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REMEDIATION OF LEAD TOXICITY BY EXOGENOUS APPLICATION OF SILICON IN RICE

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Abstract

Silicon (Si) application is reported to be very effective in mitigating different stresses; however, their impact on mitigating heavy metals, especially lead (Pb) toxicity has not been previously investigated. The objective of the current experiment was to assess the consequences of different silicon sources and rates on plant parameters of rice under Pb toxic soil condition. The study was set up at the net house of the Department of Soil Science of Patuakhali Science and Technology University during the monsoon 2024. A two factors completely randomized design with three replications was assigned to the study. Two levels of lead (0 and 100 mg Pb kg^{-1} soil as lead nitrate), and two sources of silicon (Ca silicate and Fumed silica), both at 50 and 100 mg Si kg^{-1} soil, were applied on BINA Dhan-23. The results revealed that Pb stress significantly ($p < 0.05$) reduced the shoot dry weight of rice (11.0 and 10.4 g pot^{-1} in Pb control and 100 mg Pb kg^{-1} soil treatment, respectively), whereas Si application improved the shoot dry weight. There was a strong antagonistic relation of Si with uptake of Pb by the plants. Increasing Si rates, the Pb content in shoot and root gradually decreased, with the lowest Pb contents recorded at 100 mg Si kg^{-1} soil treatment. Among the two Si sources, the fumed silica had a higher capacity to reduce Pb content by both shoot and root than calcium silicate. The Pb accumulation in the root was several folds higher than shoot. Although, 100 mg Si kg^{-1} soil was found promising to reduce Pb toxicity in plants; more dose of Si is needed to apply in future research to find out the effects of most dose of Si on the extent of reduction of Pb toxicity in plants.

Keywords: Heavy metal, Littoral zone, Root weight, Salt stress, Shoot weight.

Introduction

Lead (Pb) is the second most toxic heavy metal released into the environment, followed by arsenic (Rani *et al*., 2024). It has become an alarming contaminant in recent times due to many man-made actions like industrial chemicals use, vehicle generated toxin, emission of industrial wastages, use of contaminated water for irrigation purpose, activities of pesticide making industries or leather industries, use of metal fertilizer, chemical paints etc. (Gupta *et al*., 2024). After being discharged into the environment, Pb is assimilated by plants, causing harm to plants as well as human body through the food chain. As humans

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directly or indirectly rely on plants, there is great probability to develop poisonous effects of Pb in human body like mental disorder, neurological or cardiovascular diseases etc. (Naz *et al*., 2025). Children and aged persons are the most vulnerable to toxicity of Pb. Lead has no biological function in plants and it is not required for plants growth and development. However, Pb may enter in the plant roots through transporters or channels for other nutrients and interfere with different metabolic activities in plants or damaging plant cell (Busoms *et al*., 2021).

Rice has become firmly crucial food grain in today's world as basic food stuffs for billions and ensured safety of food, specifically among the people of South Asia (Binth., 2024). The dictate of rice production is expanding day by day due to global population growth, swift industrialization and per capita exhaustion. Nevertheless, the production is on a threat as the current nullify climate changes, dearth of safe water resources, salt stress, a confiscation of cultivable lands etc. (Jodder *et al*., 2016; Shila *et al*., 2016; Sikder *et al*., 2016; Haque 2018). Besides, in littoral zone especially in Bangladesh crop cultivation was greatly hampered by tidal water flow, salt stress, imbalanced fertilization (Haque *et al*., 2023a; 2023b; 2024a; 2025a; Haque and Haque 2023) and recent concern is heavy metal toxicity. Silicon is one of the most cost-effective ways to not only turn down heavy metal (e.g. Pb, Cd, As etc.) consumption by roots but also limit the translocation of heavy metal from root to shoot (Zhao *et al*., 2017).

Being a beneficial nutrient, the quantity of Si is ample in soil crust which contributes disease control as well as alleviates heavy metal stress (Swe *et al*., 2021; Datnoff and Rodrigues, 2005). Silicon plays a dynamic role in lessening numerous biotic and abiotic stresses thus accelerates growth of plants and enhances yield potential (Haque *et al*., 2024b). Silicon is a multifaceted constituent for plant nutrient which activates plant immune system under detrimental soil and climate state that compensates heavy metal toxicity eventually increases crop production of rice (Sume *et al*., 2023). Silicon application enhances chlorophyll content of leaf which ultimately improves vegetative growth of the plants (Sultana *et al*., 2021). Silicon lowers several stresses and metal toxicity mainly by preserving large quantities in different plant parts and strengthening the stiffness of plant cells (Yang *et al*., 2024; Akter *et al*., 2021). Surplus accretion of silicon in plants doesn't cause any harm in plants metabolism. In an earlier study we had tested silicic acid, sodium metasilicate and calcium silicate as the sources of Si on yield performance of rice, where all the sources had positive effect on rice yield but calcium silicate had the best (Haque *et al*., 2023c). In that experiment we could not include fumed silica source (SiO_2). Among different sources of Si, the particle size of fumed silica was the lowest and looks like very fine powder. We assumed that fumed silica might be more accessible for plant uptake due to its fineness.

