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Original Article

Increasing drought stress tolerance of maize seedlings through nano seed coating using ZnO, Fe_3O_4, and SiO_2

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Abstract

Drought stress negatively impacts maize growth and yield. This study evaluated the use of nano seed coating with ZnO (15, 25, 50 mg L^{-1}), Fe_3O_4 (100, 200, 300 mg L^{-1}), and SiO_2 (300, 600, 900 mg L^{-1}) to enhance maize drought tolerance during germination. Seeds were tested under osmotic stresses of 0, -0.15, and -0.30 MPa using PEG 6000. Fe_3O_4 at 300 mg L^{-1} significantly increased germination rate, first count germination, and speed of germination compared to the control at -0.30 MPa. ZnO at 50 mg L^{-1} produced the highest radicle emergence (43%) under severe stress. Additionally, Fe_3O_4 (300 mg L^{-1}) and SiO_2 (600 mg L^{-1}) coatings reduced malondialdehyde (MDA) content, indicating a decrease in oxidative damage. These results highlight the potential of nano seed coating, especially with Fe_3O_4 and ZnO, to enhance maize drought tolerance during early growth. Further field validation is recommended.

Keywords: malondialdehyde, nanoparticles, seed coating, seed viability, seed vigor

1. Introduction

Drought is a significant challenge for most countries regarding agricultural availability and production (Chukwuneme, Babalola, Kutu, & Ojuederie, 2020). Altered rainfall patterns reduce water availability, limiting crop options and increasing the risk of drought and crop failure, a phenomenon already observed in Indonesia, where climate change has impacted the agricultural sector (Ruminta, Handoko, & Nurmala, 2018; Sukarman, Mulyani, & Purwanto, 2018). Rahmah, Ilyas, and Setiawan (2020) showed that climate change worsened soil quality and water availability. Continuous water shortages can thus induce drought stress in plants.

Drought stress during early maize growth induces oxidative stress that inhibits plant growth, causes necrosis, and may lead to plant death. Supplying essential micro- and macronutrients can mitigate these effects (Matlok, Piechowiak, Krolikowski, & Balawejder, 2022). Nanotechnology enhances fertilizer efficiency because nanoparticles (≈1–100 nm) are highly reactive, target-specific, and require smaller doses (Widowati, Husnain, & Hartatik, 2011). Metal-oxide nanoparticles (NPs) such as zinc oxide

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(ZnO), magnetite (Fe_3O_4), and silicon dioxide (SiO_2) reduce cellular damage under drought by lowering reactive oxygen species (ROS) and boosting antioxidant enzymes including superoxide dismutase (SOD), catalase (CAT), and guaiacol peroxidase (POD) (Guha, Ravikumar, Mukherjee, Mukherjee, & Kundu, 2018).

Seed invigoration is a promising strategy to improve maize productivity under drought stress (Estevez-Geffriaud, Vicente, Vergara-Diaz, Reinaldo, & Trillas, 2020). It includes techniques such as seed coating, priming, and conditioning (Ilyas, 2012). Seed coating involves applying carriers containing protective agents, microorganisms, micronutrients, or growth regulators. This method enhances seed quality, protects seedlings from biotic and abiotic stresses (Palupi, Ilyas, Machmud, & Widajati, 2017; Rehman *et al*., 2020), and delivers micronutrients that support early growth and yield (Skrzypczak *et al*., 2021).

Previous studies have emphasized nano seed coating as an effective strategy for micronutrient delivery, particularly in improving seed germination and seedling vigor. ZnO NPs enhance maize germination and early growth by increasing zinc uptake and stimulating indole-3-acetic acid synthesis (Adhikari, Kundu, & Rao, 2016). Fe_3O_4 NPs improve seedling development by facilitating iron translocation (Lau *et al*., 2020), while SiO_2 NPs boost antioxidant enzyme activity and reduce malondialdehyde accumulation, preserving seed quality during storage (Tian *et al*., 2019).

