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Inducing Drought Stress Tolerance during Germination by Micronutrient Seed Priming and Coating of Maize (*Zea mays* L.)

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Abstract

Drought is a significant abiotic stress that affects the germination of many crops, including maize. Improvement in seed quality and tolerance to drought stress can be induced through seed priming and coating. This research aimed to study the effect of priming and coating on maize seed germination under drought conditions. The experiment was performed in a randomized complete block design with a split-plot arrangement and four replications. The main plot was drought stress level: control, and 10% PEG. The subplot was seed enhancement treatments, which consisted of untreated, hydropriming, osmopriming, priming with 6 mM Si, 0.075 mM Se + 10 mM Zn, 6 mM Si + 0.075 Se + 10 mM Zn, 0.8 mM melatonin, seed coating 1% NaAlg, P9: seed coating + 0.732 g $Si.kg^{-1}$ seed, P10: seed coating + 0.014 g Se + 2.875 g $Zn.kg^{-1}$ seed, P11: seed coating + 0.732 g Si + 0.014 g Se + 2.875 g $Zn.kg^{-1}$ seed, and P12: seed coating + 0.186 g $melatonin.kg^{-1}$ seed. The result showed that seed priming 0.075 mM Se + 10 mM Zn, priming 6 mM Si + 0.075 mM Se + 10 mM Zn, and seed coating + 0.732 g Si + 0.014 g Se + 2.875 g $Zn.kg^{-1}$ seed improved maize seed germination under drought stress based on germination percentage, speed of germination, root dry weight, seedling dry weight, and seedling growth rate. Seed priming or coating with micronutrients such as silicon, selenium, and zinc could serve as an effective treatment to enhance germination of maize under drought conditions.

Keywords: abiotic stress, film coating, seed enhancement treatment, seed quality

Introduction

Climate change has caused an increase in extreme events such as El Niño, a phenomenon associated with decreased rainfall intensity that leads to drought conditions. Drought as a result of El Niño has an impact on the decline of crop production, such as in maize (Irawan, 2016). A strong El Niño event in 2015 decreased Indonesian rainfall, ranging from 100-400 mm per month to 50-300 mm per month (Athoillah et al., 2017). El Niño has reduced maize production in Indonesia by 12.5% in 2023 (Kementan, 2024), whereas 20% in some regions of low-income countries, such as South Asia and Sub-Saharan Africa (Ubilava and Abdolrahimi, 2019).

Seed germination is a sensitive and critical phase in the maize life cycle that has a significant effect on productivity (Szabó et al., 2022). During germination, drought stress decreased maize production from 7,768 $kg.ha^{-1}$ to 4,945 $kg.ha^{-1}$ (Song et al., 2019). The decline in crop production under water-stressed conditions may be attributed to a decrease in seed quality. Seed quality is essential for crop production and food security, particularly during the increasing uncertainty due to climate change (Finch-Savage and Bassel, 2016). Low seed vigor decreased the plant growth rate and maize production by 23.7% and 41.5%, respectively (Golezani and Dalil, 2018).

Improvements of seed quality and tolerance to drought stress can be induced by seed priming and coating. Priming is a pre-sowing seed hydration treatment that stimulates seed metabolism, thereby preparing the seed for germination (Ilyas, 2012). Priming can enhance plant tolerance to abiotic stress by stimulating metabolic processes for germination, increasing antioxidant enzyme activity against oxidative stress, and increasing osmotic substances to maintain cellular turgor (Ibrahim, 2019). These mechanisms created a 'priming memory' in seeds (Chen and Arora, 2013). When plants undergo drought stress, the 'stress memory' from the priming process will be re-induced, resulting in a faster and more effective tolerance response (Marthandan et al., 2020).

