Influence of Silicon on Plant Uptake of Heavy Metals and Metalloid from Soil

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Abstract

Silicon, the second most abundant element of earth's crust, performs a variety of beneficial roles in soils and plants. It is involved in the mitigation of various biotic (insect pests and diseases) and abiotic stresses (salt, drought and heavy metals) .Si influences the heavy metal and metalloid uptake by plants through different mechanisms including (1) Si bioavailability in soil is influenced by biological factors, (2) by altering the soil's properties, (3) heavy metal co-precipitation, (4) heavy metals being changed into less solubility forms, (5) root architecture modification, (6) controlling antioxidant enzymes, (7) up and down-regulation of gene expression responsible for heavy metals uptake and transportation to plants .In this chapter it is discussed about the various mechanisms involved in heavy metal and metalloid uptake by Silicon. The application of industrial by products (fly ash, steel slag etc.) decreased the heavy metal uptake by transforming the soluble metals to insoluble metal silicates, phosphates and hydroxides. Si application can reduce heavy metal bioavailability in soil. Silicon nanoparticles along with Pb-resistant microbes significantly reduced the Pb concentration in plants. Si application changes mineral composition of Fe plaque in rice root which decreases both shoot As and grain As. A significant decrease in Cd and Pb toxicity of wheat along with increased grain yield can be possible by the application of organic and inorganic silicon fertilisers. Silicon nanoparticles can reduce the Cd uptake into rice grains and phloem by inhibiting the expression of low affinity cation transporter (OsLCT1). Si application mitigate Cd toxicity in cotton through reduced electrolytic leakage, malondialdehyde and hydrogen peroxide contents and improved antioxidant enzymes activity. Long-term field trials are required to evaluate the feasibility of Si application for the remediation of metal-contaminated soils.

Keywords : Silicon, heavy metals, metalloid, toxicity, remediation

Introduction-

Silicon (Si) the second most abundant element of earth's crust, performs a variety of beneficial roles in soils and plants. It is involved in the mitigation of various biotic (insect pests and diseases) and abiotic stresses (salt, drought and heavy metals) (Ma *et al.*, 2021). Amorphous elemental silicon was first isolated by Jöns Jacob Berzelius (1824), element name derived from Latin silex or silicis ("flint" or "hard stone"), includes to group 14 [IVa], having atomic number 14, atomic weight 28.086, density 2.33 gcm^{-3} Specific gravity 2.24 and oxidation state −4, (+2), +4. Heavy metals are generally defined as metals with relatively high densities, atomic weights, or atomic numbers. Examples of heavy metals include mercury (Hg), cadmium (Cd), chromium (Cr), thallium (Tl), and lead (Pb). Boron (B), silicon (Si), germanium (Ge), arsenic (As), antimony (Sb), and tellurium (Te) are commonly recognised as metalloids.

Various silicon fractions in soils

According to Souri *et al.* (2020) the main two fractions of Si in soil are liquid and solid phase. Liquid phase includes monosilicic, polysilicic acid, orano-silicon compounds etc. Amorphous and crystalline forms include to solid phase, where quartz, feldspar, mica, kaolinite, smectite includes to crystalline form and biogenic and non- biogenic include to amorphous form (Fig : 1).

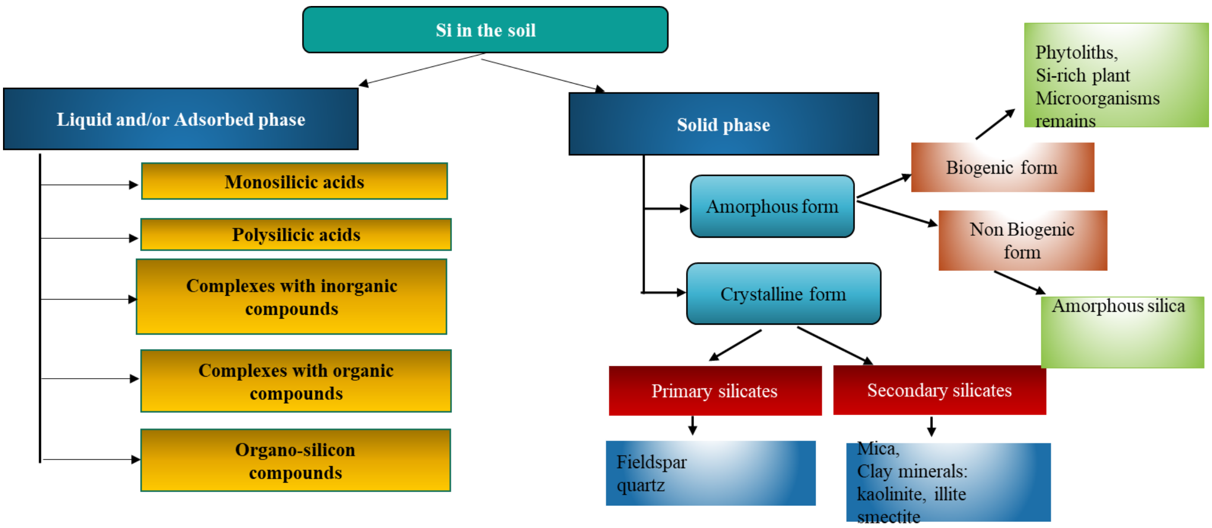


Fig 1 : Different fractions of silicon

Silica accumulator plant

Meena *et al.* (2021) reported there are three categories of Si accumulator high accumulator (>1.5% Si) - rice, sugarcane, wheat etc, intermediate accumulator (1.5% − 0.5% Si) - soybean, squash, cucumber, pumpkin etc and Non accumulator (< 0.5% Si) - sunflower , tomato, grapes etc (Table:1).

High accumulator (>1.5% Si)	Intermediate accumulator (1.5%–0.5% Si)	Non accumulator (< 0.5% Si)
Rice	Soybean	Sunflower
Sugarcane	Pumpkins	Tomato
Wheat	Cucumber	Grapes
Lentils	Rose	Snapdragon
Spinach	Squash	Gerbera
Ferns	Chrysanthemums	Petunia
Conifers	Zinnia	Pansy

Table 1 : Silica accumulator plant

Benefits of Si

Si is not thought to be necessary for the growth and development of plants, but mounting research suggests that this metalloid has advantages for plants, particularly under stressful situations. Si does, in fact, reduce the harmful consequences of abiotic stimuli, such as salt stress, drought, and heavy metals (Gaur *et al.*, 2020) (Fig : 2).

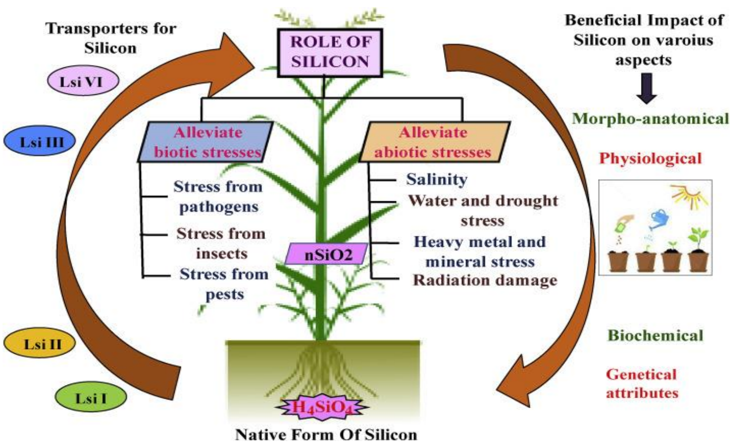


Fig 2 : Benefits of Si for plants

Plant Available Silicon (PAS)