Limited information is available on the effectiveness of ZnO, Fe_3O_4, and SiO_2 nano-seed coatings in enhancing maize drought resilience, particularly under Indonesian agro-environmental conditions. Therefore, this study aimed to evaluate the effectiveness of these NPs in improving maize germination and early seedling growth under polyethylene glycol (PEG)-induced drought stress.

2. Materials and Methods

This research was conducted from June to October 2023 at the Seed Science and Technology Laboratory, Department of Agronomy and Horticulture, Faculty of Agriculture, Bogor Agricultural University, Indonesia. Lamuru maize seeds were sourced from the Indonesian Cereals Research Institute (ICERI), Maros, South Sulawesi. The seeds, harvested on June 20, 2022, and quality-tested on July 25, 2022, had 90% germination and 11.6% moisture content. They were stored at 20 ± 1 °C and 50% relative humidity and used in July 2023.

The experiment was conducted using a split-plot design based on a randomized complete block design (RCBD). The main plot factor was osmotic stress at three levels: 0, –0.15, and –0.30 MPa. The subplot factor consisted of ten seed film coating treatments with NPs: an untreated control; ZnO at 15, 25, and 50 mg L^{-1}; Fe_3O_4 at 100, 200, and 300 mg L^{-1}; and SiO_2 at 300, 600, and 900 mg L^{-1}. The 30 treatment combinations were replicated three times, with each replicate containing 50 seeds, totaling 90 experimental units.

2.1 Nano-particles (NPs)

Analytical grade ZnO, Fe_3O_4, and SiO_2 NPs for seed coating were procured from Nano Research Company NRE Lab, **ITNANO™** (Medan, Indonesia). Characterization data showed ZnO NPs had a particle size of 57 nm, crystallite size of 15–18 nm, molecular weight of 81.38 g mol^{-1}, and 99% purity. Fe_3O_4 NPs exhibited a particle size of approximately 58 nm, a crystallite size of 16 nm, a molecular weight of 231.53 g mol^{-1}, and 99% purity. SiO_2 NPs had an 8.6 nm crystallite size, molecular weight of 60.08 g mol^{-1}, and 98% purity. Particle sizes were measured using scanning electron microscopy (SEM), while crystallite sizes were determined by X-ray diffraction (XRD).

2.2 Seed coating

Seeds were surface-sterilized in 0.5% sodium hypochlorite for 10 min, rinsed three times with distilled water, and once with deionized water. Coating treatments included 2.5% polyvinyl alcohol (PVA) and 5% tapioca polymer (Marwanto *et al*., 2020), combined with ZnO NPs (15, 25, and 50 mg L^{-1}), Fe_3O_4 NPs (100, 200, and 300 mg L^{-1}), and SiO_2 NPs (300, 600, and 900 mg L^{-1}). The polymer solution was prepared by dissolving the polymer in 100 mL of deionized water. Seeds were coated by handshaking with the nanoparticle-polymer solution in a closed container for 15 min and air-dried to approximately 11% moisture content.

2.3 Drought stress simulation and determination of seed germination indices

Germination tests were conducted using sterilized sand as the medium, sieved through a 2 mm mesh (ISTA, 2018). Each plastic box (16 × 11 × 5 cm) contained 250 g of sand and 25 seeds, incubated at 25 ± 1 °C with ~60% relative humidity, monitored using an HTC-2 digital thermo-hygrometer. PEG 6000 was used to simulate osmotic potentials of 0, −0.15, and −0.30 MPa. Treatments were maintained from sowing until day 7. Watering was done with distilled water for the control and PEG solutions for drought treatments, maintaining field capacity at 37 mL per container. Sand moisture was monitored daily, with rewatering as needed using the respective solutions.

The in-sand method was used to assess germination rate (GR), first count germination (FCG), speed of germination (SG), dry weight of normal seedlings (DW), and seedling growth rate (SGR). Radicle emergence (RE) was assessed using the between-paper (BP) method, where seeds were placed between layers of kitchen paper towels inside plastic boxes. Three layers were placed below and two above the seeds, moistened with ~16 mL of distilled water or PEG solution according to the treatment. Paper towels were kept moist throughout without adding extra solution. Tests were performed under ambient laboratory lighting without artificial illumination.