Although several literatures have described the positive role of Si in improving plant growth and yield, and reducing biotic and abiotic stresses, but the specific role of Si in remediating Pb toxicity especially in the coastal soils of Bangladesh has not been investigated. More specifically the interaction effect between Si and Pb uptake by rice plant is not well understood. Different sources of Si may have differences on affecting uptake of Pb from the soil. We hypothesized that Si application will assist plants to improve biomass yield and reduce uptake of toxic metals. Keeping those in mind the experiment was undertaken to find out the effects of different sources and rates of silicon to reduce the detrimental effect of Pb toxic in plants.

Materials and Methods

The experiment was carried out at the net house of the Department of Soil Science of Patuakhali Science and Technology University, Dumki upazila, Patuakhali district, Bangladesh throughout the monsoon season (August-October) of 2024. The research area was positioned between 22.4644°N latitude and 90.3849°E longitude at Bangladesh's south coastal region under AEZ 13 (Ganges tidal floodplains). The area was featured by low-lying land, frequent tidal flooding and many tidal rivers and creeks. The dominating crop in this area was transplanted Aman rice, often known as monsoon rice. Traditional tall rice varieties are typically grown by farmers.

Layout and treatments

The experiment was layed out in the completely randomized design with three replications. Two lead levels (0 and 100 mg Pb kg^{-1} soil) and five Si rates and sources (Si control, 50 mg Si kg^{-1} soil as Ca silicate and fumed silica, and 100 mg Si kg^{-1} soil as Ca silicate and fumed silica) were applied to BINA Dhan-23, a popular rice variety. The source of Pb was lead nitrate. The chemical composition of lead nitrate, calcium silicate and fumed silica were $Pb(NO_3)_2$, $CaSiO_3$ and SiO_2, respectively. The Bangladesh Institute of Nuclear Agriculture, located in Mymensingh, has released this rice variety (BINA Dhan-23).

Soil collection and pot preparation

Soil (0–15 cm deep) was collected from the farmer's field of Sreerampur village of Dumki upazila which was very closer to the Patuakhali Science and Technology University main campus in August 2024. The collected soils were spread on a floor for drying. Firstly randomly selected 10 sub samples amounting around 1 kg soil were poised from the collected soils and mixed thoroughly to make a composite sample. Then the composite soil was air dried for a week in the laboratory and crushed with a wooden hammer. The prepared soil was stored and finally chemical and physical analysis of soil was done following the method described by Page et al. (1982). The soil was silty clay loam in texture, which had pH of 5.7 and EC (saturation paste extract) of 1.66 dS m^{-1}. Total nitrogen content was 1.0 g kg^{-1}, organic carbon 13.1 g kg^{-1}, Bray and Kurtz phosphorous 5.8 mg kg^{-1}, exchangeable potassium 0.27 cmol kg^{-1}, available sulphur 27.0 mg kg^{-1}, total Si content 30 % and total Pb content 11 mg kg^{-1} soil. In the drying floor total soil volume was broken down into small pieces. One kg soil was weighed and taken into a plastic pot. In the same way total thirty pots were prepared in the experiment.

Fertilizer application

In the experiment the rate of N, P, K, S and Zn were 120, 20, 100, 20 and 10 mg kg^{-1} soil, respectively. However, we have used double dose of those rate in the pot. N as urea was applied at three equal splits at 7, 20 and 35 days after transplanting of seedlings. The P, K, S and Zn were applied as basal dose. According to the layout and treatment of the experiment, the Si and Pb were also applied as a basal dose.

Transplanting and intercultural operations

Seeds of BINA Dhan-23 (Aman rice) were immersed under water for one day. Then the seeds were girdled into a gunny bag and stored in hot place. Within 4 days the seeds were perfectly germinated. The sprouted seeds were sown in the seedbed at 5th August 2024. Proper care was taken on the seed bed. Seedlings were uprooted at 7th September 2024 and transplanted 4 healthy seedlings per pot. Irrigation was done in the pots following wetting and drying method. Weeding was performed manually whenever necessary. Liquid insecticide (i.e. Virtako) was sprayed at every 7 days interval and granular insecticide was applied at 7 days after transplanting to avoid insect infestation in rice plants. Algal growth was manually removed. To provide similar environment the position of all the pots were rearranged weekly.

Harvesting

The crops were harvested at maximum vegetative growth phase in 27 October 2024. The plants were trimmed at ground level. Then the roots were also collected from the pot soil and cleaned gently with water. Both the root and shoot samples were dried under sun and weighted as sun dry basis. For chemical analysis the root and shoot samples were oven dried at 62° C, grinded and passed through 20 mesh sieves.

Data recording

To assess Si content, the complete root and shoot samples were cut up at 1 mm length and merged completely. A digestion tube was filled with one gram of the sample. Three inorganic acids were used to digest the plant samples: nitric acid (HNO_3), perchloric acid ($HClO_4$), and sulfuric acid (H_2SO_4) in 5:2:1 ratio (Yoshida *et al*., 1976). According to laboratory manual for physiological studies of rice, the Si content of the digested sample was estimated. Before harvesting, the third fully expanded leaf was collected and analyzed for chlorophyll determination (Coombs *et al*., 1985).

For determination of Pb in root and shoot sample 2g dried powdered sample was weighted in a conical flask.15 ml of HNO_3 was given in the flask for pre digestion overnight. Then 5-7 ml $HClO_4$ was added and digestion was completed using hot plate at 150 °C temperature until the sample became colorless. After cooling, the solution was diluted at 50 ml volume by using distilled water. Then the amount of Pb was measured from the sample using atomic absorption spectrophotometer. The amount of shoot and root Si or Pb uptake was assessed from their particular element content and biomass production. Other growth data were collected before harvesting.