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There are many techniques of seed priming, including hydropriming, osmopriming, matriconditioning, biopriming, and nutrient priming (Rhaman et al., 2020; Waqas et al., 2019). Osmopriming is a priming method where seeds soak in an osmotic solution that uses a high molecular weight agent such as polyethylene glycol (PEG) (Goswami, 2019). PEG as a priming agent exposes seeds to a medium with low water potential, reducing the rate of water entry into seeds and improving plant stress tolerance by regulating osmotic substances (Ma et al., 2024). Osmopriming with 10% PEG has been reported to improve germination parameters of maize under drought stress, including germination rate, vigor index, seedling dry weight, as well as increased physiological indices such as antioxidant enzyme activity and proline content (Yuan et al., 2014). Abiotic stress tolerance (drought and saline) in maize can also be enhanced through melatonin priming (0.8 mM and 0.5 mM), which improved germination percentage, vigor index, root and shoot length, and seedling fresh and dry weights while decreasing electrolyte leakage, malondialdehyde (MDA), and reactive oxygen species (ROS) (Muhammad et al., 2023; Jiang et al., 2016). Melatonin is an endogenously synthesized indoleamine that acts as a signaling molecule that regulates pivotal growth and as a stress mitigant (Cai et al., 2025). Another priming method that has been recently used is seed nutrient priming, which supplies the seed with nutrients that aid in its early development, enhancing crop performance and resilience during drought (Maphalaphathwa and Nciizah, 2025). Micronutrients such as selenium (Se), zinc (Zn), and silicon (Si) significantly improved abiotic stress tolerance of plants by enhancing chlorophyll levels, photosynthetic rates, and reducing oxidative stress (Idrees et al., 2024; Ganguly et al., 2022). Nutrient priming with 0.075 mM Se, 10 mM Zn, and 6 mM Si has been reported to enhance germination indices and improve the levels of photosynthetic pigments of maize under drought stress (Nawaz et al., 2021; Parveen et al., 2019).

Seed coating is a technique that covers the seed surface with a coating material to improve plant establishment and protect plants against biotic and abiotic stresses (Paravar et al., 2023). Seed coating can enhance plant tolerance against drought stress by adding active components, such as plant nutrients and plant growth regulators, along with binders to adhere treatments to the seeds (Afzal et al., 2020; Suo et al., 2017). Seed coating with 1% sodium alginate has been reported to improve the germination of sweet corn under drought stress (Behboud et al., 2021). Sodium alginate is a superabsorbent polymer (SAP) containing hydroxyl groups that absorb and retain more water (Chang et al., 2021), enhance the capability of slow-release fertilizers, and are environmentally friendly (biodegradable) (Fertahi et al., 2021).

Seed coating with plant nutrients has been reported to improve germination indices, plant growth, and production of maize under normal conditions (John et al., 2005). Seed coating with Zn results in faster emergence, improved seedling root length, plant height, and maize production (Shabaz et al., 2015). Application of Se through seed coating was reported to enhance the antioxidant activity of fenugreek, which can help mitigate stress conditions (Al-Shammeryi, 2024). Seed coated with fertilizer containing macro- and micronutrients has been reported to increase the activity of antioxidant enzymes and maize plant above-ground biomass under drought stress (Matlok et al., 2022). Seed coating with the addition of nutrient Si increased plant growth, photosynthetic contents, and osmoprotectants of maize under saline stress (Rehman et al., 2020;). Melatonin is gradually being recognized as a potential novel plant hormone, and its application through seed coating has been reported to increase the germination rate, growth performance, and wheat yield under drought stress (Li et al., 2025).

The results of the previous studies indicated that seed enhancement treatments (priming and coating) induced maize tolerance against many environmental stresses. However, there needs to be more information about the optimum seed treatments (especially for seed coating) that can improve seed germination of maize under drought stress conditions. In this study, we compared various seed priming and coating treatments based on the chosen research literature, and some modifications were made to the seed treatment to achieve maximum germination performance of maize seeds under drought stress.

Materials and Methods

Location

The experiment was conducted from April to August 2023 at the Seed Quality Testing Laboratory, Department of Agronomy and Horticulture, Faculty of Agriculture, IPB University, Indonesia.

Maize Seeds

Maize seeds var. “Lamuru” was harvested on 20 June 2022 and collected from the Indonesian Cereal Research Institute, Maros, South Sulawesi, Indonesia. This variety has been characterized as drought sensitive (10% PEG 6000 equal to -0.19 MPa) based

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on germination percentage and vigor index (Palupi and Asnawati, 2017; Bukhari et al., 2021). The seeds were then selected based on uniformity in shape and size for further testing, according to the methods described in Efendi et al. (2009).