To evaluate drought stress effects, germination and seedling growth parameters were measured. GR was calculated as the percentage of normal seedlings at the first count (day 4) and final count (day 7), following ISTA (2018) guidelines.

$$\text{GR (\%)} = \frac{\text{Number of normal seedling at final count}}{\text{Total number of seeds tested}} \text{ x } 100\%$$

FCG was calculated based on the percentage of normal seedlings in the first count of the GR test.

$$\text{FCG (\%)} = \frac{\text{Number of normal seedling at first count}}{\text{Total number of seeds tested}} \times 100\%$$

SG was observed based on the emergence of normal seedlings every 24 h (etmal) during the germination test (seven days) (Sadjad, 1994).

$$\text{SG (\%NS etmal}^{-1}) = \sum(\text{\%ns/etmal})$$

DW was measured from normal seedlings at the final count after oven-drying at 80 °C for 24 hours (ISTA, 1995), and expressed as total dry weight per replicate. RE was calculated as the percentage of seeds with radicles at least 2 mm long within 51 ± 15 minutes at 25 ± 1 °C (Khusna, Zamzami, & Ilyas, 2021). SGR was determined as the ratio of the total dry weight of normal seedlings (ISTA, 1995).

$$\text{SGR (mg/seedling)} = \frac{\text{Seedling dry weight (mg)}}{\text{Total number of normal seedlings}}$$

The malondialdehyde (MDA) content was measured on day 7 using the thiobarbituric acid method (Liu *et al.*, 2019).

2.4 Statistical analysis

Data were analyzed using R Studio version 2023.06.1 via analysis of variance (ANOVA). Treatment means were compared using Duncan's multiple range test (DMRT) at a significance level of α = 0.05.

3. Results

The results indicated that drought stress reduced GR in untreated seeds (control), whereas nano seed coatings with ZnO (15 and 25 mg L^{-1}) and Fe_3O_4 (300 mg L^{-1}) maintained GR levels. At −0.15 MPa, ZnO and Fe_3O_4 coatings significantly improved GR compared to the control. Under more severe drought (−0.30 MPa), all nano seed coating treatments resulted in higher GR than the control (Table 1).

The effect of nano seed coating on FCG under drought stress is presented in Table 2. The FCG of control seeds declined from 35% to 17% and 15% at −0.15 MPa and −0.30 MPa, respectively. At −0.15 MPa, FCG was significantly higher than the control in seeds coated with Fe_3O_4 (200 and 300 mg L^{-1}) and SiO_2 (600 and 900 mg L^{-1}). Under −0.30 MPa drought stress, ZnO 25 mg L^{-1} and all tested Fe_3O_4 concentrations significantly increased FCG compared to the control.

Higher SG values indicate more vigorous seeds, as they germinate faster than less vigorous ones. Table 3 shows that nano seed coating influenced germination speed under different drought stress levels. SG of control seeds decreased from 17.6 %NS $etmal^{-1}$ at 0 MPa to 11.2 %NS $etmal^{-1}$ at −0.30 MPa. Treatments with ZnO at 50 mg L^{-1} and Fe_3O_4 of 300 mg L^{-1} maintained SG across drought levels. Under −0.30 MPa stress, all nano seed coating treatments, except ZnO 25 mg L^{-1} and SiO_2 900 mg L^{-1}, significantly increased SG compared to the control.

Table 1. Effect of nano-seed coating and drought stress on the germination rate (%) of maize seeds

Nano seed coating (mg L^{-1})	Drought stress (MPa)		
	0	-0.15	-0.30
Control	83.0 CDa	75.3 Eb	49.0 Cc
ZnO 15	88.0 ABCa	84.0 ABCa	80.0 Aa
ZnO 25	77.3 Da	84.7 ABa	76.0 Aa
ZnO 50	88.0 ABCa	87.0 ABab	80.0 Ab
Fe_3O_4 100	88.0 ABCa	90.7 Aa	78.0 Ab
Fe_3O_4 200	94.0 Aa	86.0 ABb	81.0 Ac
Fe_3O_4 300	83.3 BCDa	83.3 ABCDa	83.3 Aa
SiO_2 300	81.3 CDa	76.0 DEb	79.0 Aab
SiO_2 600	91.3 ABCa	82.0 BCDEb	75.0 ABb
SiO_2 900	93.3 ABa	77.0 CDEb	68.0 Bb

Note: Numbers followed by the same capital letter in the same column or the same small letter in the same row indicate that these values are not significantly different based on DMRT at the α = 5%.

