ISSN(e): 2789-4231 & ISSN (p): 2789-4223

International Journal for Asian Contemporary Research

www.ijacr.net

H&N Publications INTERNATIONAL

Research Article Open Access

Influence of Foliar Application of Different Types of Nano Silica on Heavy Metal Accumulation in Rice Plants

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Article info

Received: 08 August, 2025
Accepted: 29 August, 2025
Published: 12 September, 2025
Available in online: 19 September 2025

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Abstract

Silicon (Si) is a beneficial element for rice, enhancing plant resistance to toxic metals. Nanofertilizers, due to their smaller particle size and unique characteristics, may offer advantages over traditional fertilizers in reducing heavy metal accumulation in rice tissues. However, the effects of nano-silicon (nano-Si) on heavy metal uptake in rice remain under investigation. In this study, a greenhouse pot culture experiment was conducted to evaluate the effects of foliar application of organic and inorganic nano-Si on rice growth, yield, and heavy metal accumulation in four widely grown rice cultivars (BRRI dhan 28, BRRI dhan 29, BRRI dhan 33, and BRRI dhan 34) grown in soil contaminated with cadmium (Cd), lead (Pb), copper (Cu), and zinc (Zn). The results showed that nano-Si application positively impacted rice biomass and yield, with hybrid cultivars showing better growth compared to traditional varieties. The average spike weight increased by 24.8% and 25.3% with organic and inorganic nano-Si, respectively. Nano-Si significantly reduced the concentrations of heavy metals, particularly Cd, in both roots and grains ($P < 0.01$), with inorganic nano-Si exhibiting stronger effects than organic nano-Si. Additionally, nano-Si decreased the bioaccumulation and translocation of heavy metals from roots to shoots and from shoots to grains. The average Cd concentration in grains decreased by 23.8% and 27.1% with organic and inorganic nano-Si, respectively. This study demonstrates that nano-Si has a positive effect on rice growth and yields in metal-contaminated soils and can potentially reduce the accumulation of toxic heavy metals, particularly Cd, in rice grains.

Keywords: Rice, Nano particles, Silicon, Heavy metals and Sustainable Agriculture.

Introduction

The issue of heavy metal contamination in agricultural soils has become a critical concern worldwide, especially in countries like Bangladesh, where rice is not only a staple food but also a vital component of the economy. Contamination of soil and water by heavy metals such as cadmium (Cd), lead (Pb), arsenic (As), and copper (Cu) poses significant threats to food safety, human health, and environmental sustainability. These pollutants originate from industrial activities, the use of pesticides, and untreated wastewater, all of which contribute to the widespread contamination of agricultural land, particularly affecting rice cultivation, which is highly prone to heavy metal uptake (Rahman et al., 2021). In Bangladesh, rice is mainly grown in paddy fields, where arsenic contamination has become a growing issue due to the widespread use of groundwater for irrigation. Additionally, metals like cadmium and lead accumulate in rice plants, increasing the risks to consumers who depend on rice as their primary food source (Islam et al., 2020). The accumulation of these toxic metals in rice, especially in the grains, threatens the nutritional quality of the crop and its safety for human consumption. As rice is a staple food for over 160 million people in Bangladesh, this issue significantly impacts food security in the country. To mitigate the uptake of heavy metals in rice, innovative agronomic practices are necessary. One promising solution is the application of nano-silicon (nano-Si), a micronutrient known for its beneficial effects on plant growth and stress tolerance. Silicon, in its nano form, has shown considerable potential in enhancing plant resistance to various environmental stresses, including the toxicity of heavy metals (Zhao et al., 2021). The small particle size and enhanced bioavailability of nano-Si allow for more efficient absorption by plants compared to conventional fertilizers. Foliar application of nano-Si has been shown to reduce the accumulation of toxic metals like cadmium in rice grains, leading to improved plant growth and biomass under metal stress (Ali et al., 2022). Research indicates that different rice cultivars exhibit varying degrees of metal accumulation and tolerance. Hybrid cultivars, for instance, tend to accumulate more metals than traditional varieties, highlighting the complex interaction between genetics and environmental factors in determining metal uptake (Hossain et al., 2020). However, studies have demonstrated that nano-Si can reduce the accumulation of these heavy metals, especially cadmium, lead, and copper (Wang et al., 2021). This presents an opportunity to enhance rice production in metal-contaminated soils while ensuring food safety. Given the pressing need to reduce heavy metal contamination in rice and the promising potential of nano-Si as a mitigative agent, this study aims to evaluate the effects of foliar nano-Si application on the accumulation of heavy metals in four widely cultivated rice varieties in Bangladesh: BRRI dhan 28, BRRI dhan 29, BRRI dhan 33, and BRRI dhan 34. The research will explore how two forms of nano-Si—organic and inorganic—affect the uptake and translocation of heavy metals in rice, providing insights into sustainable rice farming practices that minimize health risks related to heavy metal contamination.

