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Benefits of Silicon Nanoparticles Priming for Zea mays L. Seed Germination and Seedling Growth Under Cadmium Stress

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Abstract: The effect of silicon nanoparticles on seed germination and seedling growth of *Zea mays* L. grown under cadmium (Cd) stress was estimated. The seeds were treated with combinations of four $CdCl_2$ concentrations (0, 25, 50 and 100 mg/L) and four Si NPs concentrations (0, 5, 10 and 20 mg/L) for 4 h before germinating in distilled water. Si NPs significantly enhanced seed germination traits (final germination percentage, mean daily germination, germination rate index, peak value and germination value) and seedling growth (seedling weight, and vigor indices) under cadmium stress but decreased mean germination time and seed mortality under cadmium stress. Therefore, the application of Si NPs could reduce Cd toxicity and enhance seed germination and seedling development in *Zea mays* L.

keywords: Cadmium, Silicon nanoparticles, Seed germination, *Zea mays* L.

1.Introduction

The three major basic cereals of the world—wheat, rice, and maize—make up a significant component of the food system, providing about 42% of the world's average diet and 37% of the total protein intake during the period 2016–2018 [1]. Maize has become the most widely grown cereal in the world with an annual production reaching 1 billion metric tons [2].

Since a few decades ago, the pollution of soil with heavy metals has become a severe threat to the world's food security, and the responsibility on society to clean it up has been steadily growing [3]. Cadmium (Cd) is one of the most hazardous heavy metals because of its non-biodegradable characteristics and high accumulation in living systems [4]. Industrial applications, pesticide and fertilizer consumption, air deposits, sewage discharges, mining and burning are the major causes of Cd entry into the soil system [5, 6]. Incredibly, high Cd levels can lead to a reduction in plant development and growth [7, 8] in addition to a decrease in plant yield [9]. The most vital stage of the plant life cycle is supposed to be seed germination [10]. Many plant species showed reductions in seed germination and seedling growth when exposed to heavy metals [11].

Maize is a largely consumed cereal that is resistant to Cd toxicity [12, 13]. Maize has been used as the best model plant for Cd bioremediation and the establishment of an alternative source of income from polluted soils because of its rapid growth and high biomass yield [14, 15].

Under stressful conditions, silicon (Si) can stimulate the growth and development of plants [16, 17]. It has been demonstrated that Si can lower the toxicity of several heavy metals in plants including Cd [18, 19]. Nanotechnology is a developing strategy to improve plant vigor, production and nutritive value under stress conditions. [20]. The nanoparticles (NPs) may increase crop output, seed germination, seedling vitality, and plant photosynthesis in addition to reducing the incidence of diseases and minimizing the loss of nutrients [21]. Among several NPs, the Si NPs have the capacity to improve plant biomass and photosynthesis under stressful conditions [22, 23, 24]. It has been reported that Si NPs have alleviated cadmium (Cd) toxicity in cereals, particularly rice and maize [25, 26]; generally, these NPs play a defensive role for plants against environmental stress conditions, including heavy metal stresses [27, 28, 29].

The purpose of the current study was to determine how Si nanoparticles can affect seed germination, seedling characteristics, and seedling vitality in maize (*Zea mays*) exposed to Cd stress.

2. Materials and methods

2.1. Plant materials and chemicals

Maize (SW10 hybrid.) seeds were kindly provided by the Agriculture Research Center, Ministry of Agriculture, Giza, Egypt. Powdered Si NPs (size of 9-27 nm and purity of 99%) were purchased from Nanotech Egypt (https://www.nanotecheg.com/main), while $CdCl_2$ was purchased from Sigma-Aldrich (https://www.sigmaaldrich.com/EG/en). Four concentrations of Si NPs were used (0, 5, 10 and 20 g/L), and the nanoparticles were dispersed in deionized water by ultrasonication for 15 minutes.

2.2. Experimental design and growth conditions

Healthy, uniform maize seeds were surface-sterilized by immersing for 10 min in 0.1% sodium hypochlorite. The seeds were then washed several times with sterilized water. Seeds were subjected to treatment combinations of four concentrations of cadmium chloride ($CdCl_2$) (0, 25, 50 and100 mg/L) and four concentrations of silicon oxide nanoparticles (Si NPs) (0, 5, 10 and 20 mg/L). For every treatment combination, ten seeds were immersed in the treatment solution for 4 h then transferred into Petri dishes lined with cotton wetted with distilled water. The experiment was conducted at 25°C (12 h of light and 12 h of darkness) for 7 days.