Experimental Design

The experiment was performed in a randomized complete block design with a split-plot arrangement and four replications. The main plot was drought stress level, which consisted of two levels: K1, control (non-stress), and K2, 10% PEG 6000 (drought stress). The subplot was seed enhancement treatments which consisted of 12 levels, viz., P1: untreated seed (control), P2: hydropriming (Nawaz et al., 2021), P3: osmopriming 10% PEG (Yuan et al., 2014), P4: priming 6 mM Si (Parveen et al., 2019), P5: priming 0.075 mM Se + 10 mM Zn (Nawaz et al., 2021), P6: priming 6 mM Si + 0.075 Se + 10 mM Zn, P7: priming 0.8 mM melatonin (Jiang et al., 2016), P8: seed coating 1% NaAlg (Behboud et al., 2021), P9: seed coating + 0.732 g Si.kg^{-1} seed, P10: seed coating + 0.014 g Se + 2.875 g Zn.kg^{-1} seed, P11: seed coating + 0.732 g Si + 0.014 g Se + 2.875 g Zn.kg^{-1} seed, and P12: seed coating + 0.186 g melatonin.kg^{-1} seed.

Seed Priming

Maize seeds were sterilized with 0.5% sodium hypochlorite (NaOCl) for 15 minutes and then rinsed four times (Yuan et al., 2014). Subsequently, the seeds were soaked in priming solution for 24 hours in a container equipped with an aerator at a room temperature of 20°C. The ratio between the seed and priming solution was 1:5 (w/v). After the priming treatment, seeds were rinsed with distilled water once and air-dried with a fan until they reached the near initial moisture content (12.0±0.1%) for 48 hours at a room temperature of 20°C.

Seed Coating

Seed coating material used sodium alginate ($NaC_6H_8O_6$) as a binder. The solution was prepared using a magnetic stirrer by dissolving 1 g sodium alginate (NaAlg) powder in 100 mL distilled water (1% w/v). The active ingredients used were the plant micronutrients sodium metasilicate (Na_2SiO_3), sodium selenate (Na_2SeO_4), zinc sulfate ($ZnSO_4.7H_2O$) (for nutrient priming), and melatonin. The micronutrients were dissolved in 5 mL of distilled water, whereas melatonin was dissolved in 5 mL of ethanol. The active ingredients were mixed with 5 mL of sodium alginate using a magnetic stirrer until thoroughly blended. The ratio of the seed coating solution to the seeds was 10 mL.kg^{-1} seeds. The seed coating process was carried out manually, following John et al., (2005) and Avelar et al., (2012). The seeds were treated with coating materials in a plastic container and then shaken for 2-3 minutes. Once thoroughly mixed, the seeds were air-dried with a fan for 24 hours until they reached the near initial moisture content (12.0±0.1%) at a room temperature of 20°C.

Measurements of Germination Indices and Drought Stress Treatments

Germination percentage (GP) was conducted using the between-paper method following Queiroz et al. (2019) with slight modification. Four replicates of 50 seeds were evenly distributed on 3-ply papers and covered with a 2-ply sheet of paper that had been moistened with either distilled water (control) or a 10% PEG 6000 solution (drought stress treatment). The papers were then rolled up with polyethylene plastic to maintain relative humidity. Germination was carried out in a germinator at a room temperature of 25°C. The moisture of germination paper rolls was continuously monitored by adding distilled water (control) and 10% PEG solution (drought stress) to keep the paper rolls wet (Badr et al., 2020). The first observation and measurement were conducted on day 4, and the final observation was conducted on day 7, according to ISTA (2018). GP is calculated using the formula:

$$GP\ (\%) = \frac{\text{Number of NS I} + \text{Number of NS II}}{\text{Total seeds germinated}} \times 100\%$$

Where:
NS I: normal seedlings on the first count (day 4)
NS II: normal seedlings on the second count (day 7)

Speed of germination (SG) was measured every day until the last observation on day 7 by counting the number of normal seedlings and the difference in hours of each observation (%NS.etmal^{-1}). SG was calculated using the formula:

$$SG\%NS.etmal^{-1} = \sum_{0}^{t} \frac{\%\ NS}{etmal} \times 100\%$$

Where:
t : observation time
% NS : percentage of normal seedlings at each observation time
etmal : observation time every 24 hours

RE was conducted using 25 seeds per experimental unit and repeated six times. The radicle emergence (RE) test was carried out following ISTA (2018). Seeds were germinated between three layers of paper towels moistened with distilled water (control) and 10% PEG (drought stress treatment) at a room

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temperature of 20°C. RE was measured by counting the number of seeds that were able to produce radicles ≥2 mm long in 66 hours.

Shoot dry weight (SDW), root dry weight (RDW), normal seedling dry weight (NSDW), and seedling growth rate (SGR) were measured according to ISTA (1995). Germination was performed by preparing 25 seeds per roll, which consisted of four replications. At the end of the test period, the normal seedling was counted, while root and shoot material were separated. The SDW, RDW, and NSDW were determined by weighing the root, shoot, and total of normal seedlings after drying them in an oven at 80°C for 24 hours. SGR was obtained by dividing NSDW by the number of normal seedlings.