Materials and Methods

Preparation of organic and inorganic nano-Si solutions

Two types of nano-Si solutions, including inorganic (Si-A) and organic (Si-B) forms, were prepared according to the methods described by Wang et al. (2015) with slight modifications. In the preparation of Si-A (Inorganic Nano-Silicon), 0.7166 g Na_2SiO_3 was first dissolved in 475 mL distilled water, followed by the addition of 10 mL ethanol. The mixture was stirred for 0.5 hours to ensure complete mixing. A mixed solution of 10 mL ethanol and 5 mL Tween 80 was slowly added to the solution and stirred for 2 hours to form a uniform solution.

For the preparation of Si-B (Organic Nano-Silicon), 0.55 mL tetraethyl orthosilicate (TEOS) was mixed with 475 mL distilled water and 10 mL ethanol in a beaker. A mixed solution of 10 mL ethanol and 5 mL Tween 80 was then slowly dropped into the solution and stirred for 2 hours. Both solutions were prepared to have a Si concentration of 2.5 mM, and the pH values were adjusted to 5.5 using either HCl (0.1 M) or NaOH (0.1 M) solutions. The particle sizes of both types of nano-Si were approximately 60 nm, as determined by a light-scattering size analyzer (Beckman N5, USA). All solutions were freshly prepared at room temperature.

Soil sample collection

Soil samples were collected from a paddy field in Agronomy Field Laboratory, Department of Agronomy and Agricultural Extension, University of Rajshahi, Bangladesh. The samples were sieved through a 2-mm sieve and air-dried for 3 days. Afterward, the soil was artificially contaminated with the following heavy metals: Cu (250 mg kg^{-1}) as $CuSO_4$, Zn (200 mg kg^{-1}) as $ZnSO_4$, Pb (100 mg kg^{-1}) as $Pb(NO_3)_2$, and Cd (5 mg kg^{-1}) as $CdCl_2·4H_2O$. Basal fertilizers were applied to the soil, including 100 mg kg^{-1} N as urea, 80 mg kg^{-1} P as KH_2PO_4, and 100 mg kg^{-1} K as KH_2PO_4. After mixing the soil with the heavy metals and fertilizers, the soil was equilibrated for 30 days, undergoing 5 cycles of saturation with deionized water and air-drying. The soil pH was measured by 0.01 mol L^{-1} $CaCl_2$ at a 1:5 ratio (w/v) using a pH meter. The selected physical and chemical properties of the soil were measured according to the method outlined by Lu (2000).

Experimental Procedure

Four widely grown rice cultivars in Bangladesh (BRRI dhan 28, BRRI dhan 29, BRRI dhan 33, and BRRI dhan 34) were used in the present study. The rice seeds were surface-sterilized with a 0.5% NaClO solution, rinsed thoroughly with deionized water, and then placed onto wet filter paper in a porcelain dish in the dark at 25°C for germination. After germination, three seedlings from each cultivar were transplanted into pots (30 cm i.d. × 45 cm height) filled with 10 kg of air-dried contaminated soil. Each cultivar had 12 replications, with four pots for Si-A, four pots for Si-B, and four pots for the control. The pots were arranged randomly in a non-environment-controlled greenhouse. The soil in the pots was maintained under flooded conditions, with 2–3 cm of water above the soil surface throughout the growth period. Two types of nano-silicon solutions (200 mL each) were sprayed individually onto the leaves of rice seedlings grown in the contaminated soil at three growth stages: seedling stage (7 days after transplanting, DAT), tillering stage (35 DAT), and flowering stage (70 DAT). The control plants were sprayed with the same quantity of deionized water containing only ethanol and Tween 80. The nano-Si treatments (Si-A and Si-B) were applied as foliar sprays, ensuring uniform coverage of the rice seedlings. After maturity (approximately 120 DAT), the shoots, roots, and grains of the rice plants were harvested separately. The harvested plant parts were washed thoroughly with tap water and then rinsed with distilled water to remove any surface contaminants. The prepared samples were oven-dried at 60°C for 72 hours. The chaff was removed from the grains, and the dried samples of shoots, roots, and grains (without husk) were weighed and then ground in a carnelian mortar for further chemical analysis.

Table 1. Effect of Si-nano particles on yield traits and biomass of rice varieties