2.3. Estimation of seed germination traits

The number of germinated seeds was counted daily. The following formulas were used to determine the seed germination traits:

Final germination percentage (FGP)= $\frac{Total\ number\ of\ germinants}{Total\ number\ of\ seeds} \times 100$ (%) [30]. (1)

Mean germination time (MGT)= Σ ($n_i d_i$) / Σn_i, where n_i= number of germinated seeds in di, day di and Σn_i = total number of seeds germinated during seven days [31].(2)

Mean daily germination (MDG) = $\frac{Total\ number\ of\ germinated\ seed\ at\ the\ final\ day}{Number\ of\ days\ to\ final\ ermination}$ (% d^{-1})[30].(3)

Germination rate index (GRI) = (n_1t_1) + (n_2t_2) + …+ (n_xt_x) / X_n, where t_1 is the number of days from the start to first germination, n_1 is the number of germinated seeds at the first day of germination and Xn is the total number of germinated seeds. Also, GRI = $\Sigma G_t/T_t$ Where, G_t is germination percentage at t^{th} day and T_t is the days of germination [32]. (4)

Daily germination speed (DGS) was calculated as:

(DGS) = $\frac{cumulative\ germination\ \%\ at\ time\ ti}{ti}$ (% d^{-1}) The cumulative germination% is the cumulative number of germinants as percentage of the total number of seeds [30]. (5)

Peak value (PV) is the maximum MDG calculated as:

(PV) = $\frac{Final\ germination\ percentage\ \%}{Number\ of\ days}$ (% d^{-1}) [30]. (6)

Germination value (GV) also called Czbator index of germination velocity, was calculated as:

GV= PV × final MDG (% d^{-1}) Where, PV is the peak value and MDG is the mean daily germination [30]. (7)

Seed mortality (SM) = $\frac{Number\ of\ non\ germinated\ seeds}{Number\ of\ observation\ days} \times 100$ (%) [33].(8)

2.4. Estimation of seedling growth traits

On the final day of the germination experiment, plumule and radicle lengths and seedling fresh weight were recorded for three seedlings. Seedlings were dried in an oven at 70°C until constant weight to determine dry weight (Lin et al., 2012). The vigor indexes of seedlings were calculated according to Orchard [34] as:

Seed Vigor index II= germination (%)× seedling dry weight (radicle+ plumule) (9)

2.5. Statistical analysis

Data of seed germination and seedling growth were obtained using a three-replication and were subjected to Two-way ANOVA using the general linear model and the mean differences were compared using Duncan's multiple range at P ≤ 0.05 using SPSS 16.0 (IBM, Armonk, New York, USA). Data Normality was tested using Shapiro-Wilk normality testing at 0.05 level. The figure was plotted using Graph Builder.

3. Results

3.1. Seedling germination traits and growth parameters of *Zea mays* treated with Si NPs

Results presented in Table (1) showed significant effects of Si NPs on all seed germination traits: final seed germination percentage (FGP), germination rate index (GRI), mean germination time (MGT), mean daily germination (MDG), peak value (PV), germination value (GV) and seed mortality (SM).

The data analysis of the effects of Si NPs treatments on the parameters of the seedlings (such as plumule length, radicle length, seedling length, seedling fresh weight, dry weight, and seedling water content) revealed that there were significant impacts of the various concentrations of Si NPs as observed in Table (2).

The highest plumule length was recorded in T2 (10 mg/L Si NPs) at 19.0 cm while the maximum values of seedling length, fresh weight and water content were observed in T3 (20 mg/L Si NP) at 36.0 cm, 0.78 g and 82.7%, respectively, compared with T0 (0 mg/L Si NPs) at 17.6 cm, 3.33 cm, 0.69 g and 70.80 %.

The results indicated that T2 (10 mg/L Si NPs) reduced plumule and seedling inhibition by 0.93 and 0.95 in addition, T2 (10 mg/L Si NPs) increased Seedling Vigor Index II by 18.1, respectively, compared with T0 (0 mg/L Si NPs), while T1 (5 mg/L Si NPs) decreased radicle inhibition by 0.96 compared with T0 (0 mg/L Si NPs) as shown in Table (3).