Si is commonly found in soil in a variety of forms, particularly quartz, silicates, biogenic SiO2 (found in things like diatoms and phytoliths), and silica gel. The soil contains amorphous, active, and water soluble forms of silicon that are all extractable. Plants can readily access the water soluble forms of silicon while the remainder of the silicon must first be transformed to a water soluble form under favourable conditions before being used by plants. (Ma *et al*., 2006). The southern dry zone (SDZ), southern transition zone (STZ), coastal zone (CZ), and central dry zone are the four main agro-climatic zones of Karnataka that Majumder et al. (2021) documented the vertical distribution of the plant accessible silicon (PAS) content in soils of (CDZ). Regardless of the crop, STZ and CZ have high DSi content (more than 40 mg kg), while SDZ and CDZ have medium DSi content (between 20 and 40 mg kg^{-1}). The lowest concentrations of DSi and AdSi were found in SDZ and CZ, respectively. In the CDZ and SDZ soil profiles of rice, the average AdSi content was 2.4 and 4 times greater than DSi, respectively. In sugarcane soil profiles, CDZ and SDZ, respectively, had AdSi contents that were 2.6 and 4 times greater than DSi levels (Table:2)

Zone	pH	Dissolved silicon (DSi) (mg kg^{-1})		Adsorbed silicon (AdSi) (mg kg^{-1})	
		Rice	Sugarcane	Rice	Sugarcane
Southern Dry Zone	7.70	25.83	23.00	115.59	113.59
Southern Transition Zone	6.96	100.05	82.23	97.29	80.30
Coastal Zone	5.72	39.10	58.73	64.34	51.31
Central Dry Zone	7.75	21.08	34.70	102.00	86.62
SEm±		7.66	13.26	10.84	18.78
CD at ≤0.05		22.40	38.79	31.73	54.95

Table 2 : Four different agro-climatic zones in Karnataka's relationship between the attributes of rice and sugarcane soils and plant-available silicon (PAS)

In order to determine the impact of different diatomite grades (diatomite-1, diatomite-2, diatomite-3, diatomite-4, and diatomite-5) and levels (0, 250, 500, 750, 1000, and 1500 kg ha-1) on silicon availability in acidic and alkaline soils under field capacity, Anitha *et al.* (2015) conducted a pot experiment. In both soil types, diatomite-3 and diatomite-4 applied at 750 kg ha-1 each together with RDF resulted in considerably higher straw and grain yields, silicon content, and rice uptake. Comparing the application of diatomite-4 @ 1000 kg ha-1 + RDF to other grades of diatomite, higher straw silicon content was found in alkaline soil. This may be due to higher silicon dissolution at higher pH levels as well as the mechanism of silicic acid distribution in the shoots and deposition in the plant parts. Diatomite-4 @ 750 kg ha-1 + RDF treatment in acidic soil resulted in greater straw Si% content (5.9%) compared to other grade of diatomite. (Fig : 3)

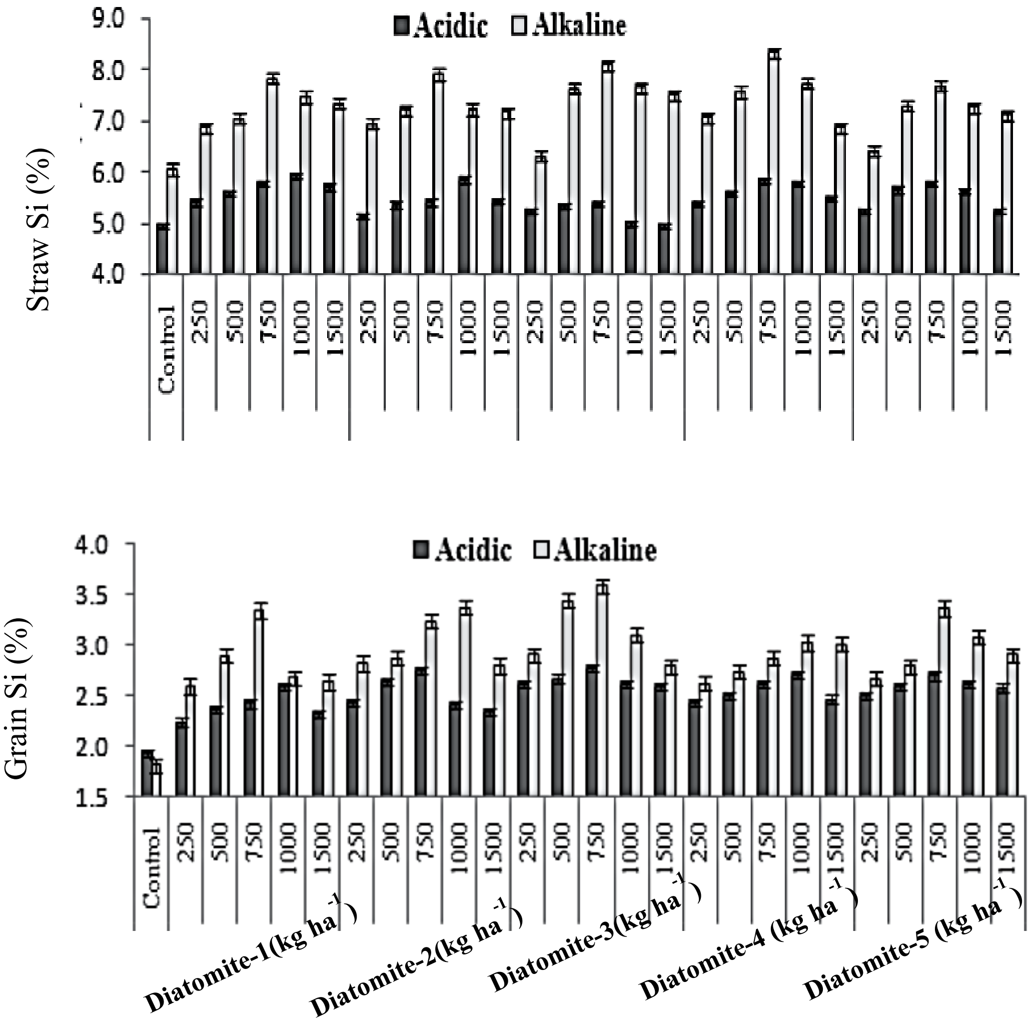


Fig 3 : Evaluation of different grades of diatomite on paddy straw and grain Si (%) plant in acidic and alkaline Soils at harvest

There was a greater dissolution of diatomite and release of silicon in both the soils and thereby diatomite can be used as sources of silicon. According to Khan *et al.* (2021) reported Plants have detoxifying systems based on silicon including (1) activation of antioxidant defense system and thus reducing the oxidative damage, (2) Removal of heavy metals and metalloid from the cells, (3) Relocation of heavy metals and metalloid at subcellular level (4) Improvement in photosynthetic system (5) Repair of injured cell membranes (6) Regulation of phytochelatins.

Si influences the heavy metal and metalloid uptake by plants through different mechanisms including (1) Si bioavailability in soil is influenced by biological factors, (2) by altering the soil's properties, (3) heavy metal co-precipitation, (4) heavy metals being changed into less solubility forms, (5) root architecture modification, (6) controlling antioxidant enzymes, (7) up and down-regulation of gene expression responsible for heavy metals uptake and transportation to plants (Khan *et al*., 2021).