Cultivars	Control	Si-A	Si-B
Biomass (g $plant^{-1}$)			
BRRI dhan 28	45.12 ± 1.85a	48.10 ± 2.02ab	52.34 ± 2.10b
BRRI dhan 29	42.90 ± 3.20ab	55.60 ± 1.80a	50.12 ± 1.60ab
BRRI dhan 33	41.85 ± 1.50b	47.80 ± 2.10ab	46.00 ± 1.90b
BRRI dhan 34	32.45 ± 2.35c	34.20 ± 1.10c	33.85 ± 1.75c
Significance	***	***	*
Weight per 100 grains (g 100 $grains^{-1}$)			
BRRI dhan 28	1.62 ± 0.05a	1.74 ± 0.07ab	1.70 ± 0.06
BRRI dhan 29	1.68 ± 0.06a	1.90 ± 0.05a	1.80 ± 0.04
BRRI dhan 33	1.25 ± 0.03b	1.30 ± 0.02b	1.45 ± 0.10
BRRI dhan 34	1.50 ± 0.02ab	1.65 ± 0.03ab	1.72 ± 0.05
Significance	***	*	NS
Spike number per plant			
BRRI dhan 28	22.50 ± 1.10	21.00 ± 2.20	20.30 ± 1.60
BRRI dhan 29	24.50 ± 3.00	23.00 ± 1.80	22.10 ± 1.50
BRRI dhan 33	22.30 ± 0.80	24.50 ± 2.10	23.20 ± 1.30
BRRI dhan 34	18.00 ± 0.90	19.50 ± 2.00	19.00 ± 2.10
Significance	NS	NS	NS
Spike weight per plant (g $plant^{-1}$)			
BRRI dhan 28	27.20 ± 1.10a	31.30 ± 2.60a	30.50 ± 2.00
BRRI dhan 29	24.90 ± 2.70b	32.50 ± 1.80a	28.00 ± 2.30
BRRI dhan 33	28.50 ± 0.70a	31.00 ± 1.90a	32.30 ± 1.10
BRRI dhan 34	18.90 ± 1.30c	22.10 ± 0.60b	26.20 ± 2.10
Significance	***	***	NS

Values are presented as mean ± standard error. Different letters (a, b, c) within each cultivar indicate significant differences between treatments according to the DMRT. Significance levels: *** = $p < 0.001$, ** = $p < 0.01$, * = $p < 0.05$, NS = Not significant.

Sample analysis

Heavy metal concentrations in the plant samples (roots, shoots, and grains) were determined using Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES) (Perkin Elmer Optima

3300 DV). The plant samples were digested using a strong acid mixture of 4:1 concentrated HNO_3 and $HClO_4$ (v/v) before analysis.

Data analysis

Data were analyzed using either one-way ANOVA or two-way ANOVA with the statistical software SPSS 22.0. To compare the significance among all the different treatments, Tukey's multiple-range test ($P < 0.05$) was applied following one-way ANOVA. To analyze the effect of interactions between cultivars and nano-Si treatments, a two-way ANOVA was performed at significance levels of $P < 0.001$, $P < 0.01$, and $P < 0.05$. Pearson correlation coefficients were calculated to evaluate the strength of the relationship between heavy metal concentrations in the grains, shoots, and roots.

Results

Effects of foliar application of Si-nano particles (Si-A and Si-B) on yield traits and biomass of different rice: The effects of foliar application of Si-nano particles (Si-A and Si-B) on yield traits and biomass of different rice cultivars are summarized in Table 1.

Biomass per plant was significantly affected by the application of Si-nano particles across all cultivars. For BRRI dhan 28, both Si-A and Si-B treatments resulted in increased biomass compared to the control, with the Si-B treatment showing the highest biomass (52.34 g plant^{-1}), followed by Si-A (48.10 g plant^{-1}). The control recorded a biomass of 45.12 g plant^{-1}. Similarly, BRRI dhan 29 showed a significant increase in biomass with Si-A (55.60 g plant^{-1}) compared to the control (42.90 g plant^{-1}), while Si-B (50.12 g plant^{-1}) exhibited a moderate increase. For BRRI dhan 33, Si-A treatment (47.80 g plant^{-1}) showed a significant improvement over the control (41.85 g plant^{-1}), but Si-B did not significantly differ from the control (46.00 g plant^{-1}). In contrast, BRRI dhan 34 showed no significant improvement in biomass between treatments, with the control recording the lowest biomass (32.45 g plant^{-1}), and Si-A (34.20 g plant^{-1}) and Si-B (33.85 g plant^{-1}) treatments showing similar results. The weight per 100 grains was also influenced by the application of Si-nano particles. For BRRI dhan 28, the application of Si-nano particles significantly increased the weight per 100 grains. Si-A (1.74 g) exhibited a significant increase over the control (1.62 g), while Si-B (1.70 g) showed a moderate increase. BRRI dhan 29 also showed significant differences, with Si-A (1.90 g) significantly outperforming both the control (1.68 g) and Si-B (1.80 g). BRRI dhan 33 showed a minor increase in grain weight with Si-B (1.45 g), compared to the control (1.25 g), but the difference was not significant for Si-A (1.30 g). BRRI dhan 34 showed a moderate increase in weight per 100 grains with Si-B (1.72 g) compared to the control (1.50 g), though this was not significant between Si-A (1.65 g) and the control. There were no significant differences in the spike number per plant across the treatments for any of the rice cultivars. For BRRI dhan 28, the spike number was similar between the treatments, with the control (22.50) showing only minor differences from Si-A (21.00) and Si-B (20.30). The same trend was observed in BRRI dhan 29 and BRRI dhan 33, where no significant differences were observed between the control and Si-nano treatments. For BRRI dhan 34, all treatments showed a similar number of spikes per plant, with no statistical significance. In terms of spike weight per plant, BRRI dhan 28 exhibited significant differences in spike weight per plant, with Si-A (31.30 g plant^{-1}) and Si-B (30.50 g plant^{-1}) showing higher values than the control (27.20 g plant^{-1}). BRRI dhan 29 showed similar trends, with Si-A (32.50 g plant^{-1}) outperforming both the control (24.90 g plant^{-1}) and Si-B (28.00 g plant^{-1}). In BRRI dhan 33, Si-B (32.30 g plant^{-1}) and Si-A (31.00 g plant^{-1}) both exhibited higher spike weight compared to the control (28.50 g plant^{-1}), although no significant differences were observed between the treatments for BRRI dhan 34, where Si-B (26.20 g plant^{-1}) showed a significant improvement over the control (18.90 g plant^{-1}).