Table 2. Effect of nano-seed coating and drought stress on the first count germination (%) of maize seeds

Nano seed coating (mg L^{-1})	Drought stress (MPa)		
	0	-0.15	-0.30
Control	35.0 Ca	17.0 Eb	15.0 DEb
ZnO 15	34.0 Ca	18.0 Eb	20.0 CDb
ZnO 25	17.0 Eb	18.0 Eb	33.0 Aa
ZnO 50	25.0 Da	22.0 DEa	20.0 CDa
Fe_3O_4 100	24.0 Db	25.0 CDEb	28.0 ABa
Fe_3O_4 200	36.0 Ca	40.0 Aa	24.0 BCb
Fe_3O_4 300	45.0 Ba	29.0 ABCDb	30.0 ABb
SiO_2 300	24.0 Dab	27.0 BCDEa	15.3 DEb
SiO_2 600	57.0 Aa	37.0 ABb	13.0 Ec
SiO_2 900	29.0 CDa	35.0 ABCa	20.0 CDa

Note: Numbers followed by the same capital letter in the same column or the same small letter in the same row indicate that these values are not significantly different based on DMRT at the α = 5%.

Table 3. Effect of nano-seed coating and drought stress on the speed of germination (%NS $etmal^{-1}$) of maize seeds

Nano seed coating (mg L^{-1})	Drought stress (MPa)		
	0	-0.15	-0.30
Control	17.6 Ba	20.0 ABa	11.2 Db
ZnO 15	11.5 Cc	13.8 Db	16.1 Ba
ZnO 25	12.3 Cb	17.7 BCa	10.5 Dc
ZnO 50	18.5 Ba	16.1 Ca	16.7 ABa
Fe_3O_4 100	18.7 Bab	20.1 Aa	17.2 ABb
Fe_3O_4 200	13.2 Cb	19.0 ABa	18.1 ABa
Fe_3O_4 300	18.9 Ba	18.7 ABa	18.7 Aa
SiO_2 300	18.5 Ba	17.6 BCa	16.0 Bb
SiO_2 600	21.0 Aa	18.8 ABb	13.5 Cc
SiO_2 900	12.2 Cb	18.5 ABCa	11.0 Db

Note: Numbers followed by the same capital letter in the same column or the same small letter in the same row indicate that these values are not significantly different based on DMRT at the α = 5%.

Based on Table 4, drought stress significantly reduced the percentage of radicle RE across all treatments, including the control. In untreated seeds, RE decreased markedly from 71.3% at 0 MPa to 45% at −0.15 MPa and further to 17% at −0.30 MPa. However, nano seed coatings with ZnO at 25 and 50 mg L^{-1}, and Fe_3O_4 at 100 and 200 mg L^{-1}, maintained RE levels under increasing drought stress, showing no significant reduction from −0.15 MPa to −0.30 MPa. At −0.30 MPa, all nano-coated seeds exhibited higher RE percentages than the control, with ZnO 50 mg L^{-1} achieving the highest RE under this stress level.

Table 5 shows that under non-stress conditions (0 MPa), the SiO_2 nano-seed coating at 900 mg L^{-1} resulted in the highest DW of normal seedlings. Under −0.15 MPa drought stress, ZnO at 15 and 25 mg L^{-1}, as well as Fe_3O_4 at 300 mg L^{-1}, produced higher DW compared to other treatments. However, at −0.30 MPa, no significant differences in DW were observed among the nano seed coating treatments.

