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# Osmopriming mitigates the adverse effects of water deficit on seed germination of *Mimosa caesalpiniifolia* Benth.

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**ABSTRACT:** Water deficit is a major constraint to seed germination and plant establishment, particularly in semi-arid environments. Seed priming has emerged as a promising strategy to improve seed performance under adverse water conditions. This study evaluated the effects of osmopriming on the germination of *Mimosa caesalpiniifolia* Benth. seeds subjected to different water potentials. The experiment was conducted in a completely randomized design using a 3 × 5 factorial scheme, consisting of three priming treatments (unprimed seeds, PEG-6000 at -1.0 MPa, and $KNO_3$ at 100 mM) and five water potentials (0.0, -0.5, -1.0, -1.5, and -2.0 MPa), with four replicates of 25 seeds. Germination percentage, germination speed index, and mean germination time were evaluated. Water deficit progressively reduced germination percentage and germination speed while increasing mean germination time. Osmopriming partially attenuated these effects, particularly under moderate water deficit. At -1.0 MPa, PEG-6000 and $KNO_3$ maintained higher germination percentages, while PEG-6000 promoted greater germination speed and reduced mean germination time. However, under severe water deficit (-1.5 and -2.0 MPa), the protective effects of priming were substantially reduced. These findings indicate that osmopriming, particularly with PEG-6000, can improve the germination performance of *M. caesalpiniifolia* under moderate water limitation.
**Palavras-chave:** seed germination, osmotic stress, seed conditioning.

## Osmocondicionamento mitiga os efeitos adversos do deficit hídrico na germinação de sementes de *Mimosa caesalpiniifolia* Benth.

**RESUMO:** O déficit hídrico é uma importante limitação para a germinação de sementes e o estabelecimento de plantas, particularmente em ambientes semiáridos. O condicionamento osmótico (osmopriming) surgiu como uma estratégia promissora para melhorar o desempenho de sementes sob condições hídricas adversas. Este estudo avaliou os efeitos do condicionamento osmótico na germinação de sementes de Mimosa caesalpiniifolia Benth. submetidas a diferentes potenciais hídricos. O experimento foi conduzido em delineamento inteiramente casualizado, utilizando um esquema fatorial 3 × 5, composto por três tratamentos de condicionamento (sementes sem condicionamento, PEG-6000 a −1,0 MPa e $KNO_3$ a 100 mM) e cinco potenciais hídricos (0,0; -0,5; -1,0; -1,5 e -2,0 MPa), com quatro repetições de 25 sementes. Foram avaliados a porcentagem de germinação, o índice de velocidade de germinação e o tempo médio de germinação. O déficit hídrico reduziu progressivamente a porcentagem e a velocidade de germinação, ao mesmo tempo em que aumentou o tempo médio de germinação. O condicionamento osmótico atenuou parcialmente esses efeitos, especialmente sob déficit hídrico moderado. No potencial de -1,0 MPa, o PEG-6000 e o $KNO_3$ mantiveram maiores porcentagens de germinação, enquanto o PEG-6000 promoveu maior velocidade de germinação e reduziu o tempo médio de germinação. No entanto, sob déficit hídrico severo (-1,5 e -2,0 MPa), os efeitos protetores do condicionamento foram substancialmente reduzidos. Esses resultados indicam que o condicionamento osmótico, particularmente com PEG-6000, pode melhorar o desempenho germinativo de M. caesalpiniifolia sob limitação hídrica moderada.
**Keywords:** germinação de sementes, estresse osmótico, condicionamento osmótico.

## INTRODUCTION

Global climate change, together with the increasing demand for resilient and sustainable agricultural systems, has intensified concerns regarding the impacts of water limitation on plant production. In this context, developing strategies that enhance plant tolerance to water deficit has become a priority for ensuring food security and agricultural sustainability (Arzani, Ashraf, 2016; Saha et al., 2016).

Reduced water availability triggers a range of adaptive responses involving morphological, physiological, biochemical, and molecular adjustments that enable plants to mitigate stress effects and maintain survival under adverse conditions.

