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Effect of boron priming on germination traits of shallot (*Allium ascalonicum* L.)

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Abstract: Shallot (*Allium ascalonicum* L.) is a vital horticultural commodity in Indonesia, valued for its culinary and medicinal properties. Seed priming, especially with boron (B), represents a promising approach to enhance germination performance. This study investigated the effects of various boron concentrations on the germination performance of shallot seeds. The experiment was conducted under screen house conditions at the Faculty of Agriculture, Hasanuddin University, in May 2024, using a randomized block design with 11 boron concentrations (0-100 mg L^{-1}) and three replications. Priming with 100 mg L^{-1} resulted in the best performance across several germination parameters, including as germination percentage (GP), germination speed index (GSI), the time required for 10% of seeds to germinate (T10), the time required for 50% of seeds to germinate (T50), mean germination time (MGT), mean germination rate (MGR), and germination speed coefficient (GSC). Regression analysis showed a strong positive linear relationship between boron concentration and both final germination percentage (r^2 = 0.84) and germination speed index (r^2 = 0.76). These findings suggest that boron priming, especially at 100 mg L^{-1}, significantly enhances germination performance of shallot seeds and may as an effective method for improving seedling vigor.

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1. Introduction

Shallot (*Allium ascalonicum* L.) is a horticultural commodity extensively cultivated by farmers across various regions in Indonesia. In addition to its widespread use as a culinary spice, shallots contain numerous bioactive compounds with potential medicinal properties, such as quercetin, flavonoids, saponins, tannins, glycosides, polyphenols, and alkaloids (Devika *et al*., 2021). The ongoing development of shallot cultivation is driven by its various advantages, including meeting national consumption needs, providing a source of income for farmers, and its potential to contribute to foreign exchange earnings. These attributes position shallots as a strategically important commodity with high economic value.

Shallot production in Indonesia reached 1,985,233 tons in 2023, an increase from 1,982,360 tons in 2022 but a decrease from 2,004,590 tons in 2021 (Central Bureau of Statistics of Indonesia, 2024). Shallot production still experiences fluctuations, often resulting in imbalances between supply and demand in the market. National demand for shallot has been increasing at a rate of approximately 5.0-6.67% annually (Shrestha *et al*., 2019). Therefore, efforts to boost production must continue, including improving the quality of planting materials by transitioning to true shallot seed (TSS). However, challenges are often encountered during the seedling process when cultivating shallots from TSS. The nursery process, which typically lasts 30-45 days before planting, extends the time required for crop production and delays harvest (Nciizah *et al*., 2020). Additionally, shallot seeds are highly susceptible to losings viability due to various factors during storage, leading to reduced germination ability and speed (Simatupang and Pangaribuan, 2022). Germination is a crucial stage in the plant life cycle that determines the success of subsequent growth stages (Atabakia *et al*., 2022).

Seed priming is an effective method for producing high-quality seedlings (Tanjung *et al*., 2021). This technique can improve initial seed germination and seedling growth (Shimizu *et al*., 2023), accelerate germination, and enhance germination performance even under extreme environmental conditions and poor soils (Chookhampa *et al*., 2023). Several factors influence seed priming, including water potential, priming agents, duration, temperature, seed vigor, and storage conditions (Farooq *et al*., 2011; Faisal *et al*., 2023). Among these, the choice of priming agent is crucial for the success of seed priming. Micronutrients, such as boron (B) can be used as priming agents to enhance plant productivity and quality (Mansouri *et al*., 2022). Boron priming enhances seed vigor and promotes better growth and seedling development compared to untreated seeds (Chakraborty and Dwivedi, 2022). As a priming agent, boron contributes to improving and stabilizing cell wall structure and has a positive impact on reducing disease severity (Pangestuti *et al*., 2021).

