 c	7.546 a	10.089 a	1.287 a	0.026 a	0.041 a	1.666 c
0.3 mM SA	76.00 c	21.444 c	2.444 b	5.035 b	9.217 b	1.190 b	0.022 b	0.043 a	3.555 a
0.6 mM SA	78.96 b	22.481 b	2.741 a	2.957 c	6.070 c	0.971 c	0.019 c	0.035 b	2.518 b
0.9 mM SA	78.96 b	22.481 b	2.741 a	2.957 c	6.070 c	0.971 c	0.019 c	0.035 b	2.518 b

Values are means. Different letters in each column indicate significant differences (Duncan's MRT, p≤0.05).

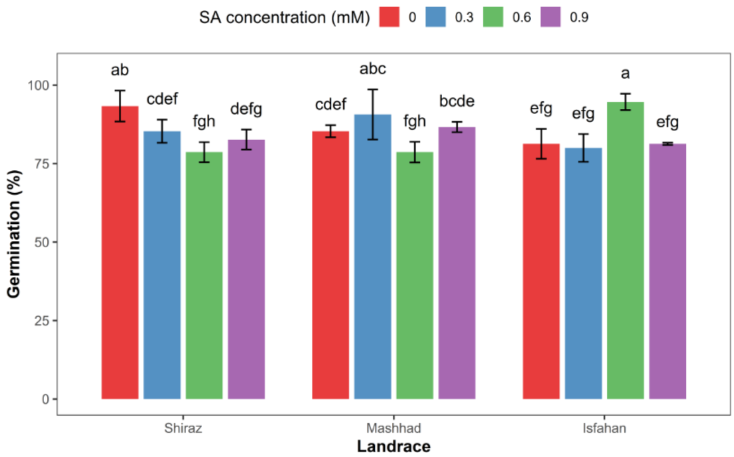

Fig. 1 Interaction effect of population and salicylic acid (SA) concentration on germination percentage (%) of Balangu. Means were compared using Duncan's multiple range test at the 5% probability level (α = 0.05). Different letters above the bars indicate significant differences among treatment combinations. Error bars represent ±1 standard error of the mean (based on three replications).

Germination percentage was significantly influenced by the interaction between landrace and SA concentration ($P < 0.01$; Fig. 1). In the Shiraz landrace, germination slightly increased at 0.3 mM SA compared with the control but declined at higher concentrations. Mashhad exhibited relatively stable germination across SA levels, suggesting a moderate tolerance to SA treatments. In contrast, the Isfahan landrace showed the highest germination percentage (94.66%) at 0.6 mM SA. However, despite this increase in germination, seedling growth traits such as shoot length and biomass were markedly reduced at the same concentration. This indicates that SA may stimulate the germination process while simultaneously limiting subsequent seedling development. Similar concentration-dependent responses have been reported in several plant species, where moderate levels of SA promote germination but excessive levels inhibit growth.

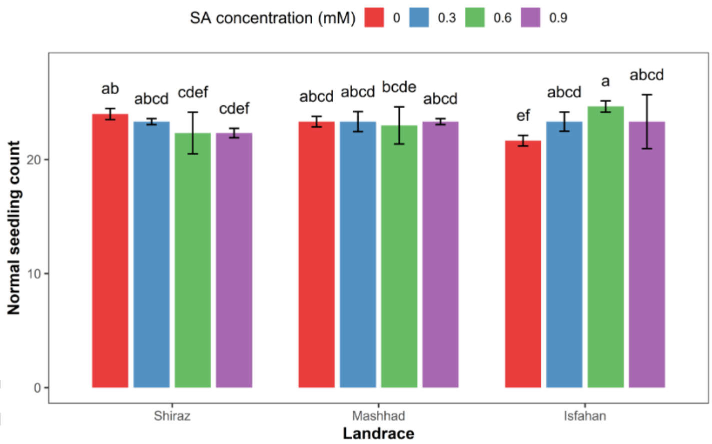

Fig. 2 Interaction effect of population and salicylic acid (SA) concentration on normal seedling count of Balangu. Means were compared using Duncan's multiple range test at the 5% probability level (α = 0.05). Different letters above the bars indicate significant differences among treatment combinations. Error bars represent ±1 standard error of the mean (based on three replications).