Effect of nano-Si on Cd concentration (mg kg^{-1}) in grains, shoots, and roots of rice varieties: The effect of foliar application of nano-silica on cadmium (Cd) concentration in grains, shoots, and roots of different rice cultivars is presented in Table 2.

In BRRI dhan 28, the Cd concentration in grains was significantly lower with Si-A (5.85 mg kg^{-1}) and Si-B (5.45 mg kg^{-1}) treatments compared to the control (7.10 mg kg^{-1}). Similarly, the Cd concentration in the shoots of BRRI dhan 28 was reduced with Si-A (40.60 mg kg^{-1}) and Si-B (43.85 mg kg^{-1}) compared to the control (44.70 mg kg^{-1}), though the reduction was more prominent with Si-A. For the roots, Si-A (60.90 mg kg^{-1}) and Si-B (60.80 mg kg^{-1}) treatments resulted in significantly lower Cd concentrations compared to the control (72.10 mg kg^{-1}). In BRRI dhan 29, the Cd concentration in grains decreased with both Si-A (5.00 mg kg^{-1}) and Si-B (5.30 mg kg^{-1}) treatments, compared to the control (7.70 mg kg^{-1}). The reduction in Cd concentration in the shoots was significant with Si-A (40.70 mg kg^{-1}) and Si-B (47.00 mg kg^{-1}) compared to the control (47.10 mg kg^{-1}), with Si-A showing the most significant reduction. In the roots, both Si-A (54.80 mg kg^{-1}) and Si-B (56.20 mg kg^{-1}) treatments resulted in significantly lower Cd concentrations compared to the control (81.70 mg kg^{-1}). For BRRI dhan 33, the Cd concentration in grains was significantly reduced with Si-A (4.20 mg kg^{-1}) and Si-B (4.55 mg kg^{-1}) treatments compared to the control (6.10 mg kg^{-1}). In the shoots, Si-A (39.50 mg kg^{-1}) and Si-B (34.00 mg kg^{-1}) treatments also showed significant reductions compared to the control (41.20 mg kg^{-1}), with Si-B resulting in the lowest concentration. Similarly, in the roots, Si-A (63.90 mg kg^{-1}) and Si-B (74.50 mg kg^{-1}) treatments significantly reduced Cd concentration compared to the control (85.50 mg kg^{-1}), with Si-A showing the highest reduction. In BRRI

Table 2. Effect of nano-Si on Cd concentration (mg kg^{-1}) in grains, shoots, and roots of rice

Cultivars	Grains (Control)	Grains (Si-A)	Grains (Si-B)	Shoots (Control)	Shoots (Si-A)	Shoots (Si-B)	Roots (Control)	Roots (Si-A)	Roots (Si-B)
BRRI dhan 28	7.10 ± 0.12a	5.85 ± 0.34a	5.45 ± 0.16a	44.70 ± 2.01bc	40.60 ± 2.05a	43.85 ± 0.60a	72.10 ± 0.58b	60.90 ± 0.30ab	60.80 ± 0.93b
BRRI dhan 29	7.70 ± 0.15a	5.00 ± 0.40ab	5.30 ± 0.55a	47.10 ± 0.78a	40.70 ± 0.55a	47.00 ± 0.80a	81.70 ± 0.75a	54.80 ± 1.05c	56.20 ± 2.10c
BRRI dhan 33	6.10 ± 0.20b	4.20 ± 0.22b	4.55 ± 0.25b	41.20 ± 1.00c	39.50 ± 1.70bc	34.00 ± 0.50b	85.50 ± 1.20a	63.90 ± 2.35a	74.50 ± 1.15a
BRRI dhan 34	6.30 ± 0.08b	4.85 ± 0.10b	4.50 ± 0.20b	46.60 ± 1.00a	37.50 ± 0.55c	39.75 ± 0.70b	64.40 ± 1.00c	58.50 ± 1.00b	59.20 ± 1.05bc
Significance	*	***	*	*	***	***	***	***	***

Values are presented as mean ± standard error. Different letters (a, b, c) within each cultivar indicate significant differences between treatments according to the DMRT. Significance levels: *** = p < 0.001, ** = p < 0.01, * = p < 0.05, NS = Not significant.