3.2. Seedling germination traits and growth parameters of *Zea mays* treated with $CdCl_2$

Results recorded in Table (1) showed no significant effects of $CdCl_2$ on all seed germination traits: final seed germination percentage (FGP), germination rate index (GRI), mean germination time (MGT), mean daily germination (MDG), peak value (PV), germination value (GV) and seed mortality (SM).

The data analysis of the effects of the different treatments of $CdCl_2$ on the parameters of the seedlings (such as plumule length, radicle length, seedling length, seedling fresh weight, dry weight, and seedling water content) revealed that there were no observed differences.

The results showed that exposure to higher concentration of cadmium (100 mg/L $CdCl_2$) reduced plumule length, radicle length, seedling length, and seedling fresh weight by 1.67 cm, 1.67 cm, 3.33 cm and 0.29 g, respectively, compared with T0 (0 mg/L $CdCl_2$) of 17.6 cm, 17.0 cm, 34.6 cm and 0.69 g, respectively, as observed in Table (2).

The data indicated that the higher concentration of Cd (100 mg/L $CdCl_2$) stimulated plumule, radicle and seedling inhibition of 11.3, 7.50 and 8.90, while T6 (100 mg/L $CdCl_2$) reduced Seedling Vigor index II (SV II) to 4.12 compared with T0 (0 mg/L $CdCl_2$) of 19.0, respectively, as shown in Table (3).

3.3. Seedling germination traits and growth parameters of *Zea mays* treated with the combinations of Si NPs and $CdCl_2$

The outcomes presented in Table (1) revealed significant effects of Si NPs and $CdCl_2$ interactions on almost all seed germination parameters including final seed germination percentage (FGP), mean daily germination (MDG), peak value (PV), germination value (GV) and seed mortality (SM). But the interactions exerted a non-significant effect on the mean germination time (MGT) and germination rate index (GRI).

The results indicated that there were significant effects of different Si NPs and $CdCl_2$ combinations on the parameters of the seedlings (such as plumule length, radicle length, seedling length, seedling fresh weight, dry weight, and seedling water content) as shown in Table (2).

The data arising from the different combinations of $CdCl_2$ and Si NPs showed that the treatments T11 (10 mg/L Si NPs + 50 mg/L $CdCl_2$), T12 (10 mg/L Si NPs + 100 mg/L $CdCl_2$), T13 (20 mg/L Si NPs + 25 mg/L $CdCl_2$) and T14 (20 mg/L Si NPs + 50mg/L $CdCl_2$) stimulated plumule length, radicle length, seedling length, seedling fresh and dry weight and water content compared with maximum concentration of $CdCl_2$ (50 and 100 mg/L) as reported in Table (2).

The results also showed that the treatments T11 (10 mg/L Si NPs + 50 mg/L $CdCl_2$), T12 (10 mg/L Si NPs + 100 mg/L $CdCl_2$), T13 (20 mg/L Si NPs + 25 mg/L $CdCl_2$) and T14 (20 mg/L Si NPs + 50mg/L $CdCl_2$) reduced the value of plumule inhibition, radicle inhibition and seedling inhibition while these treatments had positive effects on seedling vigor index I and Seedling Vigor index II compared with higher concentrations of $CdCl_2$ (50 and 100 mg/L) as observed in Table (3).