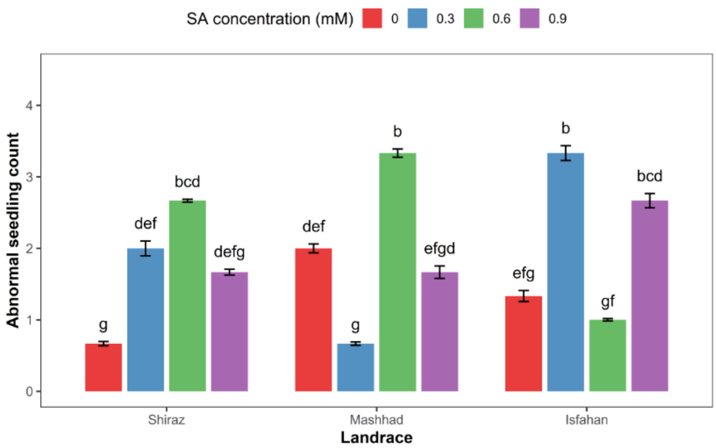

Fig. 3 Interaction effect of population and salicylic acid (SA) concentration on abnormal seedling count of Balangu. Means were compared using Duncan's multiple range test at the 5% probability level (α = 0.05). Different letters above the bars indicate significant differences among treatment combinations. Error bars represent ±1 standard error of the mean (based on three replications).

The number of normal seedlings followed a pattern similar to germination percentage (Fig. 2). Shiraz produced the highest number of normal seedlings at 0.3 mM SA, whereas Isfahan showed a decrease at higher concentrations. In addition, abnormal seedlings increased in Isfahan at 0.6 and 0.9 mM SA (Fig. 3), suggesting that elevated SA levels may interfere with normal seedling development. Although the present study did not include biochemical measurements, previous research suggests that high SA concentrations can alter hormonal balance or increase oxidative stress, which may affect seedling morphology and vigor.

Root length (Fig. 4) and shoot length (Fig. 5) were also significantly affected by the landrace × SA interaction. In Shiraz, root and shoot elongation were enhanced at 0.3 mM SA but declined at higher concentrations. Mashhad showed relatively stable growth with a slight increase at 0.6 mM SA. In contrast, both root and shoot length in the Isfahan landrace decreased progressively as SA concentration increased. This reduction in seedling growth suggests that higher SA levels may limit cell elongation and biomass accumulation.

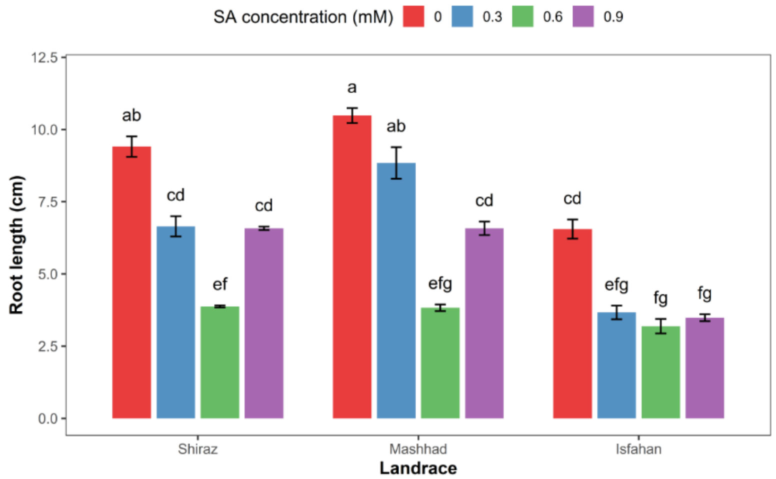

Fig. 4 Interaction effect of population and salicylic acid (SA) concentration on root length of Balangu seedlings. Means were compared using Duncan's multiple range test at the 5% probability level (α = 0.05). Different letters above the bars indicate significant differences among treatment combinations. Error bars represent ±1 standard error of the mean (based on three replications).