Statistical Analysis

Analysis of variance (ANOVA) was performed using SPSS software and Microsoft Excel at an α level of 0.05. The differences between treatments were tested by Duncan's multiple range test (DMRT) at 0.05 probability levels.

Results and Discussion

Drought stress with 10% PEG significantly reduced germination percentage for all seed enhancement treatments compared to normal conditions. All of the seed priming improved germination percentage under drought stress. The best priming treatment to increase germination percentage under drought stress was observed in priming Se + Zn (85.41%) compared to untreated seed (66%). However, there were no significant differences among seed priming treatments (Table 1). Seed priming treatment, viz., osmopriming 10% PEG, priming Si, and priming Se + Zn, decreased the percent reduction of germination percentage as affected by drought stress by 9.94%, 7.51%, and 9.14%, respectively. All seed coating treatments were shown to increase germination percentage compared to untreated seed, except for seed coating without the addition of active ingredients under drought stress.

Drought stress conditions were also found to decrease the speed of germination significantly. Under drought conditions, seed priming improved the speed of germination compared to untreated seed. Among seed priming, the best treatment to improve the speed of germination was priming Se+Zn (12.78 %NS.etmal^{-1}), and it was significantly higher compared

Table1. Effect of seed treatment on germination percentage and speed of germination of maize under normal and drought stress conditions (10% PEG)

Treatment	Germination (%)			Speed of germination (%NS.etmal^{-1})		
	Normal	Drought stress	Reduction (%)*	Normal	Drought stress	Reduction (%)*
Control	94.00 Aa	66.00 Bc	29.79	20.03 Aa	9.53 Bc	52.41
Hydropriming	95.00 Aa	82.50 Bab	13.16	20.88 Aa	12.37 Bab	40.79
Osmopriming 10% PEG	90.50 Aa	81.50 Bab	9.94	19.57 Aa	12.11 Bab	38.11
Priming Si	89.00 Aa	82.31 Bab	7.51	19.61 Aa	12.53 Bab	36.10
Priming Se+Zn	94.00 Aa	85.41 Ba	9.14	20.41 Aa	12.78 Ba	37.39
Priming Si+Se+Zn	93.97 Aa	81.00 Bab	13.80	20.90 Aa	12.28 Bab	41.24
Priming melatonin	91.50 Aa	74.98 Bb	18.06	19.94 Aa	11.16 Bb	44.04
Seed coating	93.97 Aa	67.61 Bc	28.05	20.46 Aa	9.81 Bc	52.04
Seed coating+Si	93.50 Aa	77.92 Bab	16.67	20.45 Aa	11.37 Bb	44.44
Seed coating+Se+Zn	94.00 Aa	81.00 Bab	13.83	20.32 Aa	11.75 Bab	42.18
Seed coating+Si+Se+Zn	90.00 Aa	78.00 Bab	13.33	19.60 Aa	11.32 Bb	42.25
Seed coating+ melatonin	93.00 Aa	80.12 Bab	13.85	20.19 Aa	12.16 Bab	39.78

Notes: Values followed by different capital letters in the same row and different lowercase letters in the same column mean significantly different based on the DMRT at α= 5%. *These values are the percentage of reduction compared with normal conditions. The capital letters within the same row compared normal and drought conditions under the same seed treatment. The lowercase letters within the same column compare seed treatments under normal and drought conditions.

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to priming with melatonin (11.16 %NS.etmal^{-1}) and untreated seed (9.53 %NS.etmal^{-1}) under drought conditions (Table 1). Seed coating treatments were also observed to enhance the speed of germination under stress conditions compared to untreated seed and seed coating without active ingredients. The percent reduction in germination speed under drought stress was shown to decline with seed treatments, viz., osmopriming 10% PEG, priming Si, priming Se + Zn, and seed coating + melatonin by 38.11%, 36.10%, 37.39%, and 39.78%, respectively.