Data analysis

The collected data were statistically analyzed by using a computer based software scheme named "Statistical Tool for Agricultural Research (STAR)". The least significant difference test at 95% confidence level was employed while estimating the mean separation value.

Results

Plant height and tiller production

There was no significant effect of Pb and Si and their interactions on plant height of rice (Table 1). Although not significant but Pb application at 100 mg kg^{-1} soil reduced plant height by 1.1 cm. Silicon application also showed a positive influence on plant height of rice. The single effect of Pb and Si had significant effect on number of tillers pot^{-1} but interaction effect was not significant. In Pb0 (control) treatment the number of tillers pot^{-1} was 10.3 which reduced to 9.1 in 100 mg Pb kg^{-1} soil treatment (Table 1). Silicon application significantly improved the number of tillers pot^{-1}. Among the Si rates 100 mg Si kg^{-1} soil treatment had better effect than 50 mg Si kg^{-1} soil treatment. The number of tillers pot^{-1} was significantly correlated with root and shoot dry weight, shoot Si uptake, and total chlorophyll content, and was negatively correlated with Pb content and Pb uptake parameters (Table 2).

Table 1. Single and interaction effects of lead and silicon on growth parameters of rice

Treatments	Plant height (cm)	Number of tillers pot^{-1}
Pb rates (mg Pb kg^{-1} soil)		
0	92.1	10.3 a
100	91.0	9.1 b
Significance level	ns	**
Standard error of means	0.92	0.33
Silicon rates (mg Si kg^{-1} soil)		
Si0	89.9	9.2 b
Ca silicate-Si50	91.2	9.5 ab
Fumed silica-Si50	92.9	9.2 b
Ca silicate-Si100.	91.0	10.3 a
Fumed silica-Si100	92.7	10.5 a
Significance level	ns	*
Standard error of means	1.46	0.52
Pb×Si interactions		
Pb0×Si0	90.1	9.7
Pb0×Ca silicate-Si50	91.2	9.7
Pb0×Fumed silica-Si50	94.4	9.7
Pb0×Ca silicate-Si100.	91.6	11.3
Pb0×Fumed silica-Si100	93.0	11.3
Pb100×Si0	89.7	8.7
Pb100×Ca silicate-Si50	91.3	9.3
Pb100×Fumed silica-Si50	91.3	8.7

Treatments	Plant height (cm)	Number of tillers pot^{-1}
Pb100×Ca silicate-Si100.	90.4	9.3
Pb100×Fumed silica-Si100	92.4	9.7
Significance level	ns	ns
Standard error of means	2.06	0.74
%CV	2.76	9.38

Different small letter in a column indicates that they are significantly different.*- significant at 5 % level, **- significant at 1 % level, ns- not significant, CV- Coefficient of variation

Table 2. Correlation matrix between different plant parameters of rice

6.3	Tillers pot^{-1}	Root dry weight	Shoot dry weight	Shoot Si content	Root Si content	Shoot Si uptake	Root Si uptake	Total Si uptake	Total chlorophyll content	Shoot Pb content	Root Pb content	Shoot Pb uptake	Root Pb uptake
Root dry weight	0.36*												
Shoot dry wt.	0.48**	0.30ns											
Shoot Si content	0.46*	0.23ns	0.27ns										
Root Si content	0.31ns	0.59***	0.41*	0.24ns									
Shoot Si uptake	0.59***	0.32ns	0.88***	0.70***	0.42*								
Root Si uptake	0.34ns	0.80***	0.39*	0.25ns	0.95***	0.40*							
Total Si uptake	0.58***	0.62***	0.80***	0.61***	0.75***	0.89***	0.77***						
Total chl. Cont.	0.45*	0.40*	0.47**	0.32ns	0.51**	0.51**	0.51**	0.60***					
Shoot Pb cont.	-0.54**	-0.51**	-0.46**	-0.42*	-0.39*	-0.55**	-0.46*	-0.61***	-0.27ns				
Root Pb content	-0.55**	-0.56**	-0.55**	-0.42*	-0.44*	-0.62***	-0.51**	-0.68***	-0.35*	0.97***			
Shoot Pb uptake	-0.51**	-0.41*	-0.38*	-0.44*	-0.37*	-0.50**	-0.41*	-0.55**	-0.19ns	0.97***	0.92***		
Root Pb uptake	-0.54**	-0.50**	-0.53**	-0.43*	-0.41*	-0.61***	-0.47**	-0.65***	-0.31ns	0.98***	0.99***	0.94***	
Total Pb uptake	-0.53**	-0.46*	-0.45*	-0.44*	-0.40*	-0.55**	-0.44*	-0.60***	-0.25ns	0.99***	0.97***	0.99***	0.98***

Note: *, ** and *** indicates significant at 5, 1 and 0.1 % level respectively. ns- Not significant

Root parameters

Lead application had a significant effect to reduce root length of rice having 21.5 cm in Pb control treatment which reduced to 19.9 cm in 100 mg Pb kg^{-1}soil treatment (Table 3). The single effect of Si had no significant improvement on root length of rice. The interaction between Pb and Si was also not significant. Root dry weight was significantly varied by Pb and Si but not their interactions. In Pb control treatment the mean root dry weight was 1.91 g pot^{-1} but it reduced to 1.73 g pot^{-1} in 100 mg Pb kg^{-1} soil treatment (Table 3). The root dry weight was significantly improved by the application of Si in soil. The fumed silica at both 50 and 100 mg Si kg^{-1} soil treatment recorded higher root dry weight than calcium silicate source. There were significant positive correlation of root dry weight with root Si content and uptake, and chlorophyll content, but was significant negative correlation with Pb content and uptake parameters (Table 2).