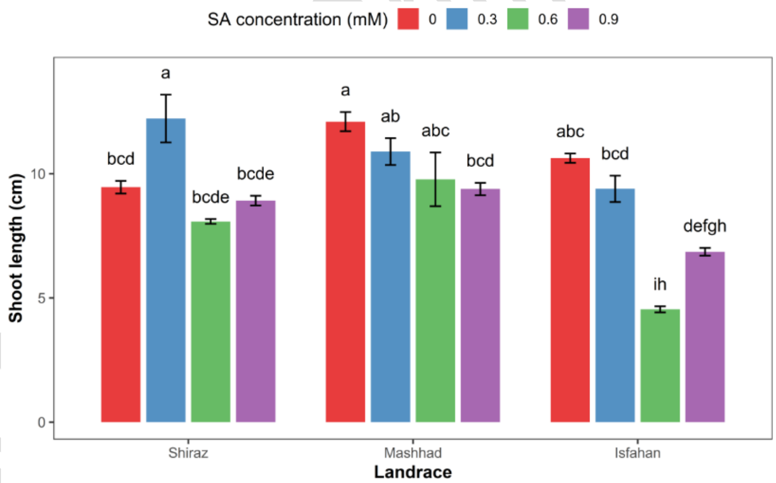

Fig. 5 Interaction effect of population and salicylic acid (SA) concentration on shoot length of Balangu seedlings. Means were compared using Duncan's multiple range test at the 5% probability level (α = 0.05). Different letters above the bars indicate significant differences among treatment combinations. Error bars represent ±1 standard error of the mean (based on three replications).

The number of ungerminated seeds (Fig. 6) generally showed an inverse relationship with germination percentage. Shiraz had the lowest number of ungerminated seeds at 0.3 mM SA, while Mashhad showed intermediate values. In Isfahan, the number of ungerminated seeds increased at 0.9 mM SA, which is consistent with the inhibitory effects observed at higher SA concentrations.

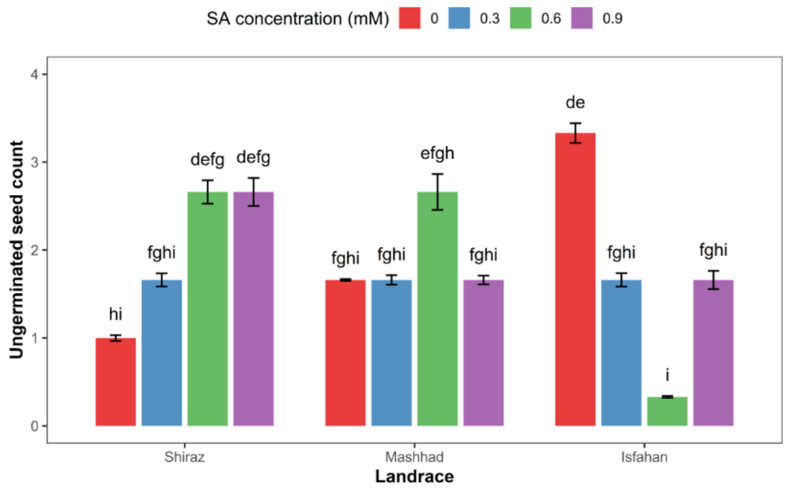

Fig. 6 Interaction effect of population and salicylic acid (SA) concentration on ungerminated seed count of Balangu. Means were compared using Duncan's multiple range test at the 5% probability level (α = 0.05). Different letters above the bars indicate significant differences among treatment combinations. Error bars represent ±1 standard error of the mean (based on three replications).

Fresh shoot weight (Fig. 7), fresh seedling weight (Fig. 8), and dry seedling weight (Fig. 9) generally decreased as SA concentration increased. While slight improvements were observed at low SA concentrations in some treatments, biomass production declined markedly at 0.6 and 0.9 mM SA, particularly in the Isfahan landrace. These results indicate that although certain SA levels may enhance germination, higher concentrations negatively affect early seedling growth.