Table 6 shows that nano seed coating with ZnO at 15 and 25 mg L^{-1}, and Fe_3O_4 at 100 and 200 mg L^{-1}, did not reduce SGR under varying drought stress conditions. At −0.15 MPa, Fe_3O_4 at 300 mg L^{-1} produced the highest SGR, significantly outperforming other treatments and the control. However, at 0 MPa and −0.30 MPa, no significant differences in SGR were observed among the nano seed coating treatments. These findings indicate that Fe_3O_4 at moderate concentrations may enhance seedling vigor under mild drought stress.

Our results showed that drought stress increased MDA content in maize seedlings (Table 7). At −0.15 MPa, nano seed coating with Fe_3O_4 at 300 mg L^{-1} significantly reduced MDA levels compared to the control. Under more severe stress (−0.30 MPa), Fe_3O_4 at 300 mg L^{-1} and SiO_2 at 600 mg L^{-1} both significantly decreased MDA content relative to the control, indicating a potential role in mitigating oxidative damage under drought conditions.

Table 4. Effect of nano-seed coating and drought stress on radicle emergence (%) of maize seeds

Nano seed coating (mg L^{-1})	Drought stress (MPa) 0	-0.15	-0.30
Control	71.3 BCDa	45.0 ABb	17.0 Dc
ZnO 15	73.3 ABCDa	50.0 Ab	26.0 Cc
ZnO 25	68.0 Da	44.7 ABb	32.7 BCb
ZnO 50	75.3 ABCDa	36.7 Bb	43.0 Ab
Fe_3O_4 100	76.0 ABCDa	47.3 Ab	35.3 ABb
Fe_3O_4 200	78.7 ABa	36.0 Bb	34.0 BCb
Fe_3O_4 300	77.3 ABCa	47.0 Ab	33.3 BCc
SiO_2 300	69.3 CDa	41.0 ABb	28.0 BCc
SiO_2 600	75.3 ABCDa	49.0 Ab	29.0 BCc
SiO_2 900	80.7 Aa	44.0 ABb	26.0 Cc

Note: Numbers followed by the same capital letter in the same column or the same small letter in the same row indicate that these values are not significantly different based on DMRT at the α = 5%.

Table 5. Effect of nano seed coating and drought stress on the dry weight of normal seedlings (g) of maize seeds

Nano seed coating (mg L^{-1})	Drought stress (MPa) 0	-0.15	-0.30
Control	4.59 BCDa	3.73 Ba	2.76 Ab
ZnO 15	4.50 BCDEa	4.95 Aa	2.90 Ab
ZnO 25	4.50 BCDEa	5.21 Aa	3.50 Ab
ZnO 50	4.20 CDEa	3.90 Ba	3.25 Aa
Fe_3O_4 100	3.89 DEa	3.13 Ba	3.52 Aa
Fe_3O_4 200	3.81 Ea	3.59 Ba	3.39 Aa
Fe_3O_4 300	4.79 ABCb	5.45 Aa	3.57 Ac
SiO_2 300	4.96 ABa	3.35 Bb	2.79 Ab
SiO_2 600	4.30 BCDEa	3.78 Bab	3.12 Ab
SiO_2 900	5.35 Aa	3.62 Bb	3.13 Ab

Note: Numbers followed by the same capital letter in the same column or the same small letter in the same row indicate that these values are not significantly different based on DMRT at the α = 5%.

Table 6. Effect of nano-seed coating and drought stress on the seedling growth rate (mg/normal seedling) of maize seeds

Nano seed coating (mg L^{-1})	Drought stress (MPa) 0	-0.15	-0.30
Control	110 Aa	96 Bab	86 ABb
ZnO 15	114 Aa	86 Ba	91 ABa
ZnO 25	97 ABa	83 Ba	84 Ba
ZnO 50	109 Aa	91 Bb	82 Bb
Fe_3O_4 100	85 Aa	80 Ba	87 Aba
Fe_3O_4 200	103 Aa	83 Ba	102 Aa
Fe_3O_4 300	104 Aa	120 Aa	86 ABb
SiO_2 300	109 Aa	81 Bb	87 ABb
SiO_2 600	104 Aa	91 Bb	90 ABb
SiO_2 900	111 Aa	85 Bb	84 Bb

Note: Numbers followed by the same capital letter in the same column or the same small letter in the same row indicate that these values are not significantly different based on DMRT at the α = 5%.