Table 3. Single and interaction effects of lead and silicon on root and shoot parameters of rice

Treatments	Root length (cm)	Root dry weight (g pot^{-1})	Shoot dry weight (g pot^{-1})
Pb rates (mg Pb kg^{-1} soil)			
0	21.5 a	1.91 A	11.0 A
100	19.9 b	1.73 B	10.4 B
Significance level	*	**	**
Standard error of means	0.72	0.005	0.20
Silicon rates (mg Si kg^{-1} soil)			
Si0	20.3	1.74 b	9.9 c
Ca silicate-Si50	20.5	1.79 ab	10.8 ab
Fumed silica-Si50	20.4	1.89 a	10.4 bc
Ca silicate-Si100.	21.8	1.78 ab	11.2 a
Fumed silica-Si100	20.7	1.91 a	11.4 a
Significance level	ns	*	**
Standard error of means	1.13	0.008	0.32
Pb×Si interactions			
Pb0×Si0	20.5	1.82	10.4
Pb0×Ca silicate-Si50	21.4	1.84	10.9
Pb0×Fumed silica-Si50	22.2	2.11	10.8
Pb0×Ca silicate-Si100.	22.4	1.86	11.4
Pb0×Fumed silica-Si100	21.0	1.92	11.6
Pb100×Si0	20.0	1.65	9.4
Pb100×Ca silicate-Si50	19.6	1.73	10.7
Pb100×Fumed silica-Si50	18.6	1.67	9.9
Pb100×Ca silicate-Si100.	21.2	1.69	11.0
Pb100×Fumed silica-Si100	20.4	1.91	11.2
Significance level	ns	ns	ns
Standard error of means	1.60	0.12	0.45
%CV	9.47	8.37	5.23

Different small letter in a column indicates that they are significantly different.*- significant at 5 % level, **- significant at 1 % level, , ns- not significant, CV- Coefficient of variation

Shoot dry weight

Both lead and different silicon rates and sources had significant influences on shoot dry weight of rice. Under without Pb stress condition the shoot dry weight was found 11.0

g pot^{-1} and it reduced to 10.4 g when 100 mg kg^{-1} soil Pb stress was imposed (Table 3). The Si control treatment had the lowest shoot dry weight (9.9 g pot^{-1}). Increasing Si rate progressively increased the shoot dry weight of rice. Over the Si sources 100 mg Si kg^{-1} soil treatment had significantly higher shoot production than 50 mg Si kg^{-1} soil treatment. Like other parameters, the interaction effect of Pb and Si was not significant. There were very strong correlation of shoot dry weight with shoot Si uptake and chlorophyll content of leaf; however, shoot dry weight significantly reduced by the increase of the Pb content and uptake by the roots and shoots (Table 2).

Silicon application ameliorates different growth and yield attributing parameters in rice like plant height, tillers number pot^{-1}, root length and root and shoot dry weight. Silicon application increased shoot dry weight by 5.0-15.2 % over different rates and sources of Si. The positive response of Si in rice was also reported by Mobaswera *et al*. (2023) in a pot experiment. Synchronization of several physiological and biochemical activities were the contributing factor for enhancing crop yield even under a number of stress condition (Asgher *et al*., 2024). Silicon application in rice soil relieves peroxidation and fatty acid deproteination occurs in plants, which fosters growth regulating variables (Greger *et al*., 2018).

In our experiment Pb application reduced tiller production by 11.7 %, root dry weight by 9.4 % and shoot dry weight by 5.5 %. However, different growth variables were progressive in silicon treatment even under Pb contaminated soil (Souri *et al*., 2023). Silicon activates the exudation of a number of organic acids (i.e. oxalic acid, acetic acid) and flavonoid phenolics in root zone (Fan *et al*., 2016). These organic acids and phenolic substances act as chelating agent of different heavy metals like Cd, Pb, Zn, Al etc. (Chandra and Keshavkant, 2021). Therefore, Si detoxifies the effects of heavy metal in plants root zone.

Shoot Si content and uptake

The Si content in rice shoot was significantly reduced by Pb application in soil. In Pb control and 100 mg Pb kg^{-1} soil treatment the Si content of shoot were 2.80 and 2.69 %, respectively (Table 4). Silicon application in the soil also improved the shoot Si content but the extent of improvement was not significant. The interaction effect on this parameter was also not significant. Single effect of both Pb and Si had significant effect on shoot Si uptake of rice, where Pb application reduced Si uptake, and Si application increased the Si uptake. The Pb control treatment recorded shoot Si uptake of 308 mg pot^{-1} and 100 mg Pb kg^{-1} soil treatment recorded shoot Si uptake of only 281 mg pot^{-1}. Among the Si rates 100 mg Si kg^{-1} soil treatment had higher effect than 50 mg Si kg^{-1} soil treatment. However, among two sources there was no significant difference on uptake of Si by rice shoot.