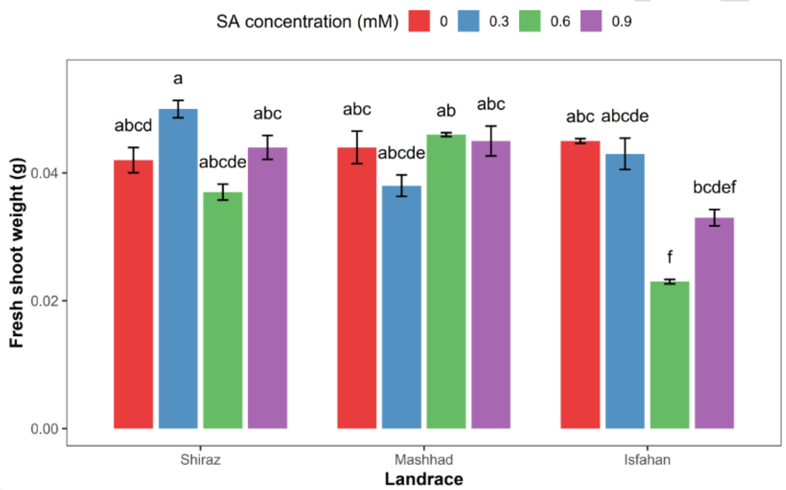

Fig. 7 Interaction effect of population and salicylic acid (SA) concentration on fresh shoot weight of Balangu seedlings. Means were compared using Duncan's multiple range test at the 5% probability level (α = 0.05). Different letters above the bars indicate significant differences among treatment combinations. Error bars represent ±1 standard error of the mean (based on three replications).

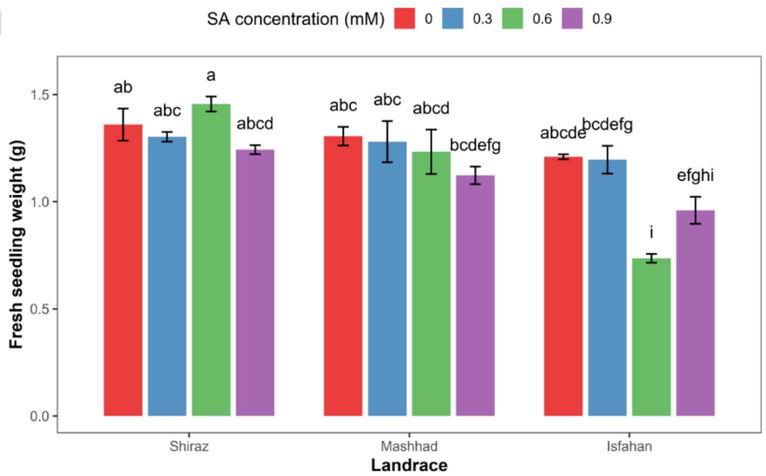

Fig. 8 Interaction effect of population and salicylic acid (SA) concentration on fresh seedling weight of Balangu. Means were compared using Duncan's multiple range test at the 5% probability level (α = 0.05). Different letters above the bars indicate significant differences among treatment combinations. Error bars represent ±1 standard error of the mean (based on three replications).

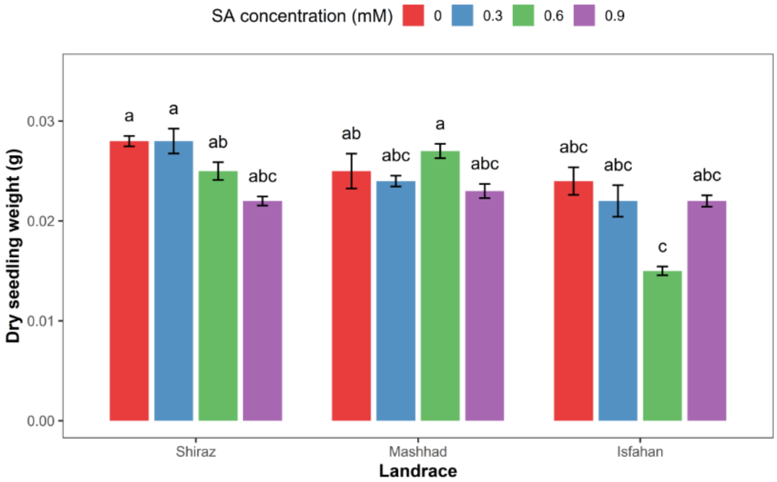

Fig. 9 Interaction effect of population and salicylic acid (SA) concentration on dry seedling weight of Balangu. Means were compared using Duncan's multiple range test at the 5% probability level (α = 0.05). Different letters above the bars indicate significant differences among treatment combinations. Error bars represent ±1 standard error of the mean (based on three replications).