Research by Rehman *et al.* (2022) reported that seed priming with 0.01% boron significantly accelerated seedling emergence and the time to reach 50% seedling emergence, improved germination index, leaf number, fresh and dry root weight, chlorophyll content, various yield parameters, and increased carbohydrate, protein, and fiber content in mung bean plants (*Vigna radiata* L.). Research by Nciizah *et al*. (2020) also revealed that seed priming with 0.01% boron reduced the number of days to seedling emergence by 94% and increased seedling fresh and dry weight, as well as the chlorophyll index by 29%, 47%, and 58%, respectively, compared to the control in maize plants (*Zea mays* L.). Mansouri *et al*. (2022) found that seed priming with boron enhanced chlorophyll and carotenoid pigment content and increased the levels of enzymatic and non-enzymatic antioxidants such as anthocyanin, superoxide dismutase, and peroxidase in wheat seeds. Based on the above reviews, this study aims to determine the effect of different boron concentrations as a priming agent on the germination performance of shallot seeds.

2. Materials and Methods

Research location and experimental design

This research was conducted under screen house conditions at the Experimental Farm of the Faculty of Agriculture, Hasanuddin University, in May 2024. The study was designed as a randomized block experiment with a single treatment factor. The treatment factor was boron concentration, which included 11 levels: 0, 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 mg L^{-1}. Each treatment level was replicated three times, resulting in a total of 33 experimental units.

Priming and germination assay

The seed variety used in this study was ‘Maserati’.

The seeds were primed with a boron solution following the specified treatment protocols. They were then placed in plastic jars containing the solution at a seed-to-solution ratio of 1:5, with an aerator added to ensure an adequate oxygen supply. The priming process lasted for 20 hours at room temperature (Ghassemi-Golezani *et al*., 2010; Farahzety *et al*., 02023; Katriani *et al.*, 2023; Faried *et al*., 2024). Afterward, the seeds were removed and air-dried at room temperature for 48 hours before further use.

Germination was evaluated using a soil and compost growth medium in a 1:1 (v/v) ratio. The medium was thoroughly mixed and placed into transparent plastic boxes with drainage holes at the bottom. Each plastic box had a volume of 500 cm³ and was filled with 500 g of the growth medium. The primed seeds were then planted by creating furrows 1 cm deep. Each plastic box contained 50 shallot seeds. After sowing, the seeds were lightly irrigated twice daily (morning and evening) with approximately 30 mL of water per application to maintain adequate soil moisture under the warm ambient conditions of the experiment. Watering volumes were carefully controlled to prevent waterlogging while providing optimal conditions for germination. The seedling emergence was observed daily until day 14.

Data collection and analysis

The parameters evaluated in this study included final germination percentage (FGP) (%), germination speed index (GSI), the time required for 10% of seeds to germinate (T10) (d), the time required for 50% of seeds to germinate (T50) (d), mean germination time (MGT) (d), mean germination rate (MGR), variance of germination time (VGT), coefficient of variation of germination time (CVGT), germination synchrony (GS), and germination speed coefficient (GSC) (Table 1). These ten parameters were calculated using observational data on the number of seeds germinating daily. Seeds were considered to have germinated when the plumule emerged above the surface of soil.

An analysis of variance (ANOVA) was conducted to test significant differences among treatments. When significant effects were found, Duncan's Multiple Range test was applied to separate means. Additionally, regression analysis was conducted to assess the relationship between boron concentration and the germination parameters. Calculations for the parameters were performed using the Seedcalc package, while data analysis and visualization were conducted using the ggplot2 and AgroR packages in RStudio version 4.2.1 (Wickham, 2016; Shimizu *et al*., 2023; R Core Team, 2024).