Drought stress has been reported to decrease the germination percentage and speed of germination in maize (Hamama and Murniati, 2010; Maksimovic, 2021). Hydropriming and priming Zn could increase the final germination percentage and speed of germination of maize due to the accomplishment of biochemical processes in germination (Choukri et al., 2022). Drought stress enhanced the production of reactive oxygen species (ROS), which led to cell damage and disrupted the developmental processes of seed germination (Sarangi et al., 2024). Therefore, it caused a decline in the percentage and speed of maize germination. Plants have two strategies to alleviate oxidative stress by producing enzymatic and non-enzymatic antioxidants such as proline (Ejaz et al., 2020). Nawaz et al. (2021) reported that priming Se + Zn increased antioxidant enzyme activity, such as catalase (CAT), superoxide dismutase (SOD), guaiacol peroxidase (GPX), and ascorbate peroxidase (APX) in maize seedlings under drought stress to scavenge ROS, thereby increasing germination percentage. According to Muhammad et al. (2023), seed priming with melatonin has been reported to increase maize germination under drought-stress conditions through reduced ROS, regulate the antioxidant defense system, and increase proline content. Kumdee et al. (2023) observed that under water stress, maize produced proline content in both root and leaf to protect the cells from damage through stabilizing proteins and membranes.

The result showed that the radicle emergence and shoot dry weight were significantly decreased under drought stress conditions compared to non-stress conditions (Table 2). Similarly, Rida et al. (2021) also reported that drought stress treatment retarded root and shoot-related traits. The reduction of seed vigor and seedling performance was due to a limited water supply for the germination process. Kolesnikov et al. (2023) reported a decrease in water absorption intensity in maize seeds under water-deficient conditions. According to Saha et al. (2022), a reduction in seed hydration leads to a slower hydrolysis process of stored carbohydrates, which affects the delays in seed emergence and seedling vigor. The maize radicle started to emerge 48 hours after germination under normal conditions, whereas it took 60 hours under 10% PEG conditions (Qadir et al., 2023). Seedlings that emerge more quickly have a longer time to develop than those that germinate later due to drought stress conditions (Queiroz et al., 2019). Therefore, the delay of seedling emergence will result in a decrease in dry matter accumulation.

Seed enhancement treatments significantly improved radicle emergence. The best priming treatment to increase radicle emergence was priming Si + Se + Zn (17.58), while the best seed coating treatment was seed coating + Si + Se + Zn (18.67), compared to untreated seed (14.42) (Table 2). The early emergence of the seed treated with priming could be due to the completion of pre-germination metabolic activities that make the seed ready for radicle protrusion (Shrestha et al., 2019). The primed seed imbibes water rapidly and revives seed metabolism through the repair and buildup of nucleic acids and proteins, resulting in early vigor, reduced time of seed emergence, and uniform emergence (Thakur et al., 2019). The previous study by John et al. (2005) showed that maize seed that was film-coated with polymer, pesticide, and plant nutrients (diammonium phosphate and micronutrient mixture) had a higher rate of water uptake, resulting in early germination and improved root length. Silicon (Si) enhanced water absorption during the imbibition process of maize seed and increased the radicle length (Nafarrate-Ramos et al., 2022). Similarly, Shabaz et al. (2015) reported increases in root length after seed coating with 2 g $ZnSO_4$ whereas Waghmare and Gadre (2018) showed that low zinc (Zn) concentrations increased proline content in the root of maize seedlings for osmotic adjustment and protein content for synthesizing stress-induced proteins.

The shoot dry weight was found to be significantly increased by seed treatments. The best seed priming to increase shoot dry weight was priming melatonin (0.44 g), priming Si + Se + Zn (0.43 g), and priming Se + Zn (0.42 g), while the best seed coating treatment was seed coating + Si + Se + Zn, (0.46 g) compared to untreated seed (0.34 g) (Table 2). Previous studies showed that nutrient priming (Si, Se, Zn) increased the shoot fresh and dry weight of maize under normal and abiotic stress conditions (Parveen et al., 2019; Basit et al., 2020; Morales-Hermandez et al., 2024). Nciizah et al. (2020) reported that micronutrient seed priming at low concentrations resulted in earlier seedling emergence and enhanced chlorophyll content index, leading to better shoot growth and higher shoot mass. It was also reported by Nawaz et al. (2021) that priming Se + Zn increased the leaf chlorophyll content of maize seedlings, supporting the

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establishment of the shoot. Hassan et al. (2020) stated that applying Zn through seed priming increased the synthesis of IAA and GA_3 under drought stress, and these hormones enhanced shoot weight and length. Matlok et al. (2022) found that plant nutrients contained in fertilizer seed coating could increase the activity of enzymatic antioxidants and decrease the ROS content, resulting in the improved weight of the above-ground part of maize plants under drought stress.