A heatmap based on standardized germination values (Fig. 10) was used to visualize differences among treatments. The results indicated that the response to SA varied among landraces, confirming a genotype-dependent pattern. However, given the relatively small dataset, the heatmap should be interpreted primarily as a visual representation rather than a definitive clustering analysis.
The reduction in dry weight at elevated SA is likely due to decreased photosynthetic capacity, impaired nutrient uptake, or enhanced catabolism. In Isfahan, the dramatic decline in dry weight at 0.6- and 0.9-mM SA indicates that high SA imposes a metabolic cost that outweighs any benefit in germination. To visualize the complex interaction, a heatmap was constructed based on standardized germination percentage (Fig. 10). A clear genotype-dependent pattern emerged: Isfahan at 0.6 mM SA showed a distinct positive response (standardized value ≈ +0.1), indicating that this specific hormone concentration synergistically enhanced germination beyond the control level. Shiraz showed negative values (≈ −0.1) at several SA concentrations, particularly at 0.3 and 0.6 mM, reflecting consistent inhibition. Mashhad displayed near-zero responses across most SA levels, suggesting neutral behavior. This confirms that the effect of SA on Balango germination is highly population-specific and non-linear, with Isfahan being the only population that benefits (in germination terms) from moderate SA application, whereas Shiraz is consistently suppressed. PCA was performed to explore multivariate relationships among traits (Figs. 11-12). The first two principal components explained 81% of total variance (PC1: 51.2%, PC2: 29.9%). Germination percentage, root length, shoot length, fresh seedling weight, dry seedling weight, and fresh shoot weight were positively associated along PC1, indicating strong positive correlations among growth-related traits.

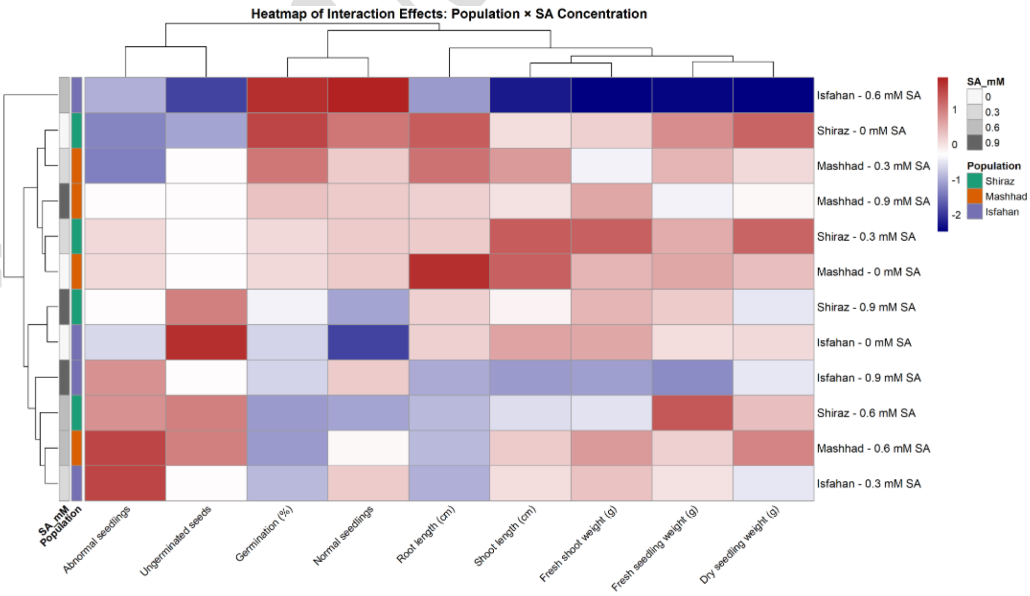

Fig. 10 Heatmap of standardized germination percentage of three Balango landraces (Isfahan, Mashhad, Shiraz) under different SA concentrations (0–0.9 mM). Red tones indicate positive deviation from control (enhanced germination), blue tones indicate negative deviation (inhibited germination), and light colors indicate neutral responses.