- **<u>Effects of silicon rich amendments on heavy metals and metalloid accumulation</u>**

    1. **Effects of silicon rich amendments on heavy metal accumulation in rice (*Oryza sativa* L.)**

In the treatments of Fly ash (FA20) and Steel slag (SS3), the concentrations of cadmium, zinc, copper, and lead (Pb) calculated using the DGT technique (the DGT pools) all dramatically dropped (Table:3), and the reduction was at least 84%. Fly ash, steel slag, and other industrial byproducts reduced the uptake of heavy metals by converting soluble metals to insoluble metal silicates, phosphates, and hydroxides (Gu *et al*., 2011)

Treatments	Cd ($\mu g\ kg^{-1}$)	Zn ($mg\ kg^{-1}$ soil)	Cu ($mg\ kg^{-1}$soil)	Pb ($mg\ kg^{-1}$ soil)	pH
Control	7.3 ± 0.30a	6.7 ± 0.73a	6.3 ± 0.79a	57 ± 7.8a	3.9–4.0d
Fly ash (20 g kg^{-1})	1.7 ± 0.18b	0.56 ± 0.07c	1.0 ± 0.07b	4.1 ± 0.50c	5.0–5.2c
Fly ash	0.06 ± 0.01c	0.01 ± 0.01c	0.76 ± 0.08b	0.30 ± 0.04c	6.3–6.5a

(40 g kg^{-1})					
Steel slag (3 g kg^{-1})	2.1 ± 0.30b	1.4 ± 0.32b	1.3 ± 0.19b	9.8 ± 2.5b	4.9–5.1c
Steel slag (6 g kg^{-1})	0.10 ± 0.17c	0.11 ± 0.07c	0.72 ± 0.06b	0.53 ± 0.15c	6.0–6.2b

Table 3 : Effects of silicon rich amendments on heavy metal accumulation in rice (*Oryza sativa* L.)

Hamsa *et al.* (2018) assess the impact of several Si sources, such as rice hull biochar, diatomaceous earth, and calcium silicate at various quantities, in reducing the uptake of heavy metals by spinach. In RDF + Diatomaceous earth @ 500 kg Si ha-1, the uptake of Cr in spinach shoot and root is 10.10 m kg^{-1} and 1.12 mg kg^{-1}, respectively, which is significantly less. Due to its increased solubility and the availability of other nutrients, diatomaceous earth application was found to be more effective than other treatments in lowering the Cr concentration in spinach shoots (Table:4).

Effect of various silicon sources on spinach's absorption of chromium

Treatments	Cr content (mg kg^{-1})after harvest	
	Shoot	Root
Control	16.20 ±0.81 a	2.45 ±0.034 a
Rice hull biochar @ 200 kg Si ha^{-1}	15.40 ±0.74 ab	2.22 ±0.031 c
Rice hull biochar @ 500 kg Si ha^{-1}	10.70± 0.54 fg	1.95 ± 0.027 ef
Diatomaceous earth @ 200 kg Si ha^{-1}	11.20 ±0.56 def	1.88 ±0.026 g
Diatomaceous earth @ 500 kg Si ha^{-1}	**10.10 ±0.50 g**	**1.12 ±0.030 h**
Calcium silicate @ 200 kg Si ha^{-1}	11.80 ±0.59 cde	1.83 ±0.026 g
Calcium silicate @ 500 kg Si ha^{-1}	10.30 ±0.52 fg	1.98 ±0.028 e

(n =3) ±SD. $p < 0.05$

Table 4 : Chromium uptake by spinach and the impact of various silicon sources

Effect of combined use of lead (Pb) resistant microbes and silicon nanoparticles (Si-NPs) on coriander (*Coriandrum sativum* L.) under Pb stress

The combination use of silicon nanoparticles (Si-NPs) and lead (Pb) resistant microorganisms was assessed by Fatemi *et al*. (2020) under Pb stress. It has been proposed that Si-NPs and Pb-resistant microorganisms could be employed to increase plant growth, photosynthesis, and antioxidant capacity, hence reducing Pb stress in coriander. The plants treated with 500 mg/kg Pb had the highest concentration of shoots and roots, whereas the plants treated with the control treatment had the lowest concentration of Pb. Comparing the identical Pb treatments with and without the application of silicon, the concentrations of Pb in the shoots and roots reduced by 22% and 2%, respectively. (Fig : 4) T1: Command, T2: 500 mg/kg of lead T3: S6 + Pb500 Inoculation, T4: S19 + Pb50 Inoculation T5: Foliar Si-NPs 1.5 mM application Si-NPs + S6 + Pb in T6, and T7: Si-NPs + S19 + Pb

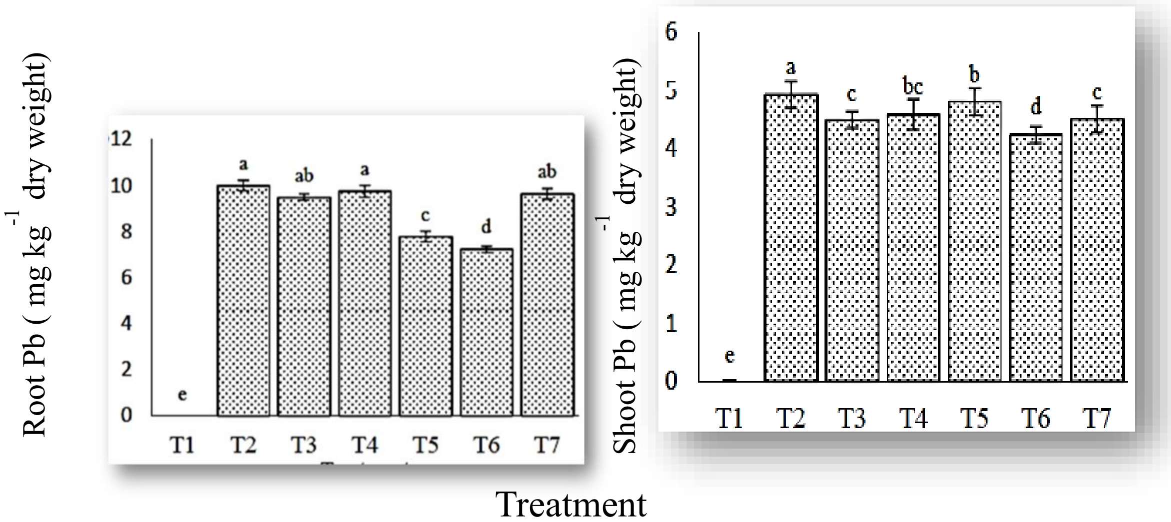
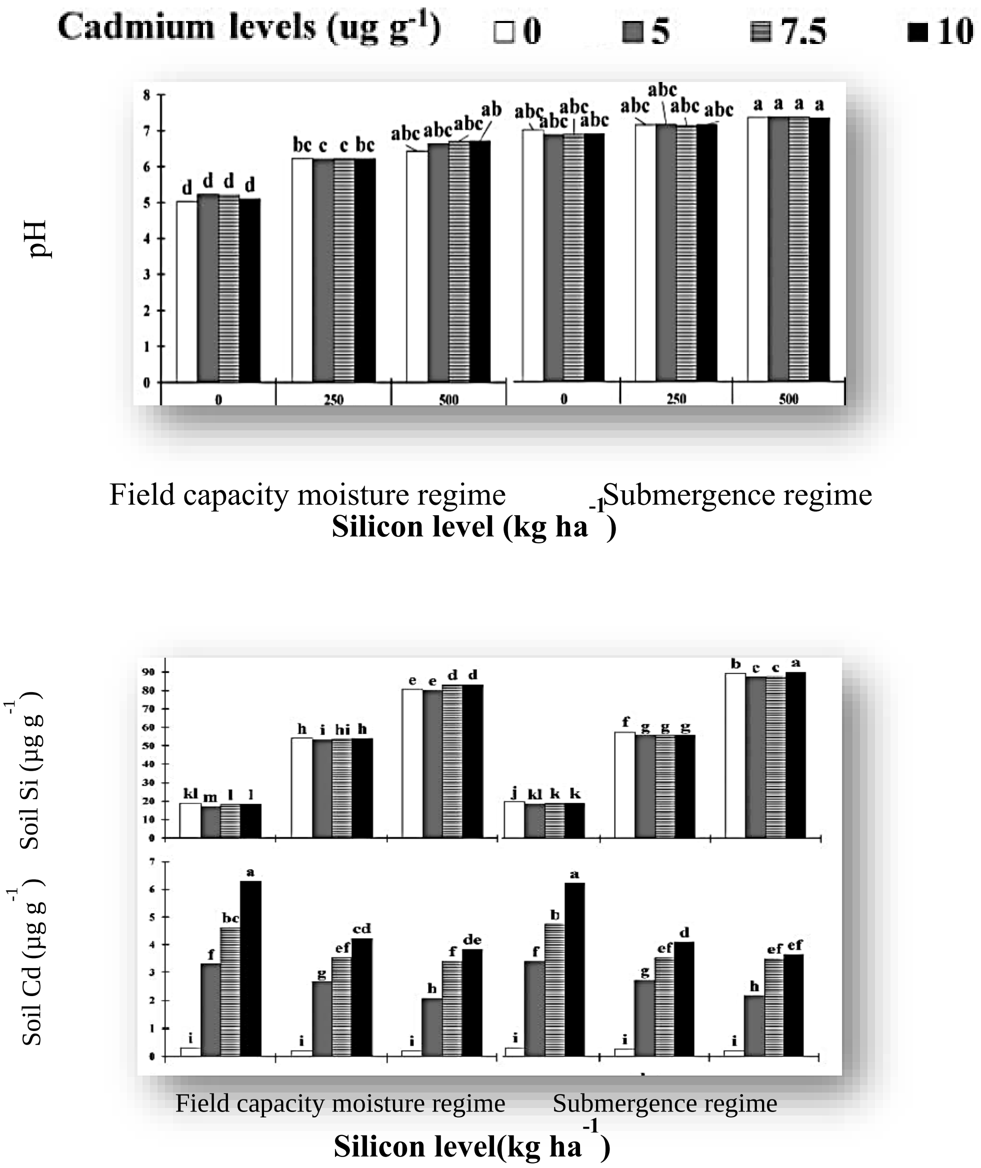