3. Results

Germination parameters

The germination parameters of shallot seeds exhibited a significant response to increasing boron concentrations (Table 2 and Table 3). The FGP rose from 80.67% at 0 mg L^{-1} to 96.00% at 100 mg L^{-1}, reflecting a 15.33% increase, which highlights boron's positive influence on germination efficiency. Similarly, GSI improved by 63.79%, from 6.96 to 11.40, indicating enhanced metabolic activity. T10 decreased from 4.03 days to 2.40 days, showing a 40.45% reduction, while T50 decreased by 33.39%, from 6.08 days to 4.05 days. MGT also improved, dropping by 28.25% from 6.30 days to 4.52 days, reflecting faster and more uniform germination under higher boron concentrations.

The application of boron significantly influenced several germination parameters of shallot seeds. MGR and GSC increased significantly with higher boron concentrations, with the highest values observed at 100 mg L^{-1}, indicating faster germination compared to the control. Although VGT and GS were not significantly affected ($p > 0.05$), lower VGT values at 20, 50, 80, and 100 mg L^{-1} suggest more uniform germination, while GS tended to improve at 20, 50, and 80 mg L^{-1}. The CVGT was significantly reduced at 20 and 50 mg L^{-1}, reflecting more consistent germination timing. Overall, boron concentrations between 50 and 100 mg L^{-1} were most effective in enhancing germination performance by improving speed, rate, and uniformity.

Regression analysis

The impact of boron concentration on various germination parameters of shallot seeds is depicted in the series of linear regression analyses (Table 4, Fig. 1). The analysis demonstrates that boron application significantly enhances several key germination parameters. For instance, FGP shows a strong positive correlation with boron concentration ($R^2 = 0.84$), indicating that higher boron levels lead to a substantial increase in germination efficiency. This suggests that boron plays a vital role in breaking seed dormancy and supporting metabolic processes essential for successful germination.

Similarly, the GSI exhibited a positive trend (R^2 =

Table 1 - Overview of the measured parameters related to seed germination

No	Parameters	Formula
1	Final germination percentage (FGP)	FGP = (n/N) x 100 n is the number of seeds germinated, and N is the total number of seed.
2	Germination Speed Index (GSI)	GSI = $\sum_{i=1}^{n}(\frac{ni}{ti})$ n is the number of seeds germinated on each day of daily counting up to the last count, and t is the number of days after the beginning of the test in each count.
3	T10 Germination (T10)	Days at which 10% cumulative germination is reached.
4	T50 Germination (T50)	T50 = $\frac{ti+\left\{\left[\frac{\frac{N}{100}}{10}-ni\right]\right\}(tj-ti)}{(nj-ni)}$ N is the final number of seeds germinated, and n_i and n_j are the total number of seeds germinated in adjacent counts in time t_i and t_j, respectively, when $n_i < \frac{N+1}{2} < n_j$
5	Mean Germination Time (MGT)	MGT = $\sum_{i=1}^{k}(\mathrm{niti}) / \sum_{i=1}^{k}\mathrm{ni}$ n_i is the number of seeds germinated per day (not the accumulated number, but the number corresponding to the i-th observation), and t_i is the time since the beginning of the germination test up to the i-th observation.
6	Mean Germination Rate (MGR)	MGR = CoVg / 100 = 1/t t is the mean germination time, and CoVg is the germination speed coefficient.
7	Variance of Germination Time (VGT)	$VGT = \sum_{i=1}^{k} ni\ (ti-t)^2 / (\sum_{i=1}^{k} ni - 1)$ t is the mean germination time, t_i is the time between the beginning of the experiment and the i-th observation (day or hour), n_i is the number of seeds germinated in time i, and k is the last count of the germination test.
8	Coefficient of Variation of Germination Time (CVGT)	CVGT= (S_t / t) 100 S_t is standard deviation of the germination time, and t is mean germination time.
9	Germination Synchrony (GS)	Sinc = ∑*Cni*, 2 / N Cni, 2 = ni (ni – 1) / 2 N = ∑*ni* (∑*ni* -1) / 2 Cni is the combination of the seeds germinated in time i, two by two, and ni is the number of seeds germinated in time i.
10	Germination Speed Coefficient (GSC)	CVG = ($\sum_{i=1}^{k} fi / \sum_{i=1}^{k} fi\,xi$) 100 f_i is the number of newly germinated seeds on day i, and x_i is the number of days from sowing.