Drought stress significantly reduced root dry weight for all the seed treatments compared to normal conditions. All of the seed priming improved root dry weight under drought stress, except for priming with Si. The best priming treatment to increase root dry weight under drought stress was priming melatonin (0.60 g), priming Si + Se + Zn (0.60 g), and priming Se + Zn (0.59 g) compared to untreated (0.40 g) (Table 3). Priming melatonin and priming Si + Se + Zn were significantly higher than osmopriming 10% PEG and priming Si. Priming melatonin and priming Si + Se + Zn could decrease the percent reduction of root dry weight as affected by drought stress by 6.25% and 16.96%, respectively. However, the root dry weight with priming melatonin yielded a low result (0.64 g) under normal conditions, which contributed to the small reduction percentage. All the seed coatings showed increased root dry weight under drought stress compared to untreated seeds, except for the seed coating without the addition of active ingredients and the seed coating + melatonin (Table 3).

Drought stress has been reported to cause a decrease in root development in maize seedlings (Radic et al., 2018). Priming maize seeds with nutrients (4% potassium nano chelate) enhanced the length and weight of the seminal root in maize seedlings under drought-stress conditions (Zahedifar and Zohrabi, 2016). Maize seminal roots play a role in the acquisition of water (Wang et al., 2023). Under saline conditions, seed priming with 100 $mg.L^{-1}$ ZnO NPs (nanoparticles) increased root length, root total volume, and number of root tips of maize (Ahmad et al., 2023), while seed priming with 4 mM Zn enhanced the root dry weight of maize by 33.1% (Rashidifard et al., 2022). Application of selenium (Se) could increase the membrane integrity and regulate ion transport (including Zn) to enhance root development, therefore resulting in the improved water status of maize under drought conditions (Nawaz et al., 2021). Seed coating with water retention materials could increase seed water holding capacity, maximizing the benefits of water in the root zone and mitigating drought stress (Jarrar and Keblawy, 2022). Seed coating with 0.5% chitosan or 1% alginate + vermiculite + kaolin + perlite + 0.4% Arabic gum enhanced the root dry weight of maize under drought stress conditions due to its ability to increase water absorption and prevent seed moisture loss (Behboud et al., 2024). Drought-tolerant maize

Table 2. Effect of seed treatment on first germination count, radicle emergence, and shoot dry weight of maize under normal and drought stress conditions (10% PEG)

Treatment	Radicle emergence	Shoot dry weight (g)
Stress level		
Normal	18.29 a	0.62 a
Drought stress	14.33 b	0.18 b
Seed treatments		
Control	14.42 c	0.34 d
Hydropriming	16.42 abc	0.40 bc
Osmopriming 10% PEG	14.33 c	0.40 bc
Priming Si	16.33 abc	0.37 cd
Priming Se+Zn	16.33 abc	0.42 abc
Priming Si+Se+Zn	17.58 ab	0.43 ab
Priming melatonin	16.83 abc	0.44 ab
Seed coating	16.50 abc	0.37 cd
Seed coating+Si	17.08 abc	0.36 cd
Seed coating+Se+Zn	15.08 bc	0.40 bc
Seed coating+Si+Se+Zn	18.67 a	0.46 a
Seed coating+melatonin	16.17 abc	0.37 cd

Notes: Values followed by different letters in the same column means significantly different based on the DMRT test at α = 5%.

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with a well-developed root system would exhibit higher shoot dry weight (Jin et al., 2018).

A significant interactive effect of drought stress and seed enhancement treatments was shown on seedling dry weight (Table 3). Drought stress was also found to decrease seedling dry weight significantly. Under normal conditions, the best seed treatment to increase the seedling dry weight was seed coating + Si + Se + Zn (2.15 g), significantly higher compared to untreated seed (1.87 g). Still, there were no significant differences with hydropriming (1.93 g), priming Se + Zn (2.07 g), priming Si + Se + Zn (2.04 g), and seed coating Se + Zn (2.01 g).