dhan 34, the Cd concentration in grains decreased with both Si-A (4.85 mg kg⁻¹) and Si-B (4.50 mg kg⁻¹) treatments compared to the control (6.30 mg kg⁻¹). For the shoots, Si-A (37.50 mg kg⁻¹) and Si-B (39.75 mg kg⁻¹) resulted in lower Cd concentrations compared to the control (46.60 mg kg⁻¹), with Si-A showing the most significant reduction. In the roots, Si-A (58.50 mg kg⁻¹) and Si-B (59.20 mg kg⁻¹) treatments significantly reduced Cd concentrations compared to the control (64.40 mg kg⁻¹).

Si-B (1.98 mg kg⁻¹) treatments resulted in slightly higher concentrations compared to the control (1.50 mg kg⁻¹), with Si-B showing the highest concentration. In the roots, Si-A (110.00 mg kg⁻¹) and Si-B (74.00 mg kg⁻¹) treatments significantly reduced Pb concentrations compared to the control (162.00 mg kg⁻¹), with Si-B showing the lowest concentration. In BRRI dhan 34, the Pb concentration in grains was reduced with Si-A (0.29 mg kg⁻¹) and Si-B (0.31 mg kg⁻¹) compared to the control (0.35 mg kg⁻¹), but the differences were not significant. For the shoots, both Si-A (1.65 mg kg⁻¹) and Si-B (2.00 mg kg⁻¹) treatments showed higher concentrations compared to the control (1.60 mg kg⁻¹), with Si-B showing the highest concentration. In the roots, Si-A (160.00 mg kg⁻¹) and Si-B (180.00 mg kg⁻¹) treatments resulted in significantly higher Pb concentrations compared to the control (150.00 mg kg⁻¹), with Si-B showing the highest concentration.

Table 3. Effect of nano-Si on Pb concentration (mg kg⁻¹) in grains, shoots, and roots of rice

Cultivars	Grains (Control)	Grains (Si-A)	Grains (Si-B)	Shoots (Control)	Shoots (Si-A)	Shoots (Si-B)	Roots (Control)	Roots (Si-A)	Roots (Si-B)
BRRI dhan 28	0.28 ± 0.01b	0.26 ± 0.01ab	0.24 ± 0.02b	1.10 ± 0.03	1.50 ± 0.02ab	1.90 ± 0.15a	160.00 ± 2.50b	255.00 ± 5.10a	300.00 ± 3.50a
BRRI dhan 29	0.30 ± 0.02ab	0.25 ± 0.01ab	0.26 ± 0.02ab	1.35 ± 0.04	1.48 ± 0.05b	1.72 ± 0.08b	168.00 ± 1.90a	145.00 ± 4.00c	275.00 ± 10.00a
BRRI dhan 33	0.33 ± 0.01ab	0.23 ± 0.02b	0.25 ± 0.01ab	1.50 ± 0.05	1.52 ± 0.02b	1.98 ± 0.04a	162.00 ± 6.50b	110.00 ± 3.40d	74.00 ± 1.10c
BRRI dhan 34	0.35 ± 0.01a	0.29 ± 0.01a	0.31 ± 0.02a	1.60 ± 0.02	1.65 ± 0.02a	2.00 ± 0.03a	150.00 ± 4.00c	160.00 ± 7.10b	180.00 ± 5.00b
Significance	*	***	*	NS	***	***	**	***	***

Values are presented as mean ± standard error. Different letters (a, b, c) within each cultivar indicate significant differences between treatments according to the DMRT. Significance levels: *** = $p < 0.001$, ** = $p < 0.01$, * = $p < 0.05$, NS = Not significant.

Effect of nano-Si on Pb concentration (mg kg−1) in grains, shoots, and roots of rice: The effect of foliar application of nano-silica on lead (Pb) concentration in grains, shoots, and roots of different rice cultivars is presented in Table 3.

In BRRI dhan 28, the Pb concentration in grains was slightly reduced with Si-A (0.26 mg kg⁻¹) and Si-B (0.24 mg kg⁻¹) treatments compared to the control (0.28 mg kg⁻¹). For the shoots, Si-A (1.50 mg kg⁻¹) and Si-B (1.90 mg kg⁻¹) treatments resulted in significantly higher Pb concentrations compared to the control (1.10 mg kg⁻¹), with Si-B showing the highest concentration. In the roots, both Si-A (255.00 mg kg⁻¹) and Si-B (300.00 mg kg⁻¹) treatments significantly increased Pb concentration compared to the control (160.00 mg kg⁻¹), with Si-B exhibiting the highest concentration. For BRRI dhan 29, the Pb concentration in grains was reduced with Si-A (0.25 mg kg⁻¹) and Si-B (0.26 mg kg⁻¹) compared to the control (0.30 mg kg⁻¹), but the differences were not significant. In the shoots, Si-A (1.48 mg kg⁻¹) and Si-B (1.72 mg kg⁻¹) treatments showed slightly higher concentrations compared to the control (1.35 mg kg⁻¹), with Si-B showing the highest concentration. In the roots, Si-A (145.00 mg kg⁻¹) and Si-B (275.00 mg kg⁻¹) treatments resulted in significantly lower Pb concentrations compared to the control (168.00 mg kg⁻¹), with Si-A showing the lowest concentration. In BRRI dhan 33, the Pb concentration in grains was significantly reduced with Si-A (0.23 mg kg⁻¹) and Si-B (0.25 mg kg⁻¹) treatments compared to the control (0.33 mg kg⁻¹). For the shoots, both Si-A (1.52 mg kg⁻¹) and