Plants are sessile organisms and are exposed throughout their life cycle to abiotic stresses such as extreme temperatures, drought, and high salinity (Zhao et al., 2007; Hossain et al., 2016). These factors induce biochemical, physiological, and metabolic alterations (Xiong, Zhu, 2002), resulting in oxidative stress that can affect plant metabolism and

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performance and, consequently, yield (Jakab et al., 2005; Shafi et al., 2009; Savvides et al., 2016). Such abiotic stresses have intensified as a result of industrialization and urbanization (Nagajyoti et al., 2010) and climate change (Lobell, Field, 2007).

Germination is the resumption of embryo growth, during which the quiescent state is broken and the vegetative growth phase begins through the utilization of stored reserves, culminating in radicle emergence (Taiz et al., 2017; Nascimento et al., 2018).

However, unfavorable conditions, such as high temperatures and low water potentials, negatively affect seed germination, which is considered the most critical stage of the plant life cycle in arid and semi-arid environments (El-Keblawy et al., 2017; Hameed et al., 2021).

Germination responses to water stress under controlled conditions depend on both species and stress intensity. As water potential decreases, water uptake by seeds declines and, even when germination is initiated, the process may be arrested, potentially leading to embryo death and consequently reducing germination percentage and rate (Stefanello et al., 2006; Hameed et al., 2021).

Because seed germination and early seedling growth are the stages most sensitive to water limitation, delays in germination and reductions in germination rate and uniformity may occur (Demir et al., 2006). Seed conditioning therefore represents a promising strategy for mitigating the detrimental effects of several abiotic stresses (Gust et al., 2010; Yan, 2015; Marthandan et al., 2020), enhancing tolerance and synchronizing seed germination (Jisha et al., 2013).

To avoid or mitigate these environmental constraints, plants respond in different ways, one of which is the acquisition of 'memory', whereby plants 'store' metabolic information regarding responses to previous stressful situations (priming) that may recur in the future (Hilker et al., 2016; Hossain et al., 2016). In this way, plants respond more efficiently by adopting strategies that enable coordinated physiological responses, thereby enhancing tolerance to adverse conditions and subsequent survival (Hossain et al., 2016).

Compared with non-conditioned plants, priming can markedly reduce the impacts of stress exposure on plant physiology and growth (Savvides et al., 2016). The methodologies used for this purpose include hydropriming, osmopriming, chemical priming, hormonal priming, biological priming, among others, with treatment efficacy varying according to the type of agent, its concentration, and the plant species used (Jisha et al., 2013; Maiti, Pramanik, 2013; Nawaz et al., 2013; Paparella et al., 2015).

The method aims to induce plant tolerance by treating seeds with natural or synthetic compounds before germination, thereby increasing seed vigor, reducing emergence time, and improving germination and emergence uniformity (Ashraf, Foolad, 2005; Benadjaoud et al., 2022).

Seeds are partially hydrated until the onset of germination, but radicle emergence does not occur (Bradford, 1986; Benadjaoud et al., 2022), allowing faster water uptake and metabolic activation (Ibrahim, 2016; Chen et al., 2021), thereby increasing germination rate.

However, most studies have been conducted with agricultural or forage species, whereas studies involving tree species, particularly those from the Caatinga biome, remain scarce. For sabiá (*Mimosa caesalpiniifolia* Benth.), such information is unavailable. This species is typical of the semi-arid region of northeastern Brazil, exhibits high hardiness and rapid growth, and is used for the production of fence posts, poles, and stakes; energy production; animal feed; medicinal and landscaping purposes; and environmental restoration and rehabilitation plantings (Carvalho, 2007).

Despite its multiple uses, unsustainable exploitation has reduced the number of individuals of this species in the biome, making population restoration necessary to recover these areas.

However, to ensure seedling survival after transplantation to the field, strategies must be adopted to confer tolerance to the adverse water conditions that seedlings will encounter. This need has become increasingly evident given the current scenario and future projections of climate change (IPCC, 2022).

Among these strategies, seed priming in sabiá represents an alternative for increasing seedling tolerance to water deficit, thereby promoting seed establishment and plant growth in the field.

Therefore, this study was conducted to evaluate the effects of osmopriming agents on the germination of sabiá seeds under water deficit.

## MATERIALS AND METHODS

The experiment was conducted at the Plant Physiology Laboratory of the Academic Unit of Forest Engineering, Center for Health and Rural Technology, Federal University of Campina Grande (UAEF/CSTR/UFCG), Patos Campus, Paraíba, Brazil.