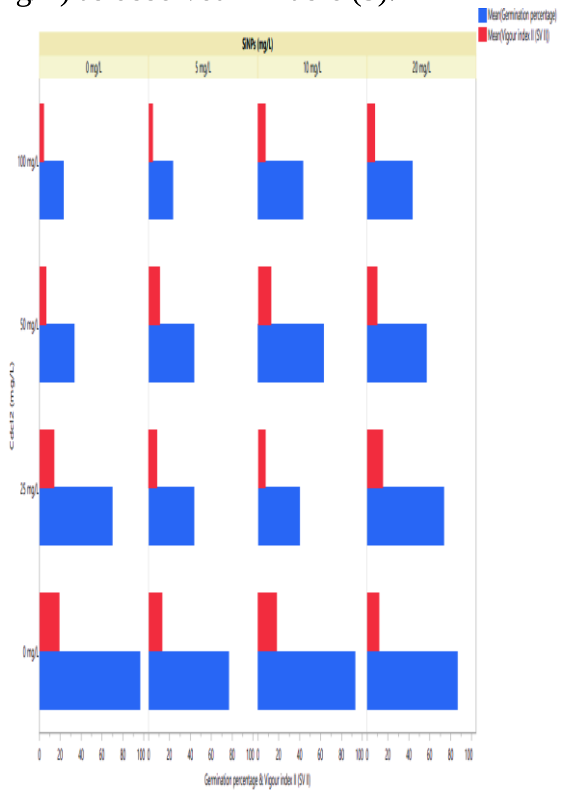

Fig. 1. Effect of silicon nanoparticles and cadmium stress on seed germination and seedling vigor of *Zea mays* L.

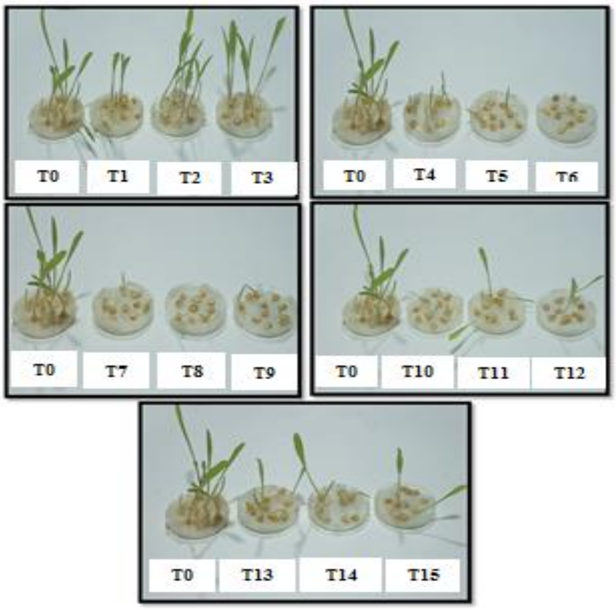

Fig.2 Effects of silicon nanoparticles and cadmium on seed germination traits of *Zea mays* L. Abbreviations: (T0 =0 mg/L Si or 0 mg/L $CdCl_2$, T1 = 5 mg/L Si N, T2 = 10 mg/L Si NPs, T3 = 20 mg/L Si NPs, T4 = 25 mg/L $CdCl_2$, T5 = 50 mg/L $CdCl_2$, T6 = 100 mg/L $CdCl_2$, T7 = 5 mg/L Si NPs + 25mg/L $CdCl_2$, T8 = 5 mg/L Si NPs + 50mg/L $CdCl_2$, T9 = 5 mg/L Si NPs + 100 mg/L $CdCl_2$, T10 = 10 mg/L Si NPs + 25 mg/L $CdCl_2$, T11 = 10 mg/L Si NPs + 50 mg/L $CdCl_2$, T12 = 10 mg/L Si NPs + 100 mg/L $CdCl_2$, T13 = 20 mg/L Si NPs + 25 mg/L $CdCl_2$, T14 = 20 mg/L Si NPs + 50 mg/L $CdCl_2$, T15 = 20 mg/L Si NPs + 100 mg/L $CdCl_2$).

Table 1 Two-way ANOVA showing the effect of the main factors: Si NPs and $CdCl_2$ and their interaction on seed germination traits of *Zea mays* L.

Variable and source of variation	**df**	**F**	**P**		**Variable and source ofvariation**	**df**	**F**	**P**
FGP					**MDG**			
Si NPs	3	45.89	.0000 ***		Si NPs	3	46.14	.0000 ***
$CdCl_2$	3	2.81	.0546 ns		$CdCl_2$	3	2.78	.0565 ns
Si NPs. × $CdCl_2$	9	6.81	.0000 ***		Si NPs. × $CdCl_2$	9	6.78	.0000 ***
GRI					**PV**			
Si NPs	3	3.15	.0380 *		Si NPs	3	45.95	.0000 ***
$CdCl_2$	3	0.87	.4621 ns		$CdCl_2$	3	2.81	.0546 ns
Si NPs. × $CdCl_2$	9	0.92	.5187 ns		Si NPs. × $CdCl_2$	9	6.81	.0000 ***
MGT					**GV**			
Si NPs	3	3.39	.0297 *		Si NPs	3	60.95	.0000 ***
$CdCl_2$	3	0.71	.5516 ns		$CdCl_2$	3	2.25	.1015 ns
Si NPs. × $CdCl_2$	9	0.88	.5520 ns		Si NPs. × $CdCl_2$	9	6.02	.0001 ***
SM								
Si NPs	3	45.88	.0000 ***					
$CdCl_2$	3	2.81	.0546 ns					
Si NPs. × $CdCl_2$	9	6.811	.0000 ***					