Principal component analysis (PCA) was performed to examine multivariate relationships among traits (Figs. 11–12). The first two principal components explained 81% of the total variation (PC1: 51.2%, PC2: 29.9%). Growth-related traits such as germination percentage, root length, shoot length, and seedling biomass were positively associated along PC1, indicating strong positive correlations among these variables. In contrast, abnormal seedlings and ungerminated seeds were positioned in the opposite direction, suggesting negative associations with seedling vigor. Treatment distribution in the PCA plot showed that higher SA concentrations tended to associate with reduced growth traits.

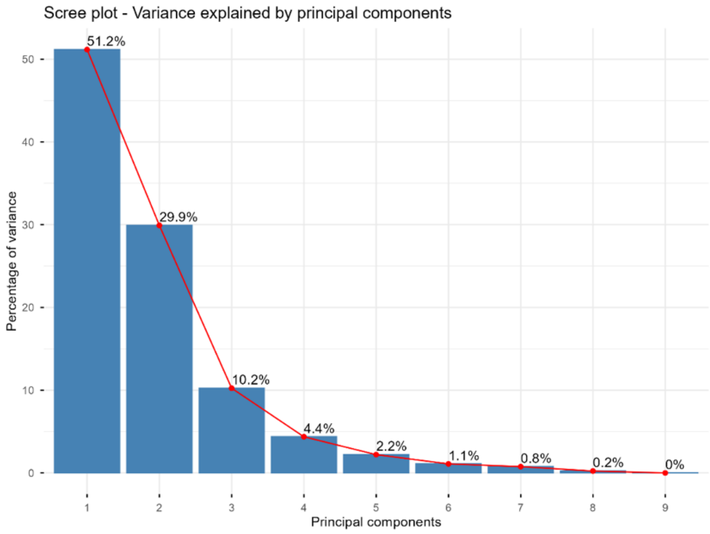

Fig. 11 Scree plot showing the percentage of variance explained by the principal components derived from germination and seedling growth traits of Balangu populations under different salicylic acid concentrations. The first two principal components (PC1 and PC2) explain 51.2% and 29.9% of the total variance, respectively, accounting for approximately 81% of the total variability in the dataset.

Overall, the results indicate that the response of Balango to salicylic acid is strongly dependent on both concentration and genotype. Under the non-stress conditions of this experiment, higher SA concentrations (≥0.6 mM) generally reduced seedling growth, even when germination percentage increased in certain cases. Therefore, the use of SA during germination should be carefully optimized. Future studies including biochemical measurements (e.g., antioxidant enzymes, ROS levels, and hormonal balance) would help clarify the physiological mechanisms underlying these responses.

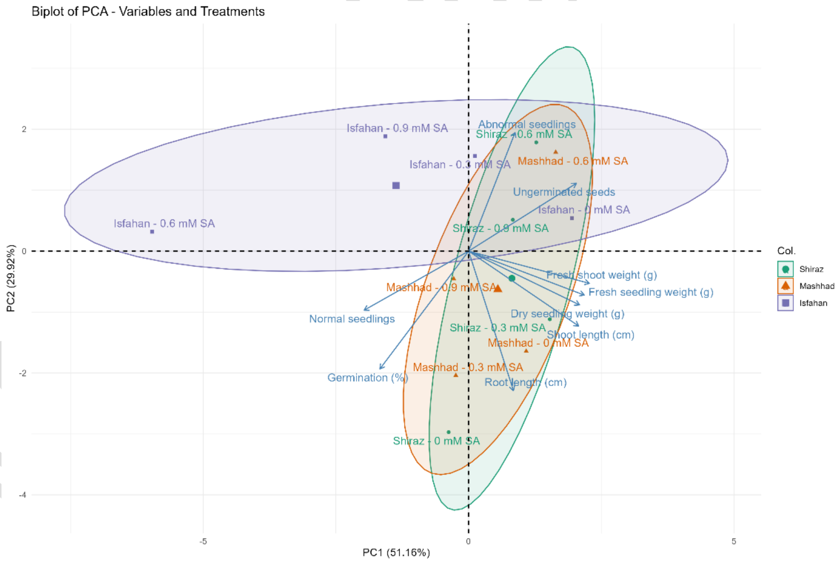

Fig. 12 PCA biplot showing the relationships among germination traits and the distribution of treatments (population × salicylic acid concentration). Arrows represent the direction and magnitude of trait contributions, while points indicate treatment combinations for the Shiraz, Mashhad, and Isfahan populations. Traits positioned in similar directions are positively correlated, whereas traits in opposite directions are negatively associated. The first two principal components explain 81% of the total variation.