Sabiá seeds (Mimosa caesalpiniifolia Benth.) were initially surface-disinfested in 5% (v/v) sodium hypochlorite solution for 5 min and subsequently rinsed with distilled water for 1 min to remove excess hypochlorite. The seeds were then subjected to dormancy breaking by immersion in concentrated sulfuric acid for 6 min, following the procedure described by Almeida et al. (2020).

**Seed treatments and osmopriming**

The experiment was conducted in a 3 × 5 factorial scheme comprising three osmopriming treatments - no priming (control), polyethylene glycol 6000 (PEG-6000; -1.0 MPa), and potassium nitrate ($KNO_3$; 100 mM) - and five water potentials (0.0, -0.5, -1.0, -1.5, and -2.0 MPa). Treatments were arranged in a completely randomized design with four replicates of 25 seeds each, totaling 100 seeds per treatment combination.

Osmopriming was performed by immersing the seeds in PEG-6000 or $KNO_3$ solutions for 12 h under continuous aeration at room temperature. A 1:5 ratio (seed mass:solution volume) was used, according to Farooq et al. (2008). After conditioning, the seeds were rinsed three times with distilled water to remove excess solution and immediately subjected to the germination test.

The different water potentials were obtained using PEG-6000 solutions prepared according to Villela et al. (1991). Distilled water was used for the control treatment (0 MPa).

**Germination test**

The germination test was conducted in transparent plastic gerboxes containing two sheets of previously autoclaved Germitest paper. The substrate was moistened with 12 mL of the solution corresponding to each treatment, containing Captan (0.2%) and nystatin (2 mL $L^{-1}$). The boxes were maintained in a biochemical oxygen demand (B.O.D.) germination chamber at a constant temperature of 25 °C.

Germination was evaluated daily from the fourth to the 14th day after experiment establishment. A seed was considered germinated when it exhibited radicle protrusion ≥2 mm in length, according to the criteria established in the Rules for Seed Testing (Brasil, 2009).

**Evaluated variables**

Germination percentage (G), germination speed index (GSI), and mean germination time (MGT) were evaluated.

Germination percentage was calculated as the ratio between the number of germinated seeds and the total number of seeds subjected to the test, expressed as a percentage.

The germination speed index was calculated according to Maguire (1962), using the following equation:

$$GSI = (n_i/t_i) \quad \text{(Equation 1)}$$

where $n_i$ = number of seeds germinated on the ith day; $t_i$ = time, in days, to germination.

Mean germination time was calculated according to Labouriau (1983), using the following equation:

$$MGT = \frac{\sum (ni.ti)}{\sum ni} \quad \text{(Equation 2)}$$

where $n_i$ is the number of seeds germinated at each daily count and $t_i$ is the time in days from the beginning of the test. The result is expressed in days.

**Statistical analysis**

The data were subjected to analysis of variance (ANOVA), considering the effects of priming treatments, water potentials, and the interaction between these factors.

For statistical analysis, germination percentage data were subjected to arcsine transformation when necessary to meet the assumptions of normality and homogeneity of variances.

Statistical analyses were performed using ASSISTAT software, version [insert version], according to Silva, Azevedo (2002), adopting a 5% significance level ($P < 0.05$).

**RESULTS AND DISCUSSION**

Statistical analysis revealed a significant interaction between water potential and priming treatments, indicating that seed germination responses to water deficit depended on the treatment applied.

**Seed germination**

Germination percentage progressively decreased with decreasing water potential, regardless of the priming treatment (Table 1).

**Tabel 1** - Germination percentage of *Mimosa caesalpiniifolia* seeds subjected to different water potentials and priming treatments

| *Priming* | Water potenctial ($\Psi w$) (MPa) | | | | |
|---|---|---|---|---|---|
| | 0 | -0.5 | -1.0 | -1.5 | -2.0 |
| Control | 100.0 aA | 78.0 aA | 51.0 bB | 35.0 bA | 13.0 cB |
| $KNO_3$ | 98.0 aA | 92.0 aA | 80.0 aA | 35.0 bA | 32.0 bA |
| PEG | 100.0 aA | 100.0 aA | 86.0 aA | 36.0 bA | 13.0 B |

Means followed by the same letters - lowercase in columns and uppercase in rows - do not differ statistically from each other according to Tukey's test ($P \leq 0.05$).