0.76), indicating that higher boron concentrations accelerated germination rate. The reductions in T10 (R^2 = 0.43) and T50 (R^2 = 0.47) further supported this, as boron shortened the time needed to reach early and intermediate germination stages. MGT showed a negative correlation (R^2 = 0.45), reflecting a decrease

Table 2 - Germination performance parameters of shallot seeds under different boron concentrations

Boron concentration (mg L^{-1})	Final germination percentage (%) ^{x}	Germination speed index ^{x}	Gemination time T10 (d) ^{x}	Gemination time T50 (d) ^{x}	Mean germination time (d) ^{x}
0	80.67 d	7.26 de	3.52 bc	5.19 bc	5.92 ab
10	82.00 d	7.42 de	3.39 bcd	5.57 ab	5.86 abc
20	82.00 d	8.10 d	3.34 bcd	4.94 bcd	5.22 bcdef
30	82.00 d	6.96 e	3.66 ab	6.08 a	6.3 0a
40	82.00 d	8.10 d	3.18 cde	4.67 cde	5.36 bcde
50	86.00 c	7.95 de	4.03 a	5.00 bcd	5.5 9bcd
60	88.67 c	9.65 bc	2.84 efg	4.34 de	4.89 def
70	88.67 c	9.40 c	2.82 efg	4.23 de	5.21 bcdef
80	92.67 b	10.52 ab	2.67 fg	4.23 de	4.65 ef
90	95.33 a	9.99 bc	2.95 def	4.41 cde	5.14 cdef
100	96.00 a	11.40 a	2.40 g	4.05 e	4.52 f
p-value	<0.01	<0.01	<0.01	<0.01	<0.01

(x) Different letters within the same column indicate statistically significant differences according to Duncan's Multiple Range Test.

Table 3 - Metabolic and synchronization parameters of shallot seed germination under different boron concentrations

Boron concentration (mg L^{-1})	Mean germination rate (x)	Variance of germination time	Coefficient of variation of germination	Germination synchrony	Germination speed coefficient (x)
0	0.169 de	2.38	25.04 bc	0.24	16.95 de
10	0.170 de	2.11	24.73 bc	0.25	17.05 de
20	0.191 bcd	0.87	17.91 c	0.34	19.12 bcd
30	0.158 e	2.57	25.31 bc	0.22	15.88 e
40	0.187 cd	2.09	24.81 bc	0.25	18.79 cd
50	0.179 cde	1.04	17.42 c	0.39	17.98 cde
60	0.204 abc	1.74	26.31 abc	0.30	20.48 abc
70	0.192 bcd	3.05	32.00 ab	0.24	19.26 bcd
80	0.215 ab	1.06	22.27 bc	0.33	21.59 ab
90	0.194 bcd	4.07	36.78 a	0.29	19.48 bcd
100	0.220 a	1.64	27.81 abc	0.28	22.08 a
p-value	<0.01	>0.05	<0.01	>0.05	<0.01

(x) Different letters within the same column indicate statistically significant differences according to Duncan's Multiple Range Test.

in total seedling emergence time, while MGR increased (R^2 = 0.47), highlighting improved metabolic efficiency and faster development. In contrast, VGT (R^2 = 0.01), CVGT (R^2 = 0.12), and GS (R^2 = 0.03) all revealed weak or negligible correlations, suggesting that boron had limited effects on uniformity, consistency, and synchronization of germination.

Conversely, GSC demonstrated a moderate positive correlation (R^2 = 0.47), emphasizing boron's role in enhancing the speed of germination completion. Overall, these findings suggested that boron effectively improved germination performance, particularly in terms of percentage and speed, while having minimal impact on uniformity and synchronization.