Table 4. Single and interaction effects of lead and silicon on silicon uptake parameters of rice

Treatments	Shoot Si content (%)	Shoot Si uptake (mg pot^{-1})	Total Si uptake (mg pot^{-1})
Pb rates (mg Pb kg^{-1} soil)			
0	2.80 a	308 a	387 a
100	2.69 b	281 b	343 b
Significance level	*	***	***
Standard error of means	0.04	6.15	7.08
Silicon rates (mg Si kg^{-1} soil)			
Si0	2.67	264 b	321 d
Ca silicate-Si50	2.77	298 a	355 c
Fumed silica-Si50	2.68	278 b	359 bc
Ca silicate-Si100.	2.84	317 a	381 b
Fumed silica-Si100	2.76	315 a	409 a
Significance level	ns	***	***
Standard error of means	0.06	9.73	11.1
Pb×Si interactions			
Pb0×Si0	2.68	278	338
Pb0×Ca silicate-Si50	2.80	304	366
Pb0×Fumed silica-Si50	2.75	298	401
Pb0×Ca silicate-Si100.	2.97	337	410
Pb0×Fumed silica-Si100	2.78	324	421
Pb100×Si0	2.66	250	304
Pb100×Ca silicate-Si50	2.74	293	345
Pb100×Fumed silica-Si50	2.61	258	318
Pb100×Ca silicate-Si100.	2.71	297	352
Pb100×Fumed silica-Si100	2.74	305	397
Significance level	ns	ns	ns
Standard error of means	0.09	13.7	15.8
%CV	4.34	5.72	5.31

Different small letter in a column indicates that they are significantly different.*- significant at 5 % level, ***- significant at 0.1 % level, , ns- not significant, CV- Coefficient of variation

Root Si content and uptake

The interaction of Pb and Si had significant effect on root Si content of rice (Fig. 1). Under Pb control condition the fumed silica source had significantly higher performance than calcium silicate source, unfortunately, there was no significant difference between 50 and 100 mg Si kg^{-1} soil rate (Fig. 1a). Under 100 mg Pb kg^{-1} soil condition only fumed silica source at 100 mg Si kg^{-1} soil treatment had significantly higher Si content than all other sources and rates of Si (Fig. 1a). The performance of different sources and rates of Si under Pb control and 100 mg Pb kg^{-1} soil condition on increasing root Si content has been given in Fig 1b. From the figure it was found that fumed silica applied at 100 mg Si kg^{-1} soil rate recorded statistically similar root Si content in Pb control and 100 mg Pb kg^{-1} soil rate. The result indicates that although Pb application generally reduced the Si content of root but regarding fumed silica at 100 mg Si kg^{-1} rate the Pb toxicity could not significantly reduced the Si content of root (Fig. 1b)

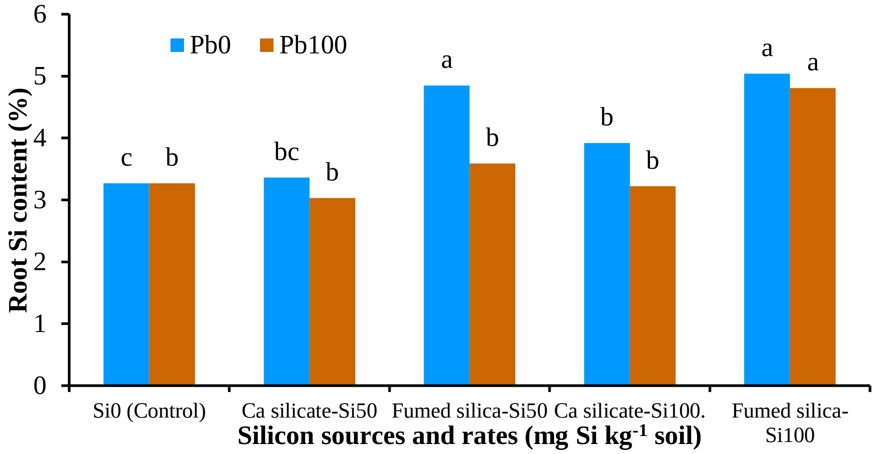

Fig. 1a

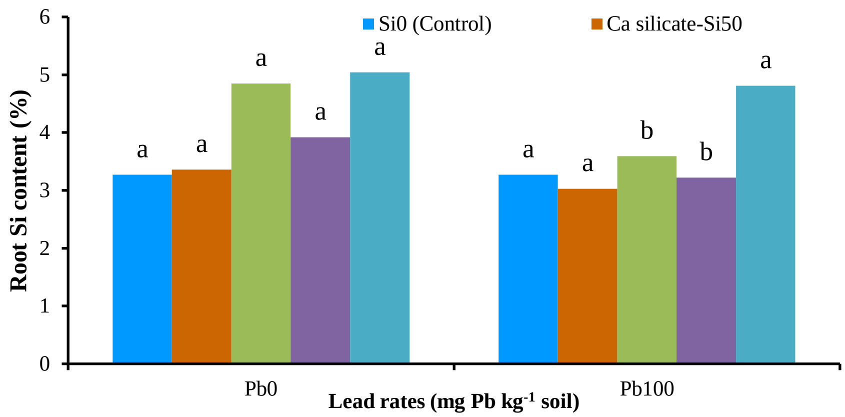

Fig. 1b

Fig. 1. Effect of lead×silicon interaction on root silicon content of rice a) Comparison of silicon at each level of lead, b) Comparison of lead at each level of silicon

Means with the same letter in same color bar are not significantly different
Significance level: Lead-***, Silicon-***, Lead:Silicon interaction-*;
Standard error: Lead-0.12, Silicon-0.19, Lead:Silicon interaction-0.27; CV (%)- 8.71

The root Si uptake was significantly affected by both single and interaction effect of Pb and Si (Fig. 2). Under Pb control condition only fumed silica source at both 50 and 100 mg Si kg^{-1} soil treatment had significantly higher Si uptake than other treatments (Fig.