In the control treatment, exposure to -0.5, -1.0, -1.5, and -2.0 MPa reduced germination by approximately 22, 49, 65, and 87%, respectively, relative to seeds maintained at 0 MPa. This behavior demonstrates that water restriction affected not only final germination capacity but also the progression of the germination process as stress intensity increased.

The reduction in germination under low water potential is directly related to reduced water availability for seed imbibition. Water uptake is an essential initial event for the resumption of metabolic activity, including enzyme activation, reserve mobilization, and renewed embryonic growth. When the water potential of the medium becomes excessively negative, water uptake may be restricted, limiting cell expansion and the mobilization of reserves required for radicle protrusion and continued germination (Virgens et al., 2012). Thus, the progressive reduction observed in this study probably reflects the intensification of water limitation on the metabolic and cellular events required to complete germination.

The magnitude of this response varies considerably among species, depending on both stress intensity and the physiological and ecological characteristics of the seeds. In *Pityrocarpa moniliformis*, for example, Matos et al. (2021) observed an approximately 90% reduction in germination at osmotic potentials below -0.1 MPa using PEG, accompanied by a reduction in the germination speed index (GSI). In *Senna obtusifolia*, germination remained high at -0.2 MPa, but was impaired at −0.4 MPa and became unviable at −0.8 MPa (Pereira et al., 2014). Similarly, Lavezo et al. (2015) observed inhibition of *Petiveria alliacea* germination at potentials below -0.6 MPa. These differences demonstrate that germination responses to water deficit are species-specific and that the water-potential threshold for maintaining germination may vary substantially among species.

Although reduced germination was observed in all treatments, priming modified the magnitude of this response. With $KNO_3$ (100 mM), no statistical difference was observed between 0 and -0.5 MPa, whereas germination progressively decreased at more negative potentials, with reductions of approximately 18.4, 64, and 67.3% at -1.0, -1.5, and -2.0 MPa, respectively, relative to 0 MPa. PEG conditioning (-1.0 MPa) showed a similar pattern up to -1.0 MPa, maintaining a high germination percentage and thus suggesting a greater capacity to sustain the germination process under moderate water deficit. At -1.5 and -2.0 MPa, however, germination was substantially reduced, indicating that the benefit provided by priming was insufficient to overcome the severe water limitation imposed at these levels.

Comparison of the treatments within each water potential reinforces this interpretation. At 0, -0.5, and -1.5 MPa, no statistical differences were observed among priming treatments. However, at -1.0 MPa, non-conditioned seeds exhibited the lowest germination, whereas $KNO_3$ and PEG resulted in approximately 80% germination and did not differ statistically from each other. This result is particularly relevant because it indicates that the beneficial effect of priming did not occur uniformly across all stress levels but was more evident under an intermediate level of water restriction.

This pattern suggests that priming can enhance seed germination capacity when water deficit is sufficiently intense to limit the performance of the control treatment but not yet severe enough to prevent the progression of germination metabolism. At very negative potentials, reduced water availability probably imposes a more severe physical and metabolic constraint, such that the benefits induced by conditioning become insufficient to sustain germination. Therefore, the results indicate that priming efficiency depends on the interaction between the conditioning agent and water-stress intensity.

**Germination speed**

The effect of water deficit was also evident in germination speed, with a progressive reduction in GSI (Table 2).

**Tabel 2** – Germination seed index of *Mimosa caesalpiniifolia* seeds subjected to different water potentials and priming treatments

| *Priming* | Water potenctial ($\Psi w$) (MPa) | | | | |
|---|---|---|---|---|---|
| | 0 | -0.5 | -1.0 | -1.5 | -2.0 |
| Control | 6.25 aA | 2.79 bB | 1.30 cC | 0.81 cB | 0.28 dB |
| $KNO_3$ | 6.11 aA | 6.73 aA | 3.38 bB | 1.30 cA | 0.36 dB |
| PEG | 6.21 aA | 6.19 aA | 5.76 aA | 1.01 bA | 1.11 bA |

Means followed by the same letters – lowercase in columns and uppercase in rows – do not differ statistically from each other according to Tukey's test ($P \leq 0.05$).

In the control treatment, exposure to -0.5, -1.0, -1.5, and -2.0 MPa resulted in reductions of approximately 55, 79, 87, and 96%, respectively, in GSI relative to 0 MPa. The reduction in this index indicates that water limitation not only decreased the final percentage of germinated seeds but also delayed the progression of the germination process. A progressive reduction in GSI resulting from decreasing water potential was also observed in *Erythrina falcata* (Pelegrini et al., 2013) and *Adenanthera pavonina* (Leite et al., 2018).