Correlation analysis

The correlation matrix illustrates the relationships between different germination parameters of shallot seeds under varying boron concentrations. GP showed a strong positive correlation with GSI (r =

Table 4 - Regression analysis of parameters

No.	Paramaters	Equation	R^2
1	Final germination percentage (%)	Y = 78.6 + 0.165	0.84
2	Germination speed index	Y = 6.77 + 0.040	0.76
3	Time to 10% seed germinated	Y = 3.69 + 0.010	0.43
4	Time to 50% seed germinated	Y = 5.55 - 0.015	0.47
5	Mean germination time	Y = 5.99 – 0.013	0.45
6	Mean germination rate	Y = 0.166 + 0.000466	0.47
7	Variance of germination time	Y = 1.82 + 0.00482	0.01
8	Coefficient of variation of germination time	Y = 21.4 + 0.0819	0.12
9	Germination synchrony	Y = 0.27 + 0.000365	0.03
10	Germination speed coefficient	Y = 16.6 + 0.0466	0.47

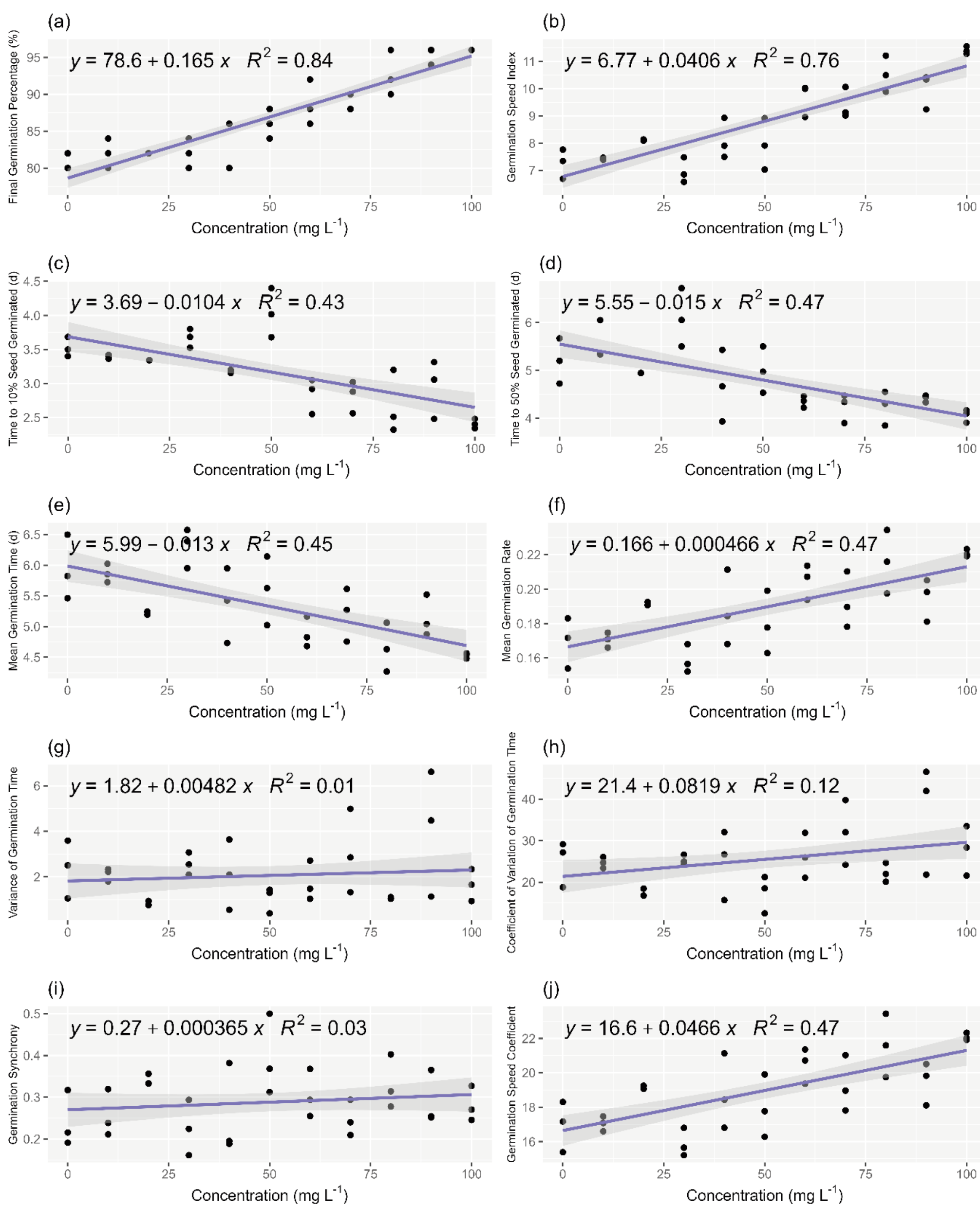

Fig. 1 - Regression analysis of each germination trait to boron concentration.

0.90), suggesting that higher germination percentages are associated with faster germination rates. However, GP negatively correlates with T10 (r = -0.64), T50 (r = -0.69), and MGT (r = -0.71), indicating that increased boron concentration reduces the time needed for germination (Fig. 2).