2a). But at 100 mg Pb kg^{-1} soil applied condition only fumed silica source at 100 mg Si kg^{-1} soil treatment had significantly higher root Si uptake compare to calcium silicate source and 50 mg Si kg^{-1} soil rate. Again when fumed silica was applied at 100 mg Si kg^{-1} soil rate the Pb toxicity could not significantly reduce the root Si uptake of rice (Fig. 2b). The results indicated that fumed silica source at 100 mg Si kg^{-1} soil rate could reduce the detrimental effect of Pb in plants. There was an antagonistic correlation of root and shoot Si content and uptake with Pb content and uptake by root and shoot (Table 2). The results endorses that increasing Si content or uptake significantly reduced the Pb content or uptake, and vice versa.

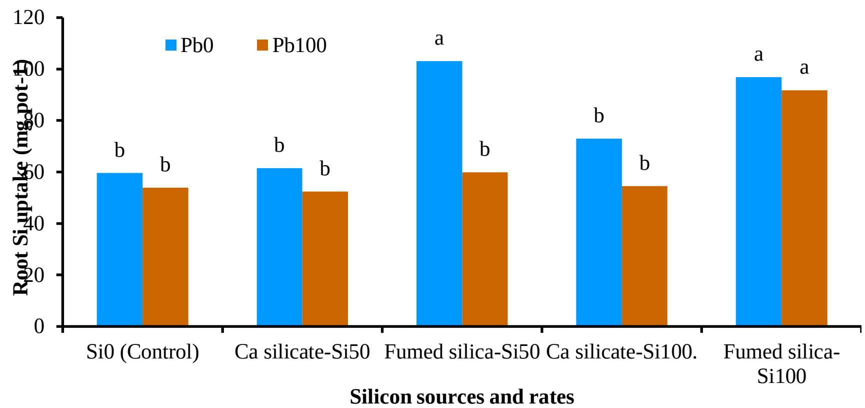

Fig. 2a

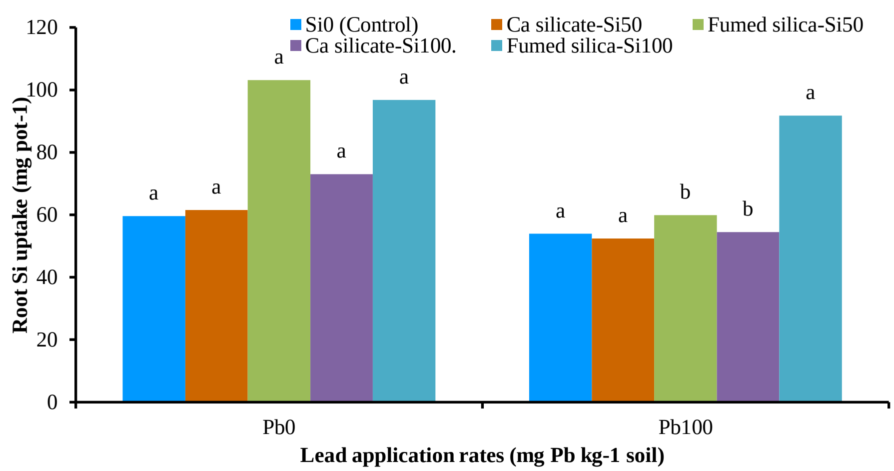

Fig. 2b

Fig. 2. Effect of lead:silicon interaction on root silicon uptake of rice a) Comparison of silicon at each level of lead, b) Comparison of lead at each level of silicon

Means with the same letter at same color bar are not significantly different
Significance level: Lead-***, Silicon-***, Lead:Silicon interaction-*;
Standard error: Lead-3.68, Silicon-5.82, Lead:Silicon interaction-8.23; CV (%)- 11.2

Total Si uptake (shoot plus root) was significantly affected only single effect of Pb and Si, but not their interactions (Table 4). Lead application reduced the Si uptake whereas Si application increased the Si uptake. Among the sources fumed silica at 100 mg Si kg^{-1} soil treatment had the highest Si uptake.

Silicon brings down lead (Pb) accumulation in plants cell by external and internal mechanisms. Externally Si rise soil pH which decline the availability of Pb by precipitating or chelating it into the soil. And internally higher Si accumulation in the shoot of rice plants persuades down-regulatory genes which restricts channels or regulatory pathway that may be associated with Pb uptake by roots of rice plants (Gong *et al*., 2023). In this way Si checks the toxic impact of Pb in rice plants. Again, silica form of silicon in soil assembled Pb silicate complexes precipitation that effectively reduced phyto-availability of toxic Pb in soil (Rachappanavar *et al*., 2024). Silicon also provokes antioxidant hormonal system and gene expression which diminishes heavy metal issues in soil (Bhat *et al*. 2019).