Table 2 Effect of silicon nanoparticles (Si NPs) and cadmium stress ($CdCl_2$) on seedling growth of *Zea mays* L. Each value is the mean of three replicates ± SE. Different superscript letters refer to significant differences (*P< 0.05*).

Treatment	Plumule length(cm)	Radicle length(cm)	Seedling length(cm)	Seedling FW (g/seedling)	Seedling DW (g/seedling)	Water content (% FW)
0 mg/L Si NPs						
0 mg/L $CdCl_2$	17.67±1.36^{a}	17.00±0.58^{a}	34.67±1.92^{a}	0.69±0.04^{b}	0.20±0.03^{b}	70.80±4.86^{c}
25 mg/L $CdCl_2$	9.17±1.01^{c}	7.00±1.53^{e}	16.17±2.49^{d}	0.49±0.08^{e}	0.20±0.04^{b}	60.40±2.20^{e}
50 mg/L $CdCl_2$	2.17±0.60^{f}	4.00±0.58^{h}	6.17±1.09^{g}	0.33±0.03i	0.20±0.03^{b}	39.83±6.58^{j}
100 mg/L $CdCl_2$	1.67±0.33^{f}	1.67±0.88i	3.33±1.20h	0.29±0.03^{k}	0.17±0.01^{c}	40.62±3.97^{j}
5 mg/L Si NPs						
0 mg/L $CdCl_2$	16.00±1.15^{a}	17.67±0.33^{a}	33.67±1.45^{a}	0.64±0.07^{c}	0.17±0.01^{c}	72.69±3.60^{b}
25 mg/L $CdCl_2$	2.67±0.33^{f}	2.33±0.33^{i}	5.00±0.58^{h}	0.41±0.06^{h}	0.18±0.02^{b}	54.67±1.53^{g}
50 mg/L $CdCl_2$	7.00±1.73^{d}	6.33±0.88^{f}	13.33±2.19^{e}	0.46±0.05^{f}	0.25±0.03^{a}	46.16±1.61^{h}
100 mg/L $CdCl_2$	7.00±2.00^{d}	6.00±3.00^{g}	7.33±1.20^{g}	0.39±0.01^{h}	0.18±0.01^{b}	54.11±1.16^{g}
10 mg/L Si NPs						
0 mg/L $CdCl_2$	19.00±0.58^{a}	15.50±1.85^{b}	32.75±3.64^{a}	0.62±0.05^{d}	0.19±0.01^{b}	70.85±0.63^{c}
25 mg/L $CdCl_2$	3.33±0.33^{f}	4.33±1.20^{h}	13.00±5.00^{e}	0.34±0.04^{i}	0.18±0.01^{b}	44.79±4.53^{i}
50 mg/L $CdCl_2$	11.00±1.15^{b}	9.00±2.08^{d}	20.00±3.00^{c}	0.50±0.03^{e}	0.19±0.05^{b}	62.35±6.50^{d}
100 mg/L $CdCl_2$	11.00±0.58^{c}	12.50±1.50^{c}	23.00±2.00^{b}	0.44±0.03^{h}	0.17±0.01^{c}	62.28±2.57^{e}
20 mg/L Si NPs						
0 mg/L $CdCl_2$	18.33±0.33^{a}	17.67±0.67^{a}	36.00±1.00^{a}	0.78±0.04^{a}	0.13±0.01^{c}	82.77±1.42^{a}
25 mg/L $CdCl_2$	10.67±0.67^{c}	11.33±1.45^{c}	22.00±2.08^{b}	0.46±0.02^{g}	0.20±0.02^{b}	55.48±2.71^{g}
50 mg/L $CdCl_2$	4.33±0.88^{e}	5.33±0.67^{g}	9.67±0.33^{f}	0.39±0.01^{h}	0.17±0.01c	57.15±1.61^{f}
100 mg/L $CdCl_2$	3.33±0.33^{f}	3.67±0.88^{h}	6.67±0.88^{g}	0.31±0.03^{j}	0.17±0.01^{c}	45.51±3.38^{i}

Table 3 Effect of silicon nanoparticles (Si NPs) and cadmium stress ($CdCl_2$) and their combination on the seedling germination traits of *Zea mays* L. Each value is the mean of three replicates ± SE. Significant differences are denoted by different superscript letters ($P < 0.05$).