GSI also exhibited significant positive correlations with MGR (r = 0.93) and VGT) (r = 0.93), showing that faster germination is linked to higher consistency in seed performance. Conversely, GSI has a strong negative correlation with MGT (r = -0.91), emphasizing that a higher speed index leads to shorter germination times. T10, T50, and MGT parameters displayed high intercorrelations, with T10 and T50 showing r = 0.78 and T50 and MGT showing r = 0.87. Parameters related to uniformity, such as VGT and GS, showed weaker and mostly non-significant correlations with the other considered parameters.

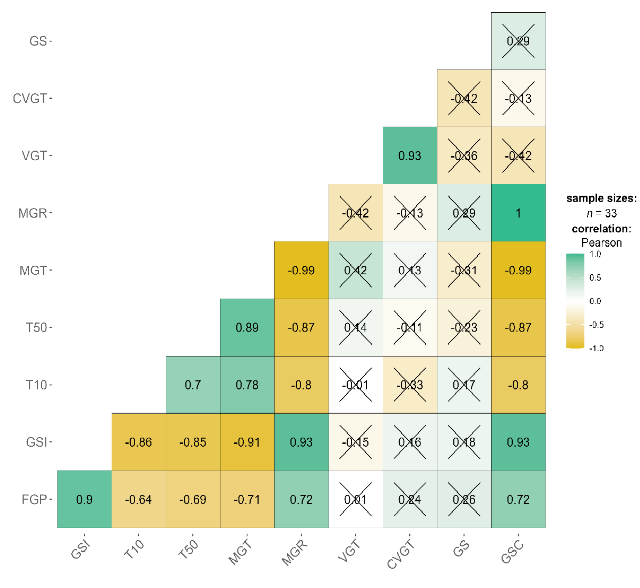

Fig. 2 - Correlation analysis among parameters.

4. Discussion and Conclusions

Seed priming is a crucial technique in agriculture aimed at enhancing seed germination and seedling establishment under various stress conditions. By promoting pre-germination metabolic activity through controlled hydration and drying, seed priming can significantly improve germination rates and seedling vigor, helping plants to overcome abiotic stresses such as salinity and drought (Chatterjee *et al*., 2018; Hameed *et al*., 2025; MacDonald and Mohan, 2025). The positive impacts of seed priming are not limited to increasing germination and vigor, but also extend to improving crop yields and quality, making it an essential practice for sustainable agriculture (Gour *et al*., 2023; Jarrar *et al*., 2024; Zhang *et al*., 2025).