Shoot and root Pb content

Both shoot and root Pb content were significantly varied by single effect of Pb and Si, and their interactions. In Pb control condition the different sources and rates of Si had no significant difference on uptake of Pb by both shoot and root (Table 5). However, when Pb was applied to the soil at 100 mg Pb kg^{-1} soil the Pb content of both shoot and root were just jumped. Interestingly, among the Si sources and rates the Pb content was significantly different. The Si control against 100 mg Pb kg^{-1} soil treatment recorded highest Pb uptake of 10.65 and 193.6 mg kg^{-1} in shoot and root, respectively. There was a strong antagonistic relation of Si with Pb content of rice plants. Increasing Si rates the Pb content was gradually decreased having lowest Pb content were recorded at 100 mg Si kg^{-1} soil treatment. Among two Si sources, the fumed silica had higher capacity to reduce Pb content by both shoot and root. The Pb accumulation in root was several folds higher than the shoot.

Table 5. Interaction effects of lead and silicon on lead concentration of rice

Silicon sources and rates (mg Si kg^{-1} soil)	Lead levels (mg Pb kg^{-1} soil)	
	0 (Control)	100
Shoot lead content (mg kg^{-1})		
Si0 (Control)	2.68 Ba	10.65 Aa
Ca silicate-Si50	2.24 Ba	9.52 Ab
Fumed silica-Si50	2.51 Ba	8.65 Ac
Ca silicate-Si100.	2.52 Ba	8.68 Ac
Fumed silica-Si100	2.24 Ba	8.18 Ac
Significance level: Lead-***, Silicon-***, Lead:Silicon interaction-***; Standard error: Lead-0.12, Silicon-0.19, Lead:Silicon interaction-0.27; CV (%)- 5.82		
Root lead content (mg kg^{-1})		
Si0 (Control)	16.3 Ba	193.6 Aa

Silicon sources and rates (mg Si kg^{-1} soil)	Lead levels (mg Pb kg^{-1} soil)	
	0 (Control)	100
Ca silicate-Si50	11.2 Ba	158.4 Ab
Fumed silica-Si50	12.3 Ba	161.0 Ab
Ca silicate-Si100.	11.5 Ba	118.2 Ac
Fumed silica-Si100	13.7 Ba	97.6 Ad
Significance level: Lead-***, Silicon-***, Lead:Silicon interaction-***; Standard error: Lead-2.00, Silicon-3.16, Lead:Silicon interaction-4.47; CV (%)- 6.90		

Different capital letter in a row indicates that the Pb effects were significantly different. Similarly different small letter in a column indicates that the Si rates were significantly different. ***- significant at 0.1 % level, CV- Coefficient of variation

Shoot and root Pb uptake

The shoot, root and total Pb uptake was significantly varied by the interaction effect of Pb and Si application (Table 6). When Pb was not applied (Pb control treatment) all the Si sources and rates had statistically identical Pb uptake by shoot and or root. But when Pb was applied at 100 mg kg^{-1} soil rate, the Pb uptake trend was changed over the sources and rates of the Si. Every cases Si control treatment had highest Pb uptake. The lowest Pb uptake was found at 100 mg Si kg^{-1} soil treatment. Among the sources of Si the fumed silica had lower total Pb uptake than calcium silicate source (Table 6). The single effect of Pb and Si also had significant impact on these Pb uptake parameters. There was an antagonistic relation of Si application with uptake of Pb by root and shoot of rice. Lead application in the soil increased Pb uptake by the plants. Interestingly application of Si in that soil drastically reduced the Pb uptake by both root and shoot; and the reduction rate was much higher in the higher rates of Si application (100 mg Si kg^{-1} soil). The reason behind that might be Pb interfere the enzymatic reactions in rice plants which alter the mineral nutrient consumption, that eventually limits plants growth by altering photosynthesis and other morphological characteristics (Guo *et al.*, 2018). Lead harmfulness prompts retard plant growth, brings down photosynthesis and limits the development of primary root also in banana and other fruits (Li *et al.*, 2012). It also extremely damages the production of Maize; Si treatment lowers these problems to a great extent by different defense mechanism (Okant, and Kaya, 2019).

Table 6. Single and interaction effects of lead and silicon on lead uptake of rice

Silicon levels	Lead levels (mg Pb kg^{-1} soil)	
	0 (Control)	100
	Shoot lead uptake (mg kg^{-1})	
Si0 (Control)	0.109 Ba	0.408 Aa
Ca silicate-Si50	0.090 Ba	0.405 Aa
Fumed silica-Si50	0.096 Ba	0.307 Ac
Ca silicate-Si100.	0.097 Ba	0.377 Ab
Fumed silica-Si100	0.093 Ba	0.355 Ab
Significance level: Lead-***, Silicon-ns, Lead:Silicon interaction-*; Standard error: Lead-0.014, Silicon-0.022, Lead:Silicon interaction-0.034; CV (%)- 10.9		
	Root lead uptake (mg kg^{-1})	
Si0 (Control)	0.030 Ba	0.318 Aa
Ca silicate-Si50	0.021 Ba	0.275 Ab
Fumed silica-Si50	0.026 Ba	0.269 Ab
Ca silicate-Si100.	0.021 Ba	0.200 Ac
Fumed silica-Si100	0.026 Ba	0.186 Ac
Significance level: Lead-***, Silicon-***, Lead:Silicon interaction-***; Standard error: Lead-0.006, Silicon-0.010, Lead:Silicon interaction-0.014; CV (%)- 12.8		
	Total lead uptake (mg pot^{-1})	
Si0 (Control)	0.139 Ba	0.726 Aa
Ca silicate-Si50	0.111 Ba	0.680 Aa
Fumed silica-Si50	0.122 Ba	0.576 Ab
Ca silicate-Si100	0.118 Ba	0.577 Ab
Fumed silica-Si100	0.119 Ba	0.541 Ab
Significance level: Lead-***, Silicon-*, Lead:Silicon interaction-*; Standard error: Lead-0.018, Silicon-0.029, Lead:Silicon interaction-0.042; CV (%)- 13.8		