Fig 4 : Effect of combined use of lead (Pb) resistant microbes and silicon nanoparticles (Si-NPs) on coriander (*Coriandrum sativum* L.) under Pb stress

2.By altering the soil's properties

To investigate the effects of silicon on soil-cadmium availability and uptake in rice cultivated in an acid soil maintained under two distinct moisture regimes, Babu *et al.* (2017) carried out a greenhouse experiment (field capacity or submergence). Due to lowering circumstances in the soil and the addition of Si as wollastonite, soil pH rose after flooding and reached 6.5 to 7.1 during harvest. Contrary to changes in soil pH, the amount of Cd^{2+} that was readily available in the soil changed. In soils that were kept in a waterlogged condition, it was lower (Fig : 5).



$p < 0.05$ by Tukey–Kramer post-hoc test.

Fig 5 : Effect of silicon amendment on soil pH and soil-cadmium availability and uptake in rice

Effect of silica fertilisation and a nano-MnO2 amendment on the composition of the bacterial community in paddy soils with elevated arsenic levels

According to Shao *et al.* (2015), Proteobacteria, Chloroflexi, and Acidobacteria were the three phyla that predominated in all of the paddy soil samples used in this investigation. Declines in the relative abundance of Chloroflexi were accompanied by increases in the relative ratio of Acidobacteria and the addition of nano-MnO2. According to earlier research, low soil pH was advantageous to Acidobacteria and substantially regulated the amount of Acidobacteria present. Arsenite methylation, volatilization, arsenite reduction, and efflux are just a few of the different ways that cyanobacteria, including Microcystis, Nostoc, and Synechocystis, detoxify arsenic. Under silica fertilisation or amendment with nano-MnO_2, the amount of bioavailable arsenic reduced (Fig : 6). If silica fertilisation or nano-MnO_2 amendment reduce arsenic biotoxicity (Table : 5), cyanobacteria may compete less fiercely, resulting in a reduction in the relative abundance of this microorganism in the environment.

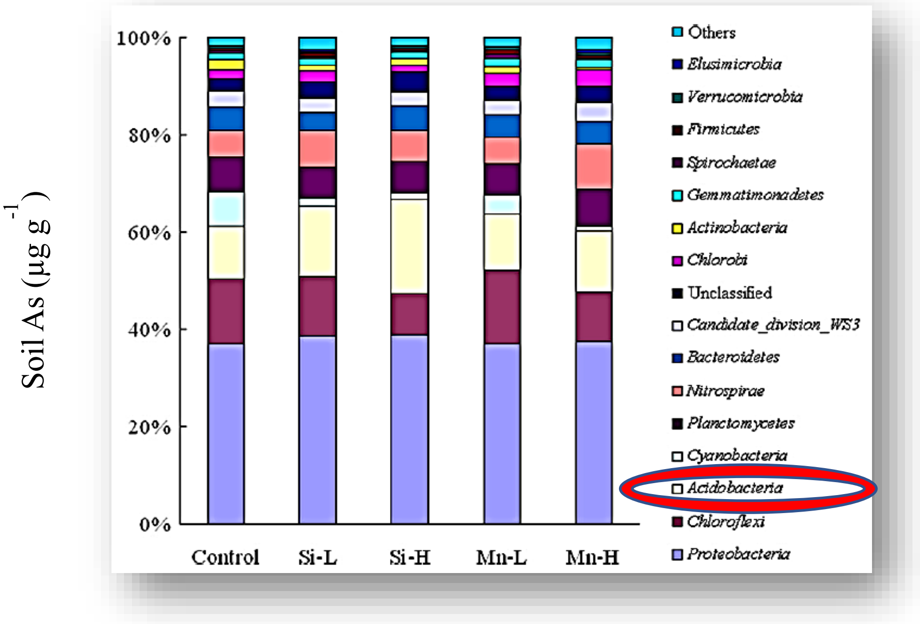


Fig 6 : Effect of silica fertilisation and a nano-MnO2 amendment on the composition of the bacterial community in paddy soils with elevated arsenic levels

Treatment	Bioavailable As (mg kg^{-1})	pH
Control	0.95 ± 0.14^{a}	7.35 ± 0.05^{a}
Si-L	0.66 ± 0.05^{b}	7.25 ± 0.07^{ab}
Si-H	0.55 ± 0.13^{bc}	7.26 ± 0.01^{b}
Mn-L	0.55 ± 0.01^{bc}	7.33 ± 0.04^{ab}
Mn-H	0.36 ± 0.02^{c}	7.25 ± 0.01^{b}

Means±SD ($p<0.05$)

Table 5 : Effect of a nano-MnO2 amendment and silica fertilisation on the bacterial diversity in arsenic-contaminated paddy soil

3.Heavy metal co-precipitation

Comparative efficacy of organic and inorganic silicon fertilizers on Cd/Pb accumulation in wheat (*Triticum aestivum* L.)

Through a soil pot experiment, the effects of three silicon fertilizers—two organic (OSiFA and OSiFB) and one inorganic (InOSiF)—on wheat heavy metal uptake and biochemical parameters in a soil with concurrent Cd and Pb contamination were evaluated and contrasted. By increasing Si uptake in roots and shoots using OSiFA, OSiFB, and InOSiF, the accumulation of Cd and Pb in wheat shoots, bran, and flour was reduced. In particular, the amount of Cd and Pb in the flour was reduced by 17%, 10%, and 31%, and by 74%, 53%, and 48%, respectively (Huang *et al.*, 2019) (Table:6).

	Cd concentration				Pb concentration				Si concentration		
	Root	Shoot	Bran	Flour	Root	Shoot	Bran	Flour	Root	Shoot	Grain
	1	1	1	1	1	1	1	1	1	1	1
Control with common fertilizer	1.07	1.44	2.22	1.46	1.06	1.67	3.72	3.84	0.57	0.84	0.90
Organosilicon fertilizer A	1.05	1.24	1	1.22	1.51	1.21	2.11	1	1	0.97	0.81
Organosilicon fertilizer B	1	1.34	1.79	1.31	1	1.30	1.50	1.82	0.90	1	0.42
Sodium silicate with common fertilizer	1.05	1	1.38	1	1.06	1	1	2.02	0.87	0.92	1

Results of standardization of raw data of Cd and Pb contents of wheat root, shoot, bran, flour, and Si content of wheat root, shoot, grain

Table 6 : Comparative efficacy of organic and inorganic silicon fertilizers on Cd/Pb accumulation in wheat (*Triticum aestivum* L.)