The significant improvement in shallot seed germination parameters in response to increasing boron concentrations highlights boron's essential role in seed physiology. The germination percentage increased by 15.33%, from 80.67% at 0 mg L^{-1} to 96.00% at 100 mg L^{-1}, demonstrating boron's positive impact on germination efficiency. This improvement is likely due to biochemical and physiological changes induced by priming, which enhance water uptake, activate metabolic pathways, and initiate early growth processes. Bajwa *et al.* (2018) similarly found that priming wheat seeds increased alpha-amylase activity, facilitating carbohydrate breakdown and providing energy for embryo development. A comparable enzymatic activation may contribute to the enhanced germination observed in shallot seeds.

Boron also accelerated germination times, as indicated by the 40.45% reduction in time to 10% germination, a 33.39% decrease in time to 50% germination, and a 28.25% reduction in mean germination time. The shortest durations were recorded at 2.40 days (T10), 4.05 days (T50), and 4.52 days (MGT), all significantly lower than the control. These findings align with previous research by Rehman *et al*. (2022), which demonstrated that boron priming accelerates the germination process. However, it is important to consider that at certain concentrations, boron can become toxic to plants (Hussain *et al*., 2011; Atique-ur-Rehman *et al*., 2020).

Additionally, boron priming enhanced the germination speed index. At 100 mg L^{-1}, the highest GSI (11.40) was recorded, whereas the control treatment had the lowest value (6.96). This suggests that boron plays a crucial role in expediting germination, likely due to its involvement in cell wall formation, membrane integrity, and metabolic regulation. Similar results were reported by Farooq *et al.* (2011), who found that boron priming significantly increased the germination index of rice seeds. Kaya and Ergin (2023), in a study conducted on *Carthamus tinctorius* seeds, also observed a linear increase in germination index with higher boron concentrations, reinforcing boron's beneficial effects on seed germination.

Interestingly, the coefficient variation of germination time increased by 105.46%, reflecting improved synchronization of the germination process. This suggests that boron not only accelerates germination but also promotes more uniform seedling establishment. However, the lack of significant differences in germination synchrony and the stability of the germination speed coefficient indicate that boron's impact is more pronounced in accelerating germination rather than reducing variability. Chookhampa *et al.* (2023) also reported that seed priming on *Andrographis paniculata*, *Sesamum indicum*, and *Abelmoschus esculentus* improves the germination performance, leading to more synchronized germination. The limited effect of boron on germination uniformity may be influenced by inherent genetic factors and environmental conditions.

Beyond improving germination rates and speed, priming has also been linked to enhanced seedling vigor and quality (Biradar *et al*., 2023; Faried *et al*., 2023). Overall, this study demonstrates that increasing boron concentrations positively influence germination percentage, speed index, and synchronization, while also accelerating the overall germination process. These findings underscore boron's potential as a seed priming agent to enhance germination efficiency and metabolic activity in shallot seeds. However, the effects observed are indeed influenced by multiple factors. The success of seed priming depends on the choice of priming agent, its concentration, the duration of priming, and the specific response of the plant species or variety (Siyar *et al.*, 2020; Corbineau *et al*., 2023; Fu *et al*., 2024; Jarrar *et al*., 2024). Moreover, priming cannot overcome issues arising from genetic factors; seeds lacking in genetic purity, will result in poorly growing plants (Reed *et al*., 2022).

Priming with 100 mg L^{-1} produced the most favorable outcomes on several germination parameters, such as final germination percentage, germination speed index, time required for 10% of seeds to germinate, time required for 50% of seeds to germinate, mean germination time, mean germination rate, and germination speed coefficient. Regression analysis showed a strong positive linear relationship between boron concentration and final germination percentage ($r^2 = 0.84$) as well as germination speed index ($r^2 = 0.76$). The study concludes that boron priming, particularly at 100 mg L^{-1}, significantly improves germination performance in shallot seeds, highlighting its potential to enhance seedling vigor and productivity. The results of this research offer valuable insights for both shallot researchers and farmers.

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