4. Discussion

Nano seed coating proved beneficial in enhancing the viability and vigor of maize seeds under drought stress. In this study, all nano seed coating treatments exhibited a higher GR compared to the control under severe drought stress (−0.30 MPa). Zaim *et al.* (2023) reported that nanoparticle-based seed coatings improve GR by facilitating water uptake during imbibition and minimizing nutrient loss through leaching, thereby enhancing nutrient availability for early growth. Similarly, at −0.15 MPa, nano seed coatings with ZnO and Fe_3O_4 significantly improved germination percentages relative to the control. Raju and Rai (2017) observed that seed polymer coating with Fe NPs at 25 ppm significantly enhanced GR, SG, seedling dry weight, and FCG in pigeon peas.

Our results demonstrated that nano-seed coatings with ZnO 25 mg L^{-1} and all concentrations of Fe_3O_4 NPs increased FCG under −0.30 MPa drought stress compared to the control. Itroutwar, Kasivelu, Ragumaram, Malaichamy, and Sevathapandian (2020) reported that nanopriming with ZnO at 100 mg L^{-1} enhanced maize FCG, leaf length, and width. Similarly, Guha *et al.* (2018) found that nanopriming with 20 mg L^{-1} zero-valent iron (nZVI) increased FCG by

Table 7. Effect of nano-seed coating and drought stress on MDA content (μmol g^{-1}) of maize seeds

Nano seed coating (mg L^{-1})	Drought stress (MPa)		
	0	-0.15	-0.30
Control	10.36 Ac	26.21 Ab	60.21 Aa
ZnO 15	9.21 Ab	22.86 Ab	48.11 ABa
Fe_3O_4 300	8.42 Ac	13.76 Bb	29.00 Ba
SiO_2 600	9.65 Ac	20.01 Ab	32.47 Ba

Note: Numbers followed by the same capital letter in the same column or the same small letter in the same row indicate that these values are not significantly different based on DMRT at the α = 5%.

1.95-fold and improved water uptake in rice. The improved germination may be linked to enhanced water uptake, triggering oxidative respiration, where accumulated H_2O_2 interacts with gibberellic acid, promoting α-amylase activity, starch hydrolysis, and ultimately, seedling vigor (Rai-Kalal, Tomar, & Jajoo, 2021).

The present study demonstrated that nano seed coatings of ZnO 50 mg L^{-1} and Fe_3O_4 300 mg L^{-1} did not reduce SG under varying drought stress levels. Younes, Hassan, Elkady, Hamed, and Dawood (2020) attributed the acceleration of germination to the ability of NPs to penetrate the seed coat, activating embryo differentiation by triggering enzymes involved in breaking seed dormancy, thereby enhancing germination speed. Additionally, all nano seed coatings increased RE percentages compared to the control, with ZnO 50 mg L^{-1} showing the highest RE at -0.30 MPa. Similarly, Korishettar *et al.* (2016) reported that polymer seed coating with 500 ppm Zn and Fe nanoparticles enhanced hydrolytic enzyme activity during early germination stages in pigeon peas, improving SG and early emergence.

Although drought stress reduces maize seedling dry weight (DW), nano-seed coatings with ZnO (15 and 25 mg L^{-1}) and Fe_3O_4 (300 mg L^{-1}) significantly improved DW under –0.15 MPa stress. Similarly, Korishettar *et al.* (2017) reported that seed polymer coatings containing Fe and Zn nanoparticles (500 ppm and 750 ppm, respectively) enhanced DW in pigeon peas, alongside increased enzymatic activities related to respiration and nutrient mobilization. The improved dry matter accumulation in maize seedlings likely results from enhanced efficiency in utilizing seed reserves (Andrade, Coelho, & Padilha, 2019).