Under drought conditions, seed priming could improve seedling dry weight compared to untreated seed, except for hydropriming, osmopriming with 10% PEG, and priming with Si. Among seed priming treatments, the best treatments to improve seedling dry weight were priming with Si + Se + Zn (1.39 g) and priming with melatonin (1.40 g). It was significantly higher compared to hydropriming (1.18 g), osmopriming 10% PEG (1.19 g), priming Si (1.08 g), and untreated seed (0.99 g) under drought conditions (Table 3). Seed coating was also observed to enhance seedling dry weight under stress conditions compared to untreated seed, except for seed coating without the addition of active ingredients and seed coating + melatonin. The percent reduction in seedling dry weight was shown to decline with seed treatments, and the lowest decrease was observed with priming melatonin and seed coating Si, at 23.57% and 26.85%, respectively. However, seed coating + Si had the lowest seedling dry weight under normal conditions.

Drought stress significantly reduced the seedling growth rate for all seed treatments compared to normal conditions. All seed priming treatments improved the seedling growth rate under drought stress. The best priming treatment to increase seedling growth rate under drought stress was observed in priming Si + Se + Zn and priming melatonin (63.75 and 61.75 mg per normal seedling). It was significantly higher than hydropriming, osmopriming 10% PEG, priming Si, and untreated seed (55.25, 51.50, 52.75, and 42.75 mg per normal seedling, respectively). All seed coating treatments increased the seedling growth rate under drought stress. The best coating treatment to increase seedling growth rate under drought stress was observed in seed coating + Si + Se + Zn, but there were no significant differences among seed coating treatments (Table 4). Priming Si + Se + Zn, priming melatonin, and seed coating + Si + Se + Zn decreased the percent reduction of seedling growth rate as affected by drought stress by 27.97%, 25.15%, and 27.61%, respectively (Table 4).

Drought stress reduced the growth and development of all crops (Zaib et al., 2023). In maize, germination

Table 3. Effect of seed treatment on root and seedling dry weight of maize in normal and drought stress conditions (10% PEG)

Treatment	Root dry weight (g)			Seedling dry weight (g)		
	Normal	Drought stress	Reduction (%)*	Normal	Drought stress	Reduction (%)*
Control	0.73 Aab	0.40 Bc	45.55	1.87 Abc	0.99 Bc	47.40
Hydropriming	0.73 Aab	0.50 Bab	31.40	1.93 Aab	1.18 Babc	39.20
Osmopriming 10% PEG	0.69 Aabc	0.49 Bb	28.73	1.90 Abc	1.19 Babc	37.45
Priming Si	0.59 Ac	0.44 Bbc	24.79	1.71 Abc	1.08 Bbc	37.04
Priming Se+Zn	0.76 Aa	0.59 Bab	21.52	2.07 Aab	1.32 Bab	36.32
Priming Si+Se+Zn	0.72 Aab	0.60 Ba	16.96	2.04 Aab	1.39 Ba	31.82
Priming melatonin	0.64 Abc	0.60 Ba	6.25	1.84 Abc	1.40 Ba	23.57
Seed coating	0.65 Abc	0.46 Bbc	27.91	1.80 Abc	1.16 Bbc	35.10
Seed coating+Si	0.65 Abc	0.49 Bb	24.03	1.69 Ac	1.23 Bab	26.85
Seed coating+Se+Zn	0.71 Aab	0.52 Bab	27.02	2.01 Aab	1.25 Bab	37.53
Seed coating+ Si+Se+Zn	0.78 Aa	0.49 Bb	36.45	2.15 Aa	1.29 Bab	40.30
Seed coating+ melatonin	0.64 Abc	0.40 Bc	38.13	1.87 Abc	1.10 Bbc	41.12

Notes: Values followed by different capital letters in the same row and different lowercase letters in the same column means significantly different based on the DMRT test at α = 5%. *These values are the percentage of reduction compared with normal conditions. The capital letters within the same row compared normal and drought conditions under the same seed treatment. The lowercase letters within the same column compare seed treatments under normal and drought conditions.

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rate and root, shoot, and seedling dry weight decreased due to low osmotic potential due to hindered seed water imbibition (Fatikhasari et al., 2022; Magar et al., 2019). Under drought stress, seed priming with Zn increased the maize seedling dry weight (Kunjammal and Sukumar, 2019), enhanced leaf area and number of leaves, induced the photosynthetic area, and further subjected it to biomass accumulation (Singhal et al., 2021). Similarly, seed coating with Zn was reported to increase the root and shoot dry weight of wheat by 22% and 25% (Mohammed and Pekşen, 2020) and improve wheat's chlorophyll content and leaf area index under drought stress (Mohammed and Pekşen, 2021). Seed priming with Si was shown to increase leaf area, shoot and root dry weights, and actual photochemical efficiency of photosystem II (Sirisuntornlak et al., 2021). Si seed priming combined with foliar spray of S induced drought tolerance in maize under drought stress by increased chloroplast pigments and elevated antioxidant enzyme activity, resulting in high biomass (Farman et al., 2022). Priming Si increased protein concentrations in germinating seeds that provide energy and amino acids to neutralize the harmful effects of drought stress, and also enhanced the upregulated antioxidant and hydrolytic enzymes, such as protease and α-amylase (Hameed et al., 2021). The enzymatic degradation process of seed storage compounds produces simple carbohydrates that can serve as an energy source for germination (Widajati et al., 2013).