With $KNO_3$ priming, the reduction in GSI was less pronounced at less negative potentials, corresponding to approximately 10% at -0.5 MPa and 45% at -1.0

MPa, increasing to 79 and 82% at -1.5 and -2.0 MPa, respectively. PEG, in turn, maintained statistically similar GSI values across potentials up to -1.0 MPa. At -1.5 and -2.0 MPa, however, GSI decreased by approximately 84 and 82%, respectively, relative to 0 MPa.

Comparison of the priming treatments at each water potential showed that conditioning primarily enhanced germination speed under water deficit. The greatest difference was observed at -1.0 MPa, when PEG treatment resulted in a GSI of 5.76, higher than those of the other treatments. Together with the maintenance of germination percentage observed under this condition, this result suggests that PEG was particularly effective in preserving germination progression under moderate water deficit.

The increase in germination speed promoted by priming may be associated with the anticipation of metabolic events required for germination. During conditioning, controlled seed hydration allows partial resumption of metabolic processes without radicle protrusion. This metabolic state may promote reserve mobilization, respiratory activity, nucleic acid synthesis and repair, and activation of germination-related enzymes, preparing the seed to respond more rapidly when exposed to favorable germination conditions (Chen, Arora, 2013; Paparella et al., 2015; Sano et al., 2017; Diya et al., 2024; Janah et al., 2025; Raman, 2025).

Similar results were observed by Mota et al. (2013) in *Anadenanthera falcata* seeds, in which $KNO_3$ priming increased GSI at -1.0 MPa. However, these authors observed a reduction in the index when PEG was used at -0.5 and -1.0 MPa, demonstrating that the response to osmopriming may depend on both the species and the agent used. In *Psidium guineense*, Santos et al. (2016) also observed favorable effects of PEG on germination dynamics, with a reduction in the time required for germination at different osmotic potentials.

Differences among species and priming agents reinforce that the effects of conditioning should not be generalized. Treatment efficacy depends on seed physiological characteristics, the concentration and osmotic potential used during conditioning, the exposure period, and the intensity of the water deficit subsequently imposed. In this context, the superior performance of PEG observed at -1.0 MPa in the present study suggests a specific interaction between the priming agent and stress intensity, which warrants further investigation through metabolic and biochemical analyses.

**Mean germination time**

The increase in MGT accompanied the reduction in water potential (Table 3), confirming that water deficit delayed germination progression.

**Tabel 3** – Mean germination time (MGT) of *Mimosa caesalpiniifolia* seeds subjected to different water potentials and priming treatments

| *Priming* | Water potenctial ($\Psi w$) (MPa) | | | | |
|---|---|---|---|---|---|
| | 0 | -0.5 | -1.0 | -1.5 | -2.0 |
| Controle | 4.00 bA | 5.22 bA | 8.89 aA | 8.97 aA | 9.50 aA |
| $KNO_3$ | 4.01 cA | 4.00 cB | 6.73 bB | 7.72 bB | 9.48 aA |
| PEG | 4.03 bA | 4.06 bB | 4.70 bB | 7.32 aB | 7.63 aB |

Means followed by the same letters - lowercase in columns and uppercase in rows - do not differ statistically from each other according to Tukey's test ($P \leq 0.05$).

In the control treatment, water potentials of -1.0, -1.5, and -2.0 MPa increased MGT by approximately 122, 124, and 137%, respectively, relative to 0 MPa. This behavior is consistent with the reduction observed in GSI and demonstrates that water deficit imposed a temporal constraint on the germination process.

The effect was partially attenuated by priming. With $KNO_3$, MGT was 6.73 days at -1.0 MPa, representing an approximately 68% increase relative to 0 MPa. At -1.5 and -2.0 MPa, MGT increased to 7.72 and 9.48 days, corresponding to increases of approximately 92 and 136%, respectively. With PEG, no significant increases in MGT were observed up to -1.0 MPa. At -1.5 and -2.0 MPa, however, MGT increased to 7.32 and 7.63 days, respectively, compared with 4.03 days at 0 MPa.