This study demonstrated that the Isfahan landrace of *Lallemantia royleana* is intrinsically superior in terms of germination percentage, normal seedling production, and radicle length compared to Mashhad and Shiraz landraces. Exogenous salicylic acid (SA) had a concentration-dependent and predominantly inhibitory effect on early growth indices, with the highest germination (94.66%) observed in Isfahan at 0.6 mM SA, but this treatment severely reduced shoot length and seedlingThe results of this study demonstrate that the response of Balango (Lallemantia royleana) seeds to salicylic acid is strongly genotype-dependent. Significant differences were observed among the three landraces in both germination characteristics and seedling growth under different SA concentrations. The Isfahan landrace exhibited the highest germination potential under control conditions and showed a temporary increase in germination percentage at 0.6 mM SA; however, this improvement was accompanied by a reduction in seedling growth traits such as shoot length and biomass. In contrast, the Shiraz and Mashhad landraces showed relatively moderate or stable responses to low SA concentrations.

Overall, higher SA concentrations (≥0.6 mM) tended to reduce several seedling growth parameters under the controlled laboratory conditions of this experiment. Therefore, the application of relatively high SA levels during germination may not be beneficial for early seedling development in Balango. However, because this study was conducted only under laboratory conditions and did not include environmental stresses or field evaluation, these results should be interpreted with caution. The superior germination performance of the Isfahan landrace suggests that this genotype may possess higher intrinsic seed vigor, although further studies are needed to confirm its performance under field conditions and different environmental stresses. Future research should evaluate lower SA concentrations, alternative priming methods, and additional physiological measurements to better understand the mechanisms underlying genotype-specific responses to salicylic acid. biomass. High SA concentrations (0.6 and 0.9 mM) increased abnormal seedlings and ungerminated seeds, particularly in Isfahan. Therefore, for optimal early establishment of Balango under non-stress conditions, we recommend selecting the Isfahan landrace and avoiding SA application at concentrations ≥0.6 mM. If dormancy breaking is needed, low SA concentrations (≤0.3 mM) may be tested with caution, but the intrinsic superiority of Isfahan makes hormonal priming unnecessary. Further studies under field conditions and with lower SA doses are required to refine these recommendations.

Seed germination and early seedling establishment are among the most sensitive developmental stages in plants and are strongly influenced by genotype and exogenous regulators such as salicylic acid (SA). In the present study, both landrace and SA concentration significantly affected germination and early growth traits of *Lallemantia royleana*, and their interaction was significant for most variables. This genotype-dependent response is consistent with previous studies indicating that SA-mediated seed priming responses vary among plant species and cultivars due to genetic differences in hormonal sensitivity and metabolic regulation [1–3].

Among the tested landraces, Isfahan exhibited superior germination performance under control conditions, suggesting higher inherent seed vigor and better physiological quality. Genetic variability in germination traits is common in medicinal and aromatic plants and often reflects adaptation to environmental conditions of the original habitat [4,5]. Previous research has shown that landrace diversity can strongly influence germination percentage, seedling vigor, and tolerance to environmental stresses [6].

A major finding of the present study was the concentration-dependent response of Balango seeds to SA. Moderate concentrations improved germination, particularly in the Isfahan landrace, while higher concentrations reduced several seedling growth traits. Such biphasic responses to SA have been widely reported and reflect its dual physiological role as both a regulatory signaling molecule and a potential stress-inducing compound when applied at high concentrations [7–9]. Low concentrations of SA may stimulate metabolic activity during germination, whereas excessive levels may disrupt cellular homeostasis and inhibit growth.

Reactive oxygen species (ROS) are known to play a key signaling role during seed germination. Controlled ROS accumulation contributes to dormancy release, endosperm weakening, and embryo growth, while excessive ROS can cause oxidative damage to cellular structures [10,11]. Salicylic acid has been shown to regulate ROS metabolism by activating antioxidant defense systems such as catalase, peroxidase, and superoxide dismutase [8,12]. Through this mechanism, SA may help maintain redox balance during the early stages of germination.