Effects of exogenous Si on Cd translocation and toxicity in rice (*Oryza sativa* L.)

In a long-term experiment with rice (*Oryza sativa* L.), Zhang *et al*. (2008) showed that the addition of Si boosted shoot and root biomass by 125–171% and by 100–106% in comparison to the zero-Si treatment (Fig : 7) In comparison to the treatment without silicon supply, silicon supply reduced the Cd concentrations in the shoot by 30–50% and the Cd distribution ratio by 25.3–46% (Table : 7).

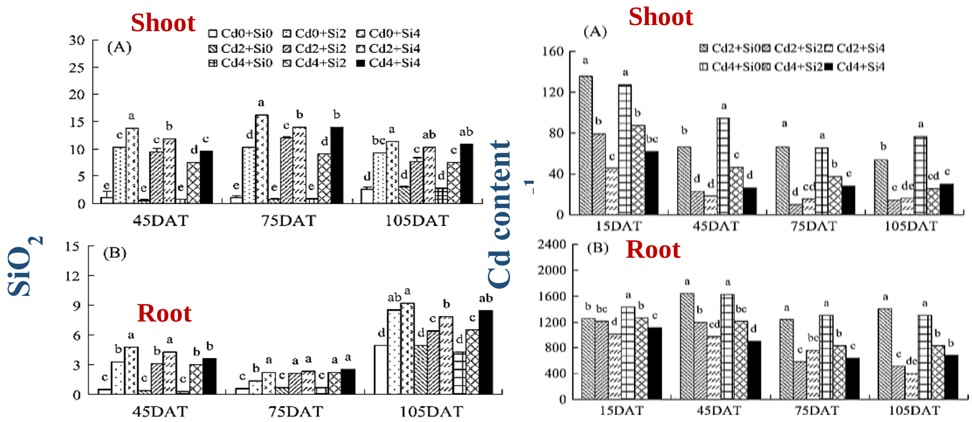


Fig 7 : Effects of exogenous Si on Cd translocation and toxicity in rice (*Oryza sativa* L.)

Cd concentration ($\times 10^{-6}$ mol L^{-1})	**SiO_2 concentration ($\times 10^{-3}$ mol L^{-1})**	**Days after Cd treatment**			
		15	45	75	105
		Cd distribution in shoots (% of total Cd in plant)			
2	0	30.0[a]	11.7[b]	12.5[a]	9.9[ab]
	2	23.1[b]	6.62[c]	5.65[b]	8.7[ab]
	4	16.2[c]	6.08[c]	4.57[b]	7.4[b]
4	0	24.2[b]	17.3[a]	11.6[a]	12.5[a]
	2	21.9[bc]	11.5[b]	11.0[a]	10.4[ab]
	4	18.5[bc]	8.1[bc]	10.5[a]	10.0[ab]

Table 7 : Effect of Si on Cd distribution in shoots of rice (*Oryza sativa* L.)

Effect of Si on changes in Fe mineral composition of Fe plaque and shoot As in rice

Amaral *et al*. (2017) evaluate Si's effects on the mineral makeup of root Fe plaques and how they affect rice's uptake of As. Si content is essential for managing the concentration of shoot As. Rice shoot As accumulation and inorganic rain As content are both affected by increasing solution Si and ferrihydrite concentration, higher Si's ability to precipitate and encrust As containing ferrihydrite, and lower ferrihdrite. As a result, As becomes less mobile as Si precipitates, resulting in plaques of As carrying ferrihydrite (Fig : 8).

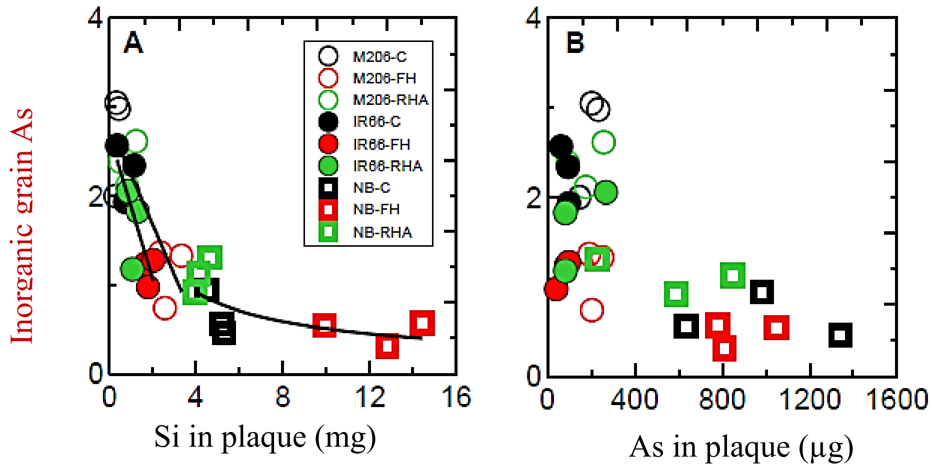
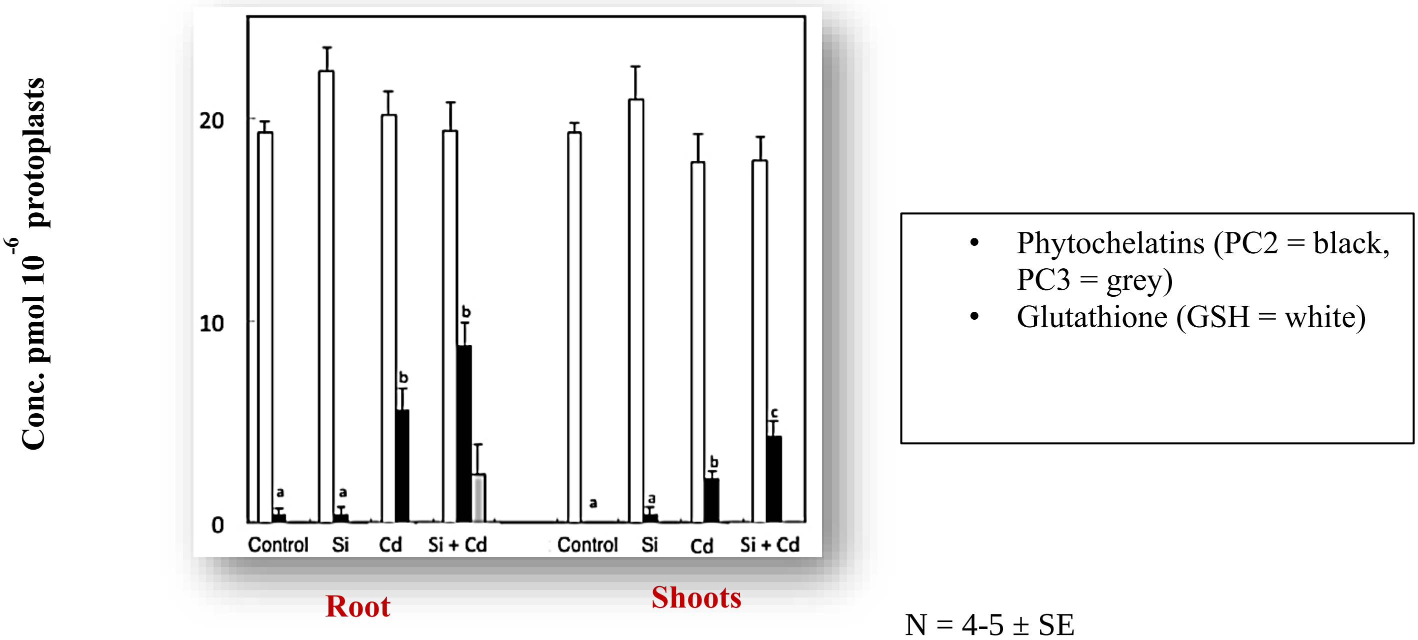