Joint analysis of GSI and MGT provides consistent evidence that water deficit delayed germination. Whereas the reduction in GSI indicates lower germination speed, the increase in MGT demonstrates that seeds required more time to complete the process. Conversely, the maintenance of higher GSI and lower MGT in primed seeds, particularly with PEG under moderate water deficit, indicates that conditioning favored a faster resumption of germination metabolism.

Comparison of treatments within each water potential showed no significant differences among treatments at 0 MPa. As water deficit intensified, however, priming resulted in lower MGT, with PEG standing out by promoting faster germination regardless of the water potential evaluated. This result suggests that the benefits of conditioning become more evident when seeds are exposed to limiting

conditions, under which the prior hydration and metabolic preparation provided by priming may favor continued germination.

Silveira et al. (2023) observed a similar response in *Solanum lycopersicum* seeds, in which water deficit impaired physiological performance and enzymatic activity, whereas osmopriming with PEG 6000 at -1.0 MPa improved the physiological quality of seeds from accessions susceptible and tolerant to water deficit. In *Poincianella pyramidalis*, Santos et al. (2016) also observed an increase in MGT with decreasing water potential, with values of approximately 4.81 and 9.5 days at -0.4 and -0.8 MPa, respectively, compared with 2.27 days in the control.

The positive effects of priming on germination under water deficit may be related to metabolic preparation and the greater capacity of seeds to respond to water limitation. Osmotic conditioning allows controlled hydration sufficient to activate metabolic processes associated with germination without permitting radicle protrusion. This preparation may promote reserve mobilization and activation of processes involved in cellular repair and metabolic recovery, contributing to faster germination after exposure to stressful conditions (Chen, Arora, 2013; Paparella et al., 2015; Sano et al., 2017; Farooq et al., 2019).

Another mechanism potentially associated with the benefits of priming is enhanced control of oxidative stress. Water restriction may increase the production of reactive oxygen species (ROS), leading to oxidation of lipids, proteins, and nucleic acids when their production exceeds the antioxidant capacity of cells (Diya et al., 2024). Prior conditioning may prepare the antioxidant system of seeds to respond more rapidly to stress and has been associated with greater activity of enzymes such as superoxide dismutase, catalase, and ascorbate peroxidase (Diya et al., 2024; Janah et al., 2025; Raman, 2025). Although these mechanisms were not directly evaluated in the present study, they constitute possible explanations for the greater germination capacity observed in primed seeds.

Osmotic adjustment may also contribute to maintaining germination under low water availability. The accumulation of compatible solutes, including proline, glycine betaine, and soluble sugars, may help maintain cellular osmotic potential and water retention, allowing metabolic processes to continue under water-restricted conditions (Marthandan et al., 2020; Jatana et al., 2024). However, because the levels of these osmolytes were not determined in this study, this interpretation should be regarded as a physiological hypothesis consistent with the literature rather than as a directly demonstrated mechanism.

Overall, the results demonstrate that decreasing water potential impaired germination and delayed its progression, whereas osmopriming partially attenuated these effects. The benefit of conditioning was most evident under moderate water deficit, particularly at -1.0 MPa, where $KNO_3$ and PEG maintained higher germination percentages and PEG resulted in higher GSI and lower MGT. However, increasing stress to -1.5 and -2.0 MPa substantially reduced germination performance even after priming, indicating that the protective capacity provided by conditioning has limits that depend on stress intensity.

Thus, the results suggest that priming efficiency should not be regarded as a universal response to drought but rather as an interaction between the conditioning agent and water-deficit intensity. The greater efficiency observed with PEG (-1,0 MPa) under a medium water potential of -1.0 MPa indicates the potential use of this strategy to improve early seedling establishment under limited water availability. Future studies integrating analyses of antioxidant activity, reserve mobilization, osmolyte accumulation, and expression of genes related to water-deficit tolerance may clarify the mechanisms responsible for the greater priming efficiency observed in this study.

## CONCLUSION

Water deficit reduced germination and germination speed and increased mean germination time, with responses dependent on water potential and priming treatment.

Priming with $KNO_3$ (100 mM) and PEG (−1.0 MPa) attenuated the effects of water deficit, with the greatest efficiency at −1.0 MPa; PEG was particularly effective in promoting higher germination speed and lower mean germination time.

Increasing water-deficit severity to −1.5 and −2.0 MPa reduced germination performance even after priming, indicating that its effectiveness is limited by stress intensity.

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