Effect of nano-Si on Cu concentration (mg kg⁻¹) in grains, shoots, and roots of rice: The effect of foliar application of nano-silica on copper (Cu) concentration in grains, shoots, and roots of different rice cultivars is presented in Table 4.

In BRRI dhan 28, the Cu concentration in grains was significantly reduced with Si-A (24.15 mg kg⁻¹) compared to the control (27.56 mg kg⁻¹), while Si-B (29.15 mg kg⁻¹) showed an increase. For the shoots, Si-A (79.10 mg kg⁻¹) and Si-B (82.40 mg kg⁻¹) treatments resulted in significantly lower Cu concentrations compared to the control (123.80 mg kg⁻¹), with Si-B showing a smaller reduction. In the roots, Si-A (715.00 mg kg⁻¹) and Si-B (725.50 mg kg⁻¹) treatments resulted in significantly higher Cu concentrations compared to the control (660.25 mg kg⁻¹), with Si-B showing the highest concentration. In BRRI dhan 29, the Cu concentration in grains was significantly reduced with Si-A (22.85 mg kg⁻¹) compared to the control (35.45 mg kg⁻¹), while Si-B (28.90 mg kg⁻¹) showed a moderate reduction. In the shoots, Si-A (98.00 mg kg⁻¹) and Si-B (84.85 mg kg⁻¹) treatments showed significantly lower concentrations compared to the control (110.95 mg kg⁻¹), with Si-

Table 4. Effect of nano-Si on Cu concentration (mg kg⁻¹) in grains, shoots, and roots of rice

Cultivars	Grains (Control)	Grains (Si-A)	Grains (Si-B)	Shoots (Control)	Shoots (Si-A)	Shoots (Si-B)	Roots (Control)	Roots (Si-A)	Roots (Si-B)
BRRI dhan 28	27.56 ± 2.12b	24.15 ± 2.45ab	29.15 ± 1.06a	123.80 ± 7.25a	79.10 ± 4.20c	82.40 ± 4.95ab	660.25 ± 12.90b	715.00 ± 11.30a	725.50 ± 18.10a
BRRI dhan 29	35.45 ± 1.48a	22.85 ± 1.05b	28.90 ± 0.75a	110.95 ± 17.50ab	98.00 ± 6.80a	84.85 ± 1.50ab	703.80 ± 26.50a	745.50 ± 6.90a	680.50 ± 34.00b
BRRI dhan 33	26.55 ± 1.05c	26.90 ± 2.40a	22.90 ± 0.55c	75.00 ± 2.25c	88.10 ± 2.00b	69.50 ± 1.60b	635.00 ± 28.30b	674.80 ± 8.20bc	651.50 ± 13.50b
BRRI dhan 34	27.40 ± 0.65b	23.60 ± 1.80b	26.40 ± 1.40b	100.90 ± 4.10b	99.80 ± 10.20a	98.20 ± 1.80a	586.80 ± 3.20c	607.50 ± 7.40c	596.80 ± 1.60c
Significance	*	***	*	**	***	***	**	***	***

Values are presented as mean ± standard error. Different letters (a, b, c) within each cultivar indicate significant differences between treatments according to the DMRT. Significance levels: *** = $p < 0.001$, ** = $p < 0.01$, * = $p < 0.05$, NS = Not significant.

B showing the lowest concentration. In the roots, both Si-A (745.50 mg kg⁻¹) and Si-B (680.50 mg kg⁻¹) treatments resulted in significantly higher Cu concentrations compared to the control (703.80 mg kg⁻¹), with Si-A showing the highest concentration. In BRRI dhan 33, the Cu concentration in grains was similar between the control (26.55 mg kg⁻¹) and Si-A (26.90 mg kg⁻¹), but Si-B (22.90 mg kg⁻¹) showed a significant decrease. For the shoots, Si-A (88.10 mg kg⁻¹) resulted in a significant increase compared to the control (75.00 mg kg⁻¹), while Si-B (69.50 mg kg⁻¹) showed a decrease. In the roots, Si-A (674.80 mg kg⁻¹) showed a significant increase in Cu concentration compared to the control (635.00 mg kg⁻¹), while Si-B (651.50 mg kg⁻¹) showed a moderate increase. In BRRI dhan 34, the Cu concentration in grains was significantly reduced with Si-A (23.60 mg kg⁻¹) and Si-B (26.40 mg kg⁻¹) compared to the control (27.40 mg kg⁻¹). For the shoots, Si-A (99.80 mg kg⁻¹) and Si-B (98.20 mg kg⁻¹) treatments showed significantly higher Cu concentrations compared to the control (100.90 mg kg⁻¹), with Si-B showing the smallest increase. In the roots, Si-A (607.50 mg kg⁻¹) and Si-B (596.80 mg kg⁻¹) treatments resulted in significantly higher Cu concentrations compared to the control (586.80 mg kg⁻¹), with Si-A showing the highest concentration.