Experimental evidence suggests that SA can enhance seed germination under abiotic stress conditions by modulating antioxidant activity and hormonal signaling pathways [13, 14]. For instance, SA seed priming improved germination and seedling growth in barley under salt stress by reducing ROS accumulation and enhancing antioxidant enzyme activity [14]. Similar positive effects of SA priming have been reported in wheat, tomato, and several medicinal plants [15–17]. Therefore, the improved germination observed at 0.6 mM SA in the Isfahan landrace may be associated with improved oxidative balance and metabolic activation during early seed imbibition.

However, increasing SA concentration to 0.9 mM significantly reduced seedling growth parameters such as shoot length and seedling dry weight. High SA concentrations may lead to phytotoxic effects, including inhibition of cell division and elongation, disruption of membrane integrity, and interference with metabolic pathways [7,8]. Previous studies have also reported growth inhibition at excessive SA concentrations in several crops, indicating that optimal concentration ranges must be carefully determined for each species and genotype [9,15].

Seed germination is also tightly regulated by the balance between abscisic acid (ABA), which maintains seed dormancy, and gibberellins (GA), which promote embryo growth and radicle emergence [18]. Salicylic acid has been reported to interact with these hormonal pathways and may indirectly influence germination by modifying ABA and GA signaling [13,18]. Although hormonal levels were not measured in the present study, the observed responses may partly reflect such hormonal interactions.

Another important observation was that treatments enhancing germination did not always promote subsequent seedling growth. Germination initiation and seedling development involve different physiological processes and metabolic demands [19]. While SA may accelerate early metabolic activation leading to radicle protrusion, excessive concentrations could limit subsequent biomass accumulation or elongation growth.

Evidence from other *Lallemantia* species also supports the responsiveness of this genus to salicylic acid treatments. Seed priming with SA has been reported to enhance germination and seedling growth of *Lallemantia iberica* under drought stress conditions [20]. Similarly, positive effects of SA on germination characteristics and seedling vigor have been reported in Balango (*Lallemantia royleana*) under salinity stress [6]. These findings suggest that SA-mediated priming could be a useful strategy for improving germination and establishment of medicinal plants belonging to the Lamiaceae family.

Overall, the results of the present study indicate that salicylic acid influences Balango germination and early seedling growth in a concentration-dependent and genotype-specific manner. Moderate SA levels can enhance germination performance, particularly in the Isfahan landrace, while higher concentrations may inhibit seedling development. These findings highlight the importance of optimizing SA concentration and considering genetic variability among landraces when applying hormonal priming techniques to medicinal plant production systems.

CONCLUSION

The Isfahan landrace achieved maximum germination (94.66%) at 0.6 mM SA, yet this same concentration reduced root length by 61% (from 7.55 to 2.96 cm) and dry weight by 27% compared to controls. PCA revealed that 81% of trait variability was explained by growth-related parameters, confirming that SA's effects are genotype-dependent and concentration-critical. The 0.3 mM SA optimally balanced germination enhancement with growth maintenance, while higher concentrations imposed metabolic costs that diminished seedling vigor. These findings underscore the necessity of population-specific SA optimization for Balangu cultivation.

Conflict of Interests

All authors declare no conflict of interest.

Ethics approval and consent to participate

No human or animals were used in the present research.

Ethical issues

Ethical issues (including plagiarism, data fabrication, double publication) have been completely observed by the authors.

Consent for publication

All authors read and approved the final manuscript for publication.

Availability of data and material

All the data are embedded in the manuscript.

Authors' contributions

Conceptualization: S.M.R.S.
Data curation: H. O.
Formal analysis: M.M.M.
Investigation: D.R.N.
Methodology: A.S.S.
Project administration: S.M.R.S.
Resources: S.M.R.S.
Supervision: B. F-N.
Validation: A.S.S.
Visualization: S.M.R.S.
Writing–original draft: A.S.S., B. F-N.
Writing–reviewing & editing: All authors.

Informed Consent

The authors declare not used any patients in this research.

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