The results revealed differences between seed priming and coating. Hydropriming resulted in a higher germination percentage, speed of germination, and root dry weight of maize under drought stress. However, seed coating without active ingredients did not differ from untreated seeds under drought stress. These results suggest seed priming can improve seed quality even without adding active ingredients, compared to seed coating alone. On the other hand, additional nutrients showed a synergistic effect on improving seed quality in both seed priming and coating treatments.

In summary, maize germination improved consistently under drought stress conditions by seed priming Se + Zn, priming Si + Se + Zn, seed coating + Se + Zn, and seed coating + Si + Se + Zn. The highest results for radicle emergence, root and shoot dry weight, seedling dry weight, and seedling growth rate were obtained using priming Si + Se + Zn and seed coating + Si + Se + Zn. These results may be attributed to the beneficial role of these nutrients in seed priming and coating using Si, Se, and Zn.

Zinc (Zn) is an essential micronutrient that alleviates drought stress by improving plant water relations, cell membrane stability, osmolytes accumulation, endogenous hormones (auxins, gibberellins, and melatonin), and antioxidant system activities (Hassan et al., 2020). Zn modulates the expression of aquaporins (AQPs), which influence DNA synthesis

Table 4. Effect of seed treatment on seedling growth rate of maize in normal and drought stress conditions (10% PEG)

Treatment	Seedling growth rate (mg per normal seedling)		
	Normal	Drought stress	Reduction (%)*
Control	82.25 Aabc	42.75 Bc	48.02
Hydropriming	83.50 Aabc	55.25 Bb	33.83
Osmopriming 10% PEG	80.25 Aabc	51.50 Bb	35.83
Priming Si	76.00 Ac	52.75 Bb	30.59
Priming Se+Zn	86.00 Aab	57.75 Bab	32.85
Priming Si+Se+Zn	88.50 Aa	63.75 Ba	27.97
Priming melatonin	82.50 Aabc	61.75 Ba	25.15
Seed coating	77.75 Abc	57.00 Bab	26.69
Seed coating+Si	76.25 Ac	60.25 Bab	20.98
Seed coating+Se+Zn	86.50 Aa	60.50 Bab	30.06
Seed coating+ Si+Se+Zn	88.75 Aa	64.25 Ba	27.61
Seed coating+melatonin	81.50 Aabc	55.50 Bab	31.90

Notes: Values followed by different capital letters in the same row and different lowercase letters in the same column mean significantly different based on the DMRT test at α = 5%. *These values are the percentage of reduction compared with the normal condition.

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and mitotic activity in the root tip and encourage the formation of lateral roots, thereby enhancing the root's ability to absorb water (Prajapati et al., 2025). Selenium (Se) is an essential element incorporated into a group of proteins called seleno proteins (Sonet et al., 2019). Seleno proteins act as antioxidants in plant metabolism through the glutathione peroxidase (GSH) pathway, which acts to combat ROS in plants under drought stress conditions (Lanza and Reis, 2021). Silicon alleviates plant drought stress by enhancing root water uptake through improving root growth, osmotic driving forces, hydraulic conductance, and regulating aquaporin activity and gene expression, thus improving plant water status and balance (Wang et al., 2021). These findings could help farmers to mitigate the adverse effects of drought stress at early growth through seed treatments. Further studies are needed to assess the effectiveness of these treatments on different crops in various field conditions and at different growth stages.

Conclusions

Drought stress under 10% PEG reduced the germination parameters of maize seeds. Seed treatment with micronutrients Si, Se, and Zn through priming and coating effectively alleviated the adverse effect of drought stress during the germination stage. Priming treatment using 0.075 mM Se + 10 mM Zn, or 6 mM Si + 0.075 mM Se + 10 mM Zn, and seed coating by NaAlg 1% + 0.732 g Si + 0.014 g Se + 2.875 g Zn.kg-1 seeds improved germination indices of maize under drought stress condition.

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