Different capital letter in a row indicates that the Pb rates were significantly different. Similarly different small letter in a column indicates that the Si rates were significantly different. *- significant at 5 % level, ***- significant at 0.1 % level, ns- Not significant, CV- Coefficient of variation

Chlorophyll content

The chlorophyll a, chlorophyll b, total chlorophyll and carotenoid content were significantly influenced only by the application of Si. The lowest chlorophyll a, chlorophyll b, total chlorophyll and carotenoid content of 3.58, 1.03, 4.60 and 1.63 mg g^{-1} fresh leaf, respectively were noticed in Si control treatment, and all were progressively increased with increasing Si rates (Table 7). The 50 mg Si kg^{-1} soil treatment had higher chlorophyll content than Si control treatment. Every cases highest chlorophyll and carotenoid contents were found in 100 mg Si kg^{-1} soil treatment. Among the sources fumed silica had the higher capacity to produce pigments of the leaves. Although the effect of Pb was not significant, but in value it reduces all the pigment granules. In agreement with our findings Aslam *et al*. (2021) reported that lead toxicity hampers physiological and metabolic actions including reduction of chlorophyll a and chlorophyll b levels, which reduce the photosynthetic capacity of rice leaves, consequently hinders plant growth and development. In our experiment Si application increased the chlorophyll content of rice which ultimately assists plant to reduce the toxicity of Pb.

Table 7. Single and interaction effects of lead and silicon on chlorophyll and carotenoid content of rice leaves

Treatments	Chlorophyll a content (mg g^{-1} fresh leaf)	Chlorophyll b content (mg g^{-1} fresh leaf)	Total chlorophyll content (mg g^{-1} fresh leaf)	Carotenoids content (mg g^{-1} fresh leaf)
Pb rates (mg Pb kg^{-1} soil)				
0	3.90	1.19	5.08	1.78
100	3.83	1.12	4.95	1.75
Significance level	ns	ns	ns	ns
Standard error of means	0.09	0.04	0.08	0.04
Silicon rates (mg Si kg^{-1} soil)				
Si0	3.58 c	1.03 b	4.60 c	1.63 c
Ca silicate-Si50	3.79 bc	1.16 ab	4.95 b	1.74 bc
Fumed silica-Si50	3.79 bc	1.15 ab	4.94 b	1.73 bc
Ca silicate-Si100.	4.03 ab	1.15 ab	5.17 ab	1.83 ab
Fumed silica-Si100	4.14 a	1.29 a	5.43 a	1.90 a
Significance level	*	*	***	**
Standard error of means	0.14	0.06	0.14	0.06
Pb×Si interactions				
Pb0×Si0	3.63	1.05	4.68	1.64
Pb0×Ca silicate-Si50	3.83	1.17	5.00	1.75
Pb0×Fumed silica-Si50	3.81	1.16	4.97	1.75
Pb0×Ca silicate-Si100.	4.07	1.25	5.32	1.86
Pb0×Fumed silica-Si100	4.14	1.30	5.45	1.91
Pb100×Si0	3.52	1.00	4.52	1.62
Pb100×Ca silicate-Si50	3.76	1.15	4.91	1.74
Pb100×Fumed silica-Si50	3.77	1.14	4.91	1.71
Pb100×Ca silicate-Si100.	3.98	1.05	5.03	1.80
Pb100×Fumed silica-Si100	4.13	1.27	5.40	1.89
Significance level	ns	ns	ns	ns
Standard error of means	0.21	0.09	0.19	0.09
%CV	6.70	10.3	4.84	6.61

Different small letter in a column indicates that they are significantly different.*- significant at 5 % level, **- significant at 1 % level, ***- significant at 0.1 % level, ns- not significant, CV- Coefficient of variation

Conclusion

Lead is considered toxic heavy metal for plants. Lead application at a rate of 100 mg kg^{-1} soil hinders plants growth by accumulation in plants cell and interferes with plants metabolism. All forms of silicon improved plant growth in Pb affected soil but among them fumed silica at a rate of l00 mg Si kg^{-1} soil rate was more potential in limiting Pb toxicity. Because of its delicate form, fumed silica can easily dissipate in soil and augment soil properties. It is readily assimilated by plants, nourishes plants health and makes plant more tolerant at unfavorable situations. Findings of the current research will assist policy makers, agriculturists, farmers and the ultimate consumers about production and consumption of safe foods. In future higher doses of both Si and Pb from the current study could be applied in rice using various types of soil to find out the dynamics of those elements in soil and plants.

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Author's contribution

The study conception, formulation of the research program, provision of materials, statistical data analysis, preparation of tables and graphs, manuscript editing, and research project funding were carried out by M A. Haque. Fieldwork, chemical analyses, and data collection were conducted by S. Pranto, S. Islam, P. S. Dhrubo, M. M. Soha, and F. N. Lamia. The initial draft of the manuscript was prepared by Samsunnahar Pranto. Md Lutfar Rahman performed the heavy metal analysis of soil and plant samples. All authors reviewed and approved the final version of the manuscript.

Conflict of Interest

The author has declared no conflict of interest.

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