Treatment	Plumule inhibition	Radicleinhibition	Seedling inhibition	Seedling vigor index II (SV II)
0 mg/L Si NPs				
0 mg/L $CdCl_2$	17.67±1.36^{a}	17.00±0.58^{a}	34.67±1.92^{a}	19.05±2.22^{a}
25 mg/L $CdCl_2$	9.17±1.01^{c}	7.00±1.53^{e}	16.17±2.49^{d}	14.08±3.27^{d}
50 mg/L $CdCl_2$	2.17±0.60^{f}	4.00±0.58^{h}	6.17±1.09^{g}	6.62±0.82^{j}
100 mg/L $CdCl_2$	1.67±0.33^{f}	1.67±0.88i	3.33±1.20h	4.12±1.65^{k}
5 mg/L Si NPs				
0 mg/L $CdCl_2$	16.00±1.15^{a}	17.67±0.33^{a}	33.67±1.45^{a}	12.88±2.05^{e}
25 mg/L $CdCl_2$	2.67±0.33^{f}	2.33±0.33^{i}	5.00±0.58^{h}	8.17±2.05^{i}
50 mg/L $CdCl_2$	7.00±1.73^{d}	6.33±0.88^{f}	13.33±2.19^{e}	10.66±1.68^{g}
100 mg/L $CdCl_2$	7.00±2.00^{d}	6.00±3.00^{g}	7.33±1.20^{g}	4.03±1.02^{k}
10 mg/L Si NPs				
0 mg/L $CdCl_2$	19.00±0.58^{a}	15.50±1.85^{b}	32.75±3.64^{a}	18.13±1.03^{b}
25 mg/L $CdCl_2$	3.33±0.33^{f}	4.33±1.20^{h}	13.00±5.00^{e}	7.19±0.80^{i}
50 mg/L $CdCl_2$	11.00±1.15^{b}	9.00±2.08^{d}	20.00±3.00^{c}	12.54±3.84^{f}
100 mg/L $CdCl_2$	11.00±0.58^{c}	12.50±1.50^{c}	23.00±2.00^{b}	7.30±1.44^{i}
20 mg/L Si NPs				
0 mg/L $CdCl_2$	18.33±0.33^{a}	17.67±0.67^{a}	36.00±1.00^{a}	11.56±0.38^{g}
25 mg/L $CdCl_2$	10.67±0.67^{c}	11.33±1.45^{c}	22.00±2.08^{b}	15.02±1.74^{c}
50 mg/L $CdCl_2$	4.33±0.88^{e}	5.33±0.67^{g}	9.67±0.33^{f}	9.67±1.16^{h}
100 mg/L $CdCl_2$	3.33±0.33^{f}	3.67±0.88^{h}	6.67±0.88^{g}	7.24±0.94^{i}

Discussion

It is known that seed germination plays a significant role in plant growth and development as it is the initial stage of plant structure building [35]. The contamination of soil with heavy metals is a serious issue because of their harmful impacts on crops [21, 36].

Compared to all other heavy metals, cadmium has more serious impacts. Utilization of silicon nanoparticles has been found to be more effective than fertilizer application to reduce cadmium stress [37]. Si NPs alleviate

Cd stress by enhancing plant tolerance to Cd stress through reducing soil Cd bioavailability and mobility, preventing the uptake and movement of Cd, sequestering Cd into vacuoles, and regulating the rate of transpiration [22]. Si has an inhibitory effect on Cd transport from the roots to the plumules that has been observed in various plants [38, 39]. The purpose of the current study was to determine how Si nanoparticles affected seed germination, seedling characteristics, and seedling vitality in maize (*Zea mays*) exposed to Cd during the germination stage. All seed germination parameters were significantly reduced after Cd treatment (FGP, GRI, MDG, PV and GV) in *Z. mays*, whereas MGT and SM increased. The highest increase in MGT and SM and the most negative effect on seed germination parameters were recorded in Cd (100 mg/L). Our findings were consistent with previous research, which found a decrease in seed germination percentage as Cd concentration increased in canola, wheat, and safflower [40]. [40].