The highest SGR at -0.15 MPa drought stress was observed with Fe_3O_4 nano-seed coating at 300 mg L^{-1}. Li *et al.* (2021) reported that Fe_3O_4 NPs at 50 mg L^{-1} increased chlorophyll content in rice by 26.9% and mitigated stress by reducing oxidative damage and lowering concentrations of stress-related phytohormones such as gibberellin and indole-3-acetic acid. Similarly, iron oxide nanoparticles (IO-NPs) have been shown to enhance maize growth, chlorophyll content, and stem and leaf length. Acting as phytoferritin cores within plants, IO-NPs are not fully dissolved and may serve as a slow-release iron source. Therefore, IO-NPs have the potential as a novel iron fertilizer for crop improvement (Pariona, Martinez, Hdz-Garcia, Cruz, & Hernandez-Valdes, 2017).

The elevated MDA levels observed under drought stress indicate oxidative damage caused by lipid peroxidation. MDA serves as a key marker of membrane damage resulting from excessive accumulation of ROS. Mazhar *et al.* (2022a) reported that drought stress disrupts the lipid bilayer structure of membranes, leading to increased MDA levels. In this study, nano seed coatings with Fe_3O_4 at 300 mg L^{-1} and SiO_2 at 600 mg L^{-1} significantly reduced MDA content under -0.30 MPa osmotic stress, suggesting a protective effect against oxidative damage.

The mechanisms by which these NPs reduce oxidative stress vary. Fe_3O_4 NPs act as nano-catalysts by enhancing α-amylase activity, accelerating starch breakdown, and supporting early seedling metabolism (Afzal, Sharma, & Singh, 2021). They also serve as essential cofactors for antioxidant enzymes such as SOD, POD, and CAT, thereby enhancing ROS detoxification (Alharby & Ali, 2022; Elanchezhian *et al*., 2017). Additionally, Fe_3O_4 nanoparticles regulate respiration, osmoregulation, and secondary metabolism under drought stress conditions (Moradi & Siosemardeh, 2023; Rezayian, Niknam, & Arabloo, 2023).

In contrast, SiO_2 NPs protect membrane stability by suppressing ROS-induced aquaporin overactivity and enhancing antioxidant defenses (Sharf-Eldin *et al*., 2023). They also facilitate osmotic adjustment through the accumulation of soluble sugars and amino acids, as well as by promoting K^+ translocation (Zargar, Mahajan, Bhat, Nazir, & Deshmukh, 2019). These biochemical processes contribute to maintaining cellular homeostasis under stress conditions. The observed reduction in MDA thus not only serves as a biochemical marker of stress alleviation but also correlates with improved seedling vigor. This finding aligns with previous studies showing that Fe and Si nanoparticle priming decreased MDA levels and enhanced drought tolerance in wheat and flax (Mazhar *et al*., 2022b; Raza *et al*., 2023).

5. Conclusions

This study demonstrated that nano seed coating is a promising strategy to enhance maize seedling performance under drought stress. Among the treatments, ZnO at 50 mg L^{-1} resulted in the highest radicle emergence (43%) under -0.30 MPa, indicating superior effectiveness compared to other formulations and the control. Fe_3O_4 at 300 mg L^{-1} improved seed viability, vigor, and seedling growth, while Fe_3O_4 and SiO_2 coatings reduced oxidative stress by lowering MDA levels. These findings suggest that nano seed coating, particularly ZnO at 50 mg L^{-1}, could be integrated into seed enhancement protocols to improve maize establishment in drought-prone areas. However, further large-scale field trials and environmental impact assessments are necessary before widespread adoption in sustainable agriculture.

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Author Contributions

Widia Sri Fatma: Investigation, Methodology, Data curation, Data analysis, Writing – original draft. Satriyas Ilyas: Conceptualization, Methodology, Supervision, Writing

– review and editing, Funding acquisition. Sri Wilarso Budi: Conceptualization, Methodology, Supervision. Ladiyani Retno Widowati: Conceptualization, Methodology, Supervision.

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