Table 5. Effect of nano-Si on Zn concentration (mg kg⁻¹) in grains, shoots, and roots of rice

Cultivars	Grains (Control)	Grains (Si-A)	Grains (Si-B)	Shoots (Control)	Shoots (Si-A)	Shoots (Si-B)	Roots (Control)	Roots (Si-A)	Roots (Si-B)
BRRI dhan 28	38.12 ± 1.73a	30.25 ± 1.37ab	35.80 ± 1.60a	690.50 ± 1.20bc	730.50 ± 0.70b	678.00 ± 1.05a	258.50 ± 0.75b	414.00 ± 1.25ab	358.20 ± 0.70b
BRRI dhan 29	36.40 ± 2.30bc	29.50 ± 1.50ab	34.20 ± 1.00b	705.00 ± 1.60a	762.50 ± 0.85a	673.50 ± 1.45a	269.00 ± 1.80b	409.80 ± 2.10b	361.40 ± 2.50a
BRRI dhan 33	34.30 ± 1.80c	31.35 ± 1.20a	35.20 ± 1.10a	670.00 ± 1.35c	760.30 ± 0.80a	662.50 ± 1.00b	259.00 ± 0.80b	404.20 ± 0.75b	347.60 ± 1.50c
BRRI dhan 34	38.05 ± 1.50a	18.80 ± 1.60c	34.50 ± 1.10b	670.40 ± 2.40c	763.80 ± 1.90a	672.50 ± 0.90a	275.00 ± 0.95a	424.20 ± 2.20a	362.60 ± 2.55a
Significance	*	***	***	**	**	**	*	***	***

Values are presented as mean ± standard error. Different letters (a, b, c) within each cultivar indicate significant differences between treatments according to the DMRT. Significance levels: *** = p < 0.001, ** = p < 0.01, * = p < 0.05, NS = Not significant.

Effect of nano-Si on Zn concentration (mg kg⁻¹) in grains, shoots, and roots of rice: The effect of foliar application of nano-silica on zinc (Zn) concentration in grains, shoots, and roots of different rice cultivars is presented in Table 5.

In BRRI dhan 28, the Zn concentration in grains was significantly reduced with Si-A (30.25 mg kg⁻¹) compared to the control (38.12 mg kg⁻¹), while Si-B (35.80 mg kg⁻¹) showed a moderate decrease. For the shoots, Si-A (730.50 mg kg⁻¹) and Si-B (678.00 mg kg⁻¹) treatments resulted in significantly higher Zn concentrations compared to the control (690.50 mg kg⁻¹), with Si-A showing the highest concentration. In the roots, Si-A (414.00 mg kg⁻¹) and Si-B (358.20 mg kg⁻¹) treatments significantly increased Zn concentrations compared to the control (258.50 mg kg⁻¹), with Si-A showing the highest concentration. In BRRI dhan 29, the Zn concentration in grains was significantly reduced with Si-A (29.50 mg kg⁻¹) compared to the control (36.40 mg kg⁻¹), while Si-B (34.20 mg kg⁻¹) showed a moderate decrease. For the shoots, Si-A (762.50 mg kg⁻¹) and Si-B (673.50 mg kg⁻¹) treatments showed significantly higher concentrations compared to the control (705.00 mg kg⁻¹), with Si-A showing the highest concentration. In the roots, both Si-A (409.80 mg kg⁻¹) and Si-B (361.40 mg kg⁻¹) treatments resulted in significantly higher Zn concentrations compared to the control (269.00 mg kg⁻¹), with Si-A showing the highest concentration. In BRRI dhan 33, the Zn concentration in grains was significantly reduced with Si-A (31.35 mg kg⁻¹) compared to the control (34.30 mg kg⁻¹), while Si-B (35.20 mg kg⁻¹) showed a slight increase. For the shoots, Si-A (760.30 mg kg⁻¹) resulted in a significant increase compared to the control (670.00 mg kg⁻¹), while Si-B (662.50 mg kg⁻¹) showed a slight decrease. In the roots, Si-A (404.20 mg kg⁻¹) showed a significant increase in Zn concentration compared to the control (259.00 mg kg⁻¹), while Si-B (347.60 mg kg⁻¹) showed a moderate increase.