In the current experiment, application of Si NPs stimulated seed capacity by enhancing the seed germination parameters. Si NPs concentrations as high as 10 mg/L improved seed germination parameters. The use of 20 mg/L of Si NPs was found to be the most effective treatment, providing the highest values for FGP, MDG, PV and GV. These outcomes support the findings of Nair [41] who noticed that the presence of FITC-labeled silica nanoparticles improved the germination of rice seedlings. An Increase in the rate of germination may be due to the uptake and consumption of Si NPs by plant seeds [42].

Our results showed that Si NPs can reduce Cd toxicity in *Z. mays* at the germination stage by increasing FGP, GRI, MDG, PV and GV. However, the outcomes revealed that Si NPs decreased MGT and SM in comparison with those in Cd-treated seeds. These results are in agreement with that of Emamverdian [43] who revealed that Si NPs can diminish Cd toxic effects in Moso bamboo (*Phyllostachys edulis*) at the seedling stage by improving the germination index (GI), germination percentage (GP), and germination rate (GR). Among the combined treatments, T11 (10 mg/L Si NPs + 50 mg/L $CdCl_2$), T12 (10 mg/L Si NPs+ 100 mg/L $CdCl_2$), T13 (20 mg/L Si NPs+ 25 mg/L $CdCl_2$) and T14 (20 mg/L Si NPs+ 50 mg/L $CdCl_2$) demonstrated the highest values for FGP, GRI, MDG, PV and GV and decreased MGT and SM in comparison with the higher Cd concentrations. The reduction of cadmium accumulation in the maize leaves was mediated by the binding of cadmium ions onto Si NPs during the germination stage. In addition, Si NPs reduced the amount of cadmium that migrated from the root to the plumule and leaves, which was thought to be the cause of enhanced germination and seedling growth characteristics [43].

The analyses of seedling growth characteristics and seedling vigor revealed that there are significantly inhibitory impacts for Cd at 100 mg/L. These findings are in line with those of Gowayed in *Zea mays* [44] and Gowayed and Kadasa in *Vicia faba* [45]. Excess Cd is harmful and reduces the growth and biomass of maize [46, 47, 48]. Within a few hours of Cd application to the root medium, Cd can be absorbed by plant roots and transmitted very easily to other areas of the plant [49]. Heavy metals' ability to interfere with cell division, mainly by inducing chromosomal abnormalities and aberrant mitosis, may be the source of their ability to limit root extension [50]. When cadmium is present in the media, it reduces transpiration rates that cause a reduction in plumule growth [9].

The current data revealed that the utilization of Si NPs had a significant impact on seedling growth characteristics (plumule length, root length, seedling length, seedling fresh weight and dry weight and water content)**.** The highest root, seedling systems, fresh weight and seedling water content were recorded when Si NPs was used by rate of 20 mg/l, while 10 mg/l showed the longest plumule system and seedling dry weight. Obviously, germinating maize seeds with Si NPs presence produced stronger seedlings than the control. In addition, it was also noted that NPs may enhance seed germination and seedling vigor in stressful environments [20]. Si NPs can ameliorate heavy metal stress in plants [27, 28, 29] e.g. in *Phyllostachys edulis* treated with Cd at the germination stage [46]. The data obtained revealed that Si NPs increased plumule length and root length when exposed to cadmium treatments, this enhancement can be related to the application of Si NPs that increase cell wall elasticity [51] and lead to the translocation and compartmentalization of Cd in vacuoles [18].

The results of the present study revealed that Si NPs increased the seedling biomass of maize seedlings under cadmium stress. The enhancement can be due to the role of Si NPs in increasing nutritional status [52, 53]. We assume that silicon improves maize seedling biomass under Cd stress by enhancing plant nutrient absorption. Our results showed that silicon could enhance seedling vigor in *Z. mays* under Cd stress. These results agree with those of Ali et al. [52] who stated that Si NPs could eliminate Cd levels in plant tissue. Si NPs would therefore stimulate seedling vigor by decreasing Cd rates.

4. References

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