Fig 8 : Effect of Si on changes in Fe mineral composition of Fe plaque As in rice

4. Heavy metals being changed into less solubility forms Effect of silicate on Cd uptake into cells of wheat by phytochelatins formation

To investigate whether and how silicate (Si) effects cadmium (Cd) uptake at the cellular level in wheat, Greger *et al.* (2015) performed a pot experiment in wheat. Plants treated to all four treatments had their roots and shoots examined for the expression of genes related to Cd absorption, including phytochelatin (PC) content and PC gene (PCS1) expression (Fig : 9). Si promoted PC formation in the presence of Cd. Si-treated plants had higher PCS1 expression, which was much stronger in plants that had received Cd treatment. Protoplasts exposed to Cd or Cd^{2+} + Si contained PC2. Plants exposed to all treatments and controls both contained glutathione (GSH). Cell wall-bound Si hindered Cd absorption into cells, preventing Cd uptake into cells. Si may affect both the release of Cd from the inner side of the membrane and the binding of Cd to the membrane's uptake sites. Additionally, additional Si might bind to one Cd transporter, preventing the transport in the event that an other transport route is available. Treatments are : Control = 0 mM Si + 0 µM Cd, Si = 1 mM Si, Cd = 1 µM, Si+Cd = 1 mM Si + 1 µM Cd



N = 4-5 ± SE

Fig 9 : Effect of silicate on Cd uptake into cells of wheat by phytochelatins formation

Effect of silica nanoparticles in alleviating Cd toxicity in rice cells

Cui *et al*. (2017) carried out an experiment and used the CELLQuest programme to monitor the rice cells that had been treated. The threshold was established by the fluorescence emission in M2 areas, which represented the dead cells. The live cells and the dead cells, respectively, were represented by the fluorescence emission in the M1 and M2 regions. The vitality of the cells after the various treatments can be clearly seen in the data. The proportion of live cells exhibited the reverse tendency, and the number of dead cells was much higher in the absence of the SiNPs than it was in the presence of them (M1 area)(Fig : 10). After 48 hours of cultivation under the control circumstances, it was found that there were significantly more dead cells (65.5%) than live cells (34.5%). However, the inclusion of 19 nm, 48 nm, and 202 nm SiNPs significantly increased the proportion of live cells to 95.4%, 78.6%, and 66.2%, respectively. The average Cd content in cells and protoplasts grew gradually with rising Cd concentrations in the medium in the absence of the SiNP treatments, and the Cd content of the protoplasts was only marginally lower than that of the cells. The diameter of SiNPs was favourably linked with the Cd concentrations of the cells and protoplasts. The amount of Cd^{2+} entering cells was reduced in a size-dependent way as a result of the large particles offering fewer Cd^{2+} binding sites than the small particles. More Cd binding sites are made available by the increased Si concentration in cell walls, which prevents Cd from entering cells (Fig : 11).

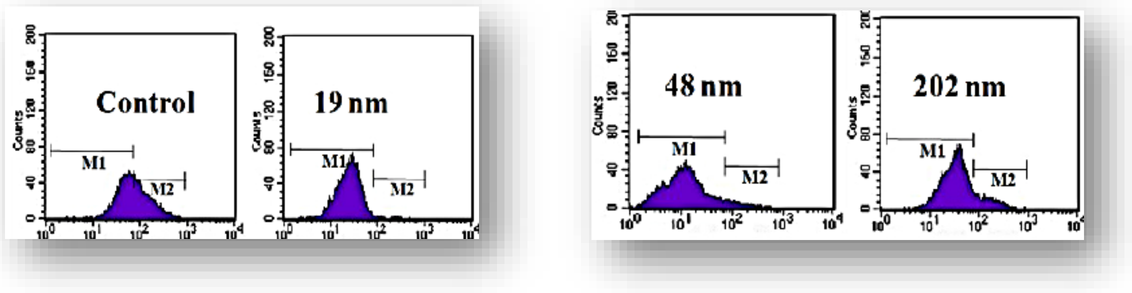
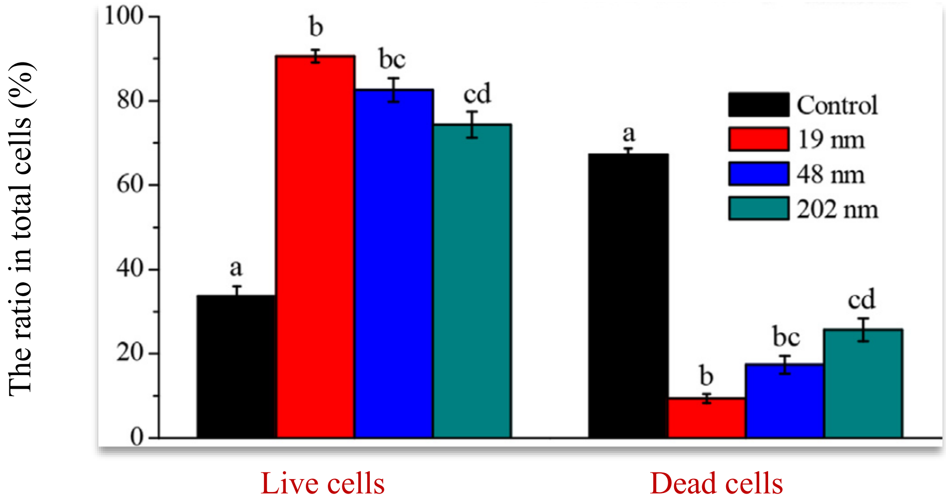
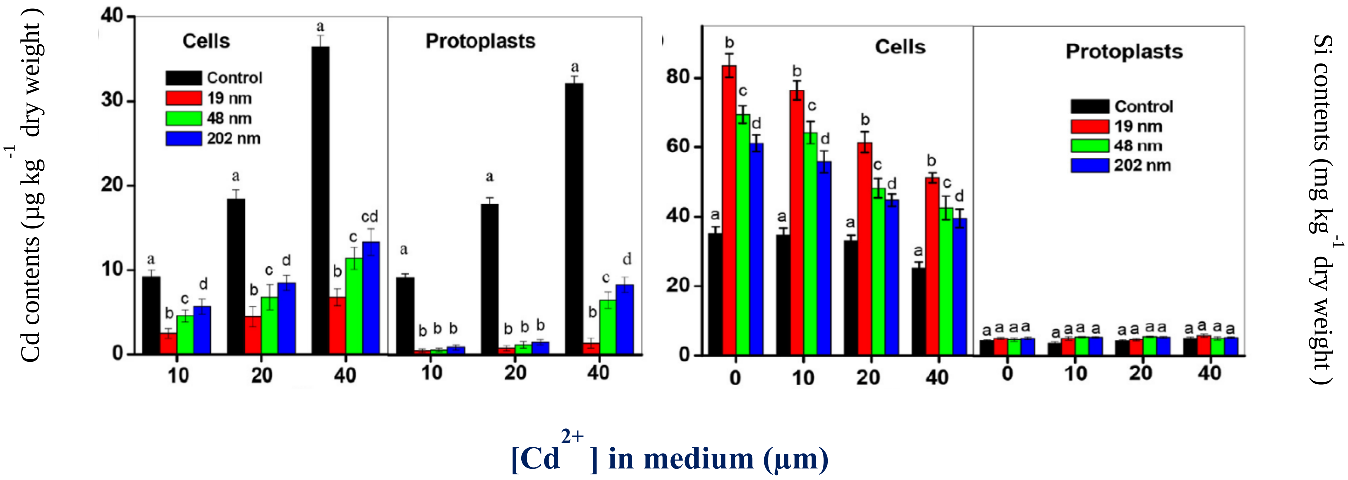


Fig 10 : Fluorescence emission in the M1 and M2 regions





Tukey's test ($P < 0.05$).

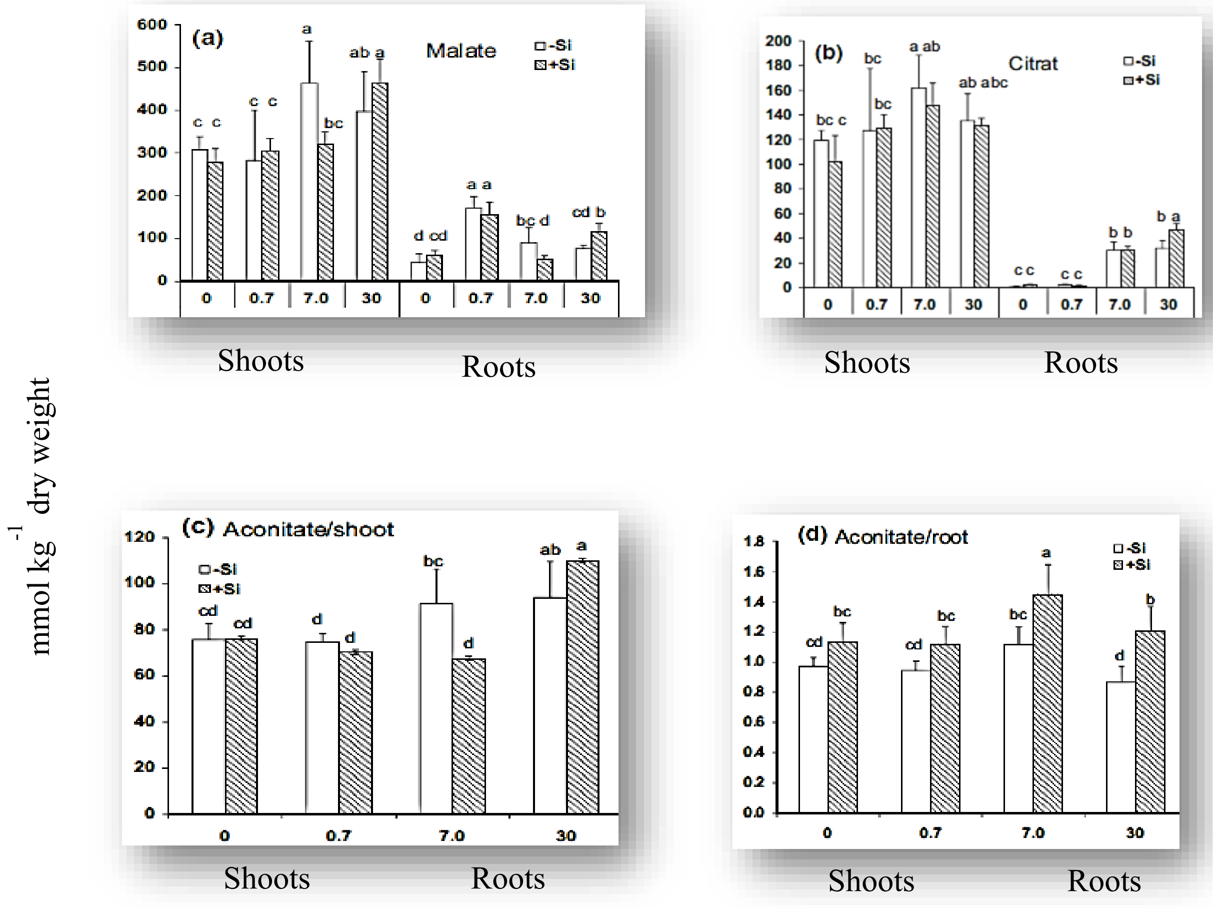
Fig 11 : Effect of silica nanoparticles in alleviating Cd toxicity in rice cells

Effect of Si on Cu uptake by wheat seedlings (*Triticum turgidum* L.) by complex formation

The influence of Si on Cu tolerance in durum wheat (*Triticum turgidum* L.) grown in 0, 0.7, 7.0, and 30 M Cu without and with 1.0 mM Si (Table:8) was investigated in a hydroponic study, along with the mechanisms involved in reducing Cu toxicity. Compared to the same Cu treatment without Si, Si application considerably reduced the concentration of Cu in the shoots in the Cu 30 M + Si treatment. In the Si treatment, the concentration of malate, citrate, and aconitate (Fig : 12) was higher in the shoots than the roots, which can bind the Cu and prevent its concentration by complex formation (Keller *et al.*, 2014*)*.

Treatment		**Si**	**Cu**
0 µM Cu, 0 mM Si n = 3	**m**	**0.77**	**0.00**
	sd	**0.12**	**0.00**
7 µM Cu, 0 mM Si n = 4	**m**	**0.12**	**0.04**
	sd	**0.05**	**0.00**
30 µM Cu, 0 mM Si n = 4	**m**	**0.75**	**0.04**
	sd	**0.35**	**0.02**
0 µM Cu, 1 mM Si n = 3	**m**	**1.23**	**0.00**
	sd	**0.32**	**0.00**
7 µM Cu, 1 mM Si n = 4	**m**	**0.63**	**0.03**
	sd	**0.30**	**0.02**
30 µM Cu, 1 mM Si n = 4	**m**	**0.48**	**0.08**
	sd	**0.19**	**0.01**

Table 8 : Effect of Si on Cu uptake by wheat seedlings (*Triticum turgidum* L.) by complex formation



[Cu] in solution µM

Bars represent sd of four replicates, P ≥ 0.05

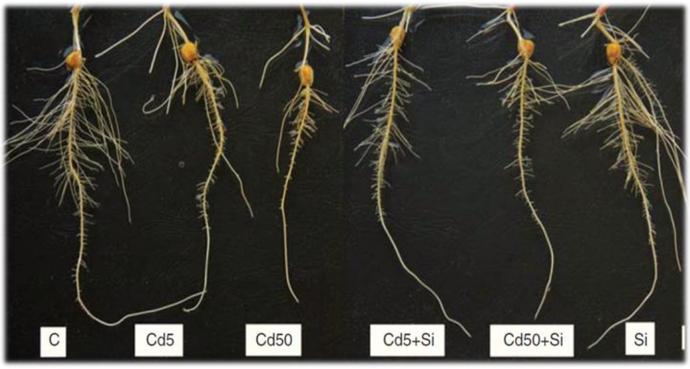
Fig 12 : Effect of silicon on Cu uptake by wheat seedlings (*Triticum turgidum* L.) by complex formation

5. Root architecture modification

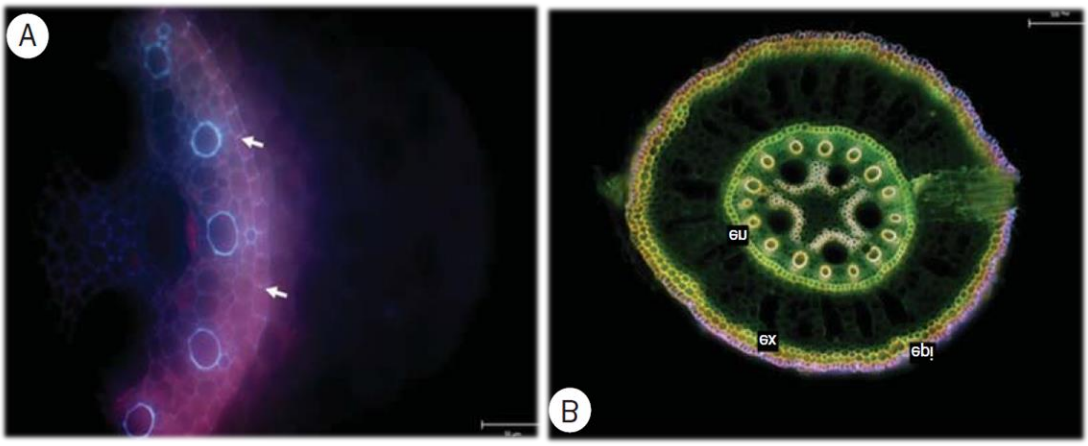
Effect of silicon on root modification and uptake of cadmium in young maize plants

In order to assess the impact of Si on Cd uptake and cellular distribution in connection to the growth of root tissues, Vaculik *et al.* (2012) performed a hydroponic experiment on a maize plant. Compared to controls, the addition of Si improved the branching of seminal roots.

Increased Cd treatment was favourably linked with the Cd concentration in maize roots. Compared to control plants, roots treated with Cd5 developed casparian bands and, in particular, suberin lamellae closer to the root apex. Individual endodermal cells began to suberize farther away from the root apex in Si-treated roots than in control roots. When compared to untreated rice plants, si improved the suberization and lignification of root tissues in both the exodermis and the endodermis. Exodermis is less effective than endodermis at blocking apoplasmic Cd transfer(Fig : 13).



Scale bar= 10 mm



(A) Cross-section of the root of young maize (scale bar = 50 mm).

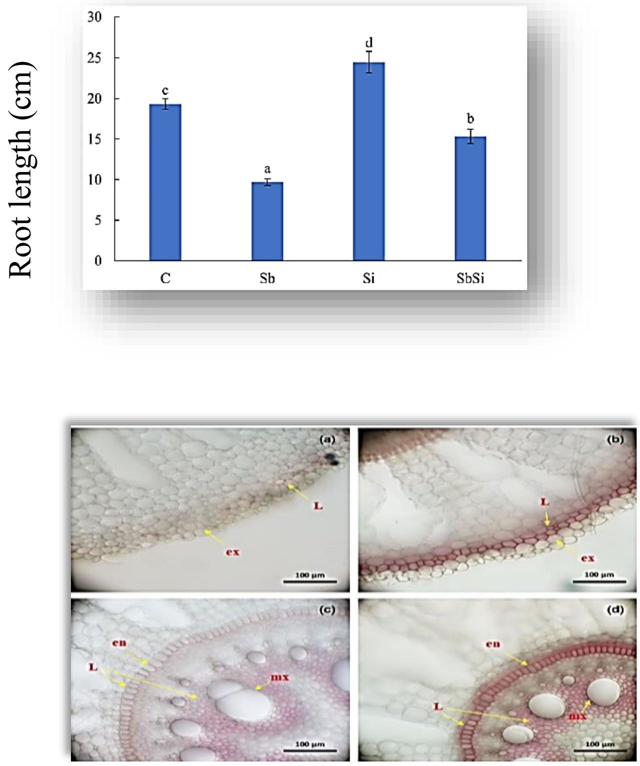
(B) Cross-section of the basal part of young maize plants (scale bar =200 mm).

- epi = epidermis;
- ex = exodermis;
- en = endodermis

Fig 13 : Effect of silicon on root modification and uptake of cadmium in young maize plants

By altering the root architecture, si can reduce antimony phytotoxicity in giant reed (*Arundo donax* L.)

Shetty *et al.* (2021) carried out a greenhouse experiment to test the gigantic reed's tolerance to Sb toxicity and the ability of Si to lessen its phytotoxicity. Despite Sb just marginally increased root lignification compared to control plants, lignified central pith, including proto and early metaxylem vessels, and notably deeply lignified endodermal layer, were identified in SbSi treated roots considerably closer to the root apex than in Sb treated plants (Fig : 14). The fact that Si-enhanced lignification of root structures likely restricts Sb translocation to the shoot further explains why SbSi treated plants have lower Sb concentrations in their shoots (Fig :15).



Lignification (red color)a,b=30%, c,d=90% of root length

(L lignification, ex exodermis, en endodermis, mx meta xylem)

C = Control, Sb = Sb 20 mg L, Si = 1 mM,SbSi = Sb 20 mg L + Si 1 Mm

Means ± SE (n = 3). $p < 0.05$.

Fig 14 : Effect of Si in alleviating antimony phytotoxicity in giant reed (*Arundo donax* L.) by changing root architechture

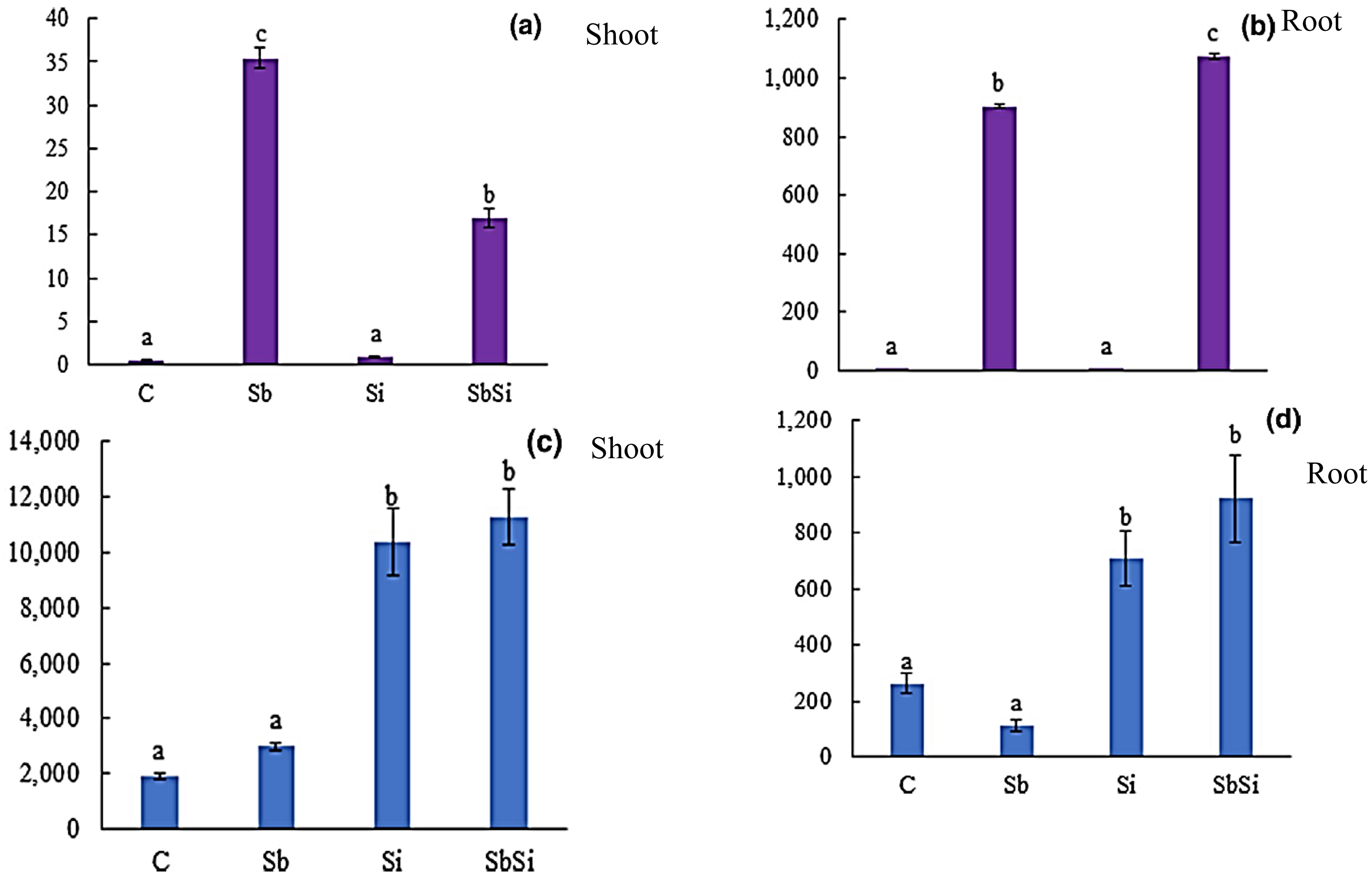