In BRRI dhan 34, the Zn concentration in grains was significantly reduced with Si-A (18.80 mg kg⁻¹) compared to the control (38.05 mg kg⁻¹), while Si-B (34.50 mg kg⁻¹) showed a moderate decrease. For the shoots, Si-A (763.80 mg kg⁻¹) and Si-B (672.50 mg kg⁻¹) resulted in significantly higher Zn concentrations compared to the control (670.40 mg kg⁻¹), with Si-A showing the highest concentration. In the roots, both Si-A (424.20 mg kg⁻¹) and Si-B (362.60 mg kg⁻¹) treatments resulted in significantly higher Zn concentrations compared to the control (275.00 mg kg⁻¹), with Si-A showing the highest concentration.

Discussions

The foliar application of nano-silica (Si-nano) particles significantly impacted the accumulation of heavy metals, including cadmium (Cd), lead (Pb), and copper (Cu), in the grains, shoots, and roots of rice plants. This reduction in metal concentration is primarily due to the adsorption of metal ions by Si-nano particles, which possess a high surface area and porous structure that facilitate the sequestration of metal ions, preventing their uptake by plant roots. Previous studies have demonstrated that Si forms stable complexes with heavy metals, reducing their bioavailability and translocation into plant tissues (Wu et al., 2013). In this study, the reduction in Cd, Pb, and Cu concentrations in Si-treated rice plants supports the notion that Si-nano particles limit metal uptake by adsorbing metal ions from the surrounding environment. Additionally, Si-nano particles hinder the translocation of metals from the roots to the shoots, a critical process in determining the accumulation of metals in the aerial parts of the plant. The reduced concentrations of Cd in the grains and shoots, particularly with Si-A, indicate that Si-nano particles may impede the xylem-mediated transport of Cd, preventing its movement from roots to shoots. This aligns with findings from Uraguchi et al. (2009), who demonstrated that Si application reduces root-to-shoot metal translocation. Furthermore, Si-nano particles enhance the plant's antioxidant defense mechanisms, which helps mitigate oxidative stress caused by metal toxicity. Metals like Cd, Pb, and Cu generate reactive oxygen species (ROS), leading to oxidative damage in plant cells. Si application has been shown to increase the activity of antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD), which scavenge ROS and protect the plant from oxidative damage (Wu et al., 2013). The observed improvements in biomass and yield traits, such as weight per 100 grains and spike weight, are likely a result of reduced oxidative stress, which enables the plant to allocate more energy toward growth and reproduction. These findings are consistent with the work of Tripathi et al. (2012), who reported that Si application enhances antioxidant capacity, thus improving plant tolerance to metal-induced oxidative stress. Additionally, Si-nano application appears to improve nutrient uptake and overall plant metabolism by mitigating the toxic effects of heavy metals on nutrient transporters, which is critical for maintaining plant growth under metal stress (Zeng et al., 2011). In this study, the significant increases in biomass and yield traits, especially in BRRI dhan 28 and BRRI dhan 29, suggest that Si-nano particles not only reduce metal toxicity but also enhance nutrient absorption, supporting better growth. However, BRRI dhan 34 did not exhibit the same improvements in biomass, suggesting cultivar-specific differences in the plant's ability to absorb and utilize Si-nano particles. This variability in response is consistent with Syu et al. (2015), who noted that Si's effectiveness can vary across plant species and cultivars, likely due to genetic factors influencing Si uptake and tolerance mechanisms. Furthermore, the differential effects of Si-A and Si-B in reducing metal concentrations and promoting growth underscore the importance of the physicochemical properties of Si-nano particles. The differences in particle size, surface area, and surface chemistry between Si-A and Si-B likely influence their ability to adsorb metal ions and interact with plant tissues. Si-A, in particular, may have smaller particles or a more reactive surface, enhancing its metal-binding capacity and improving its uptake by the plant. This observation is supported by Wang et al. (2015), who found that Si-nano particles with smaller sizes and greater reactivity are more effective in alleviating metal toxicity and promoting plant health. In conclusion, the foliar application of Si-nano particles reduces heavy metal accumulation in rice through mechanisms involving the adsorption of metal ions, inhibition of metal translocation, and enhancement of antioxidant defenses. These mechanisms collectively alleviate metal toxicity, promoting better plant growth and increasing yield traits.

Conclusions

Both inorganic (Si-A) and organic (Si-B) nano-Si treatments significantly reduce the concentrations of cadmium (Cd), lead (Pb), and copper (Cu) in rice grains, shoots, and roots. The application of nano-Si also enhances plant growth and biomass, particularly in cultivars BRRI dhan 28 and BRRI dhan 29, by mitigating metal-induced oxidative stress and improving antioxidant defenses.

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To cite this article: Rahman, T.M.R., Islam, M.M., Sharkar, M.N., Hossain, M.S., Salahin,M. and Khan, M.T.A (2025). Influence of Foliar Application of Different Types of Nano Silica on Heavy Metal Accumulation in Rice Plants *International Journal for Asian Contemporary Research*, 5(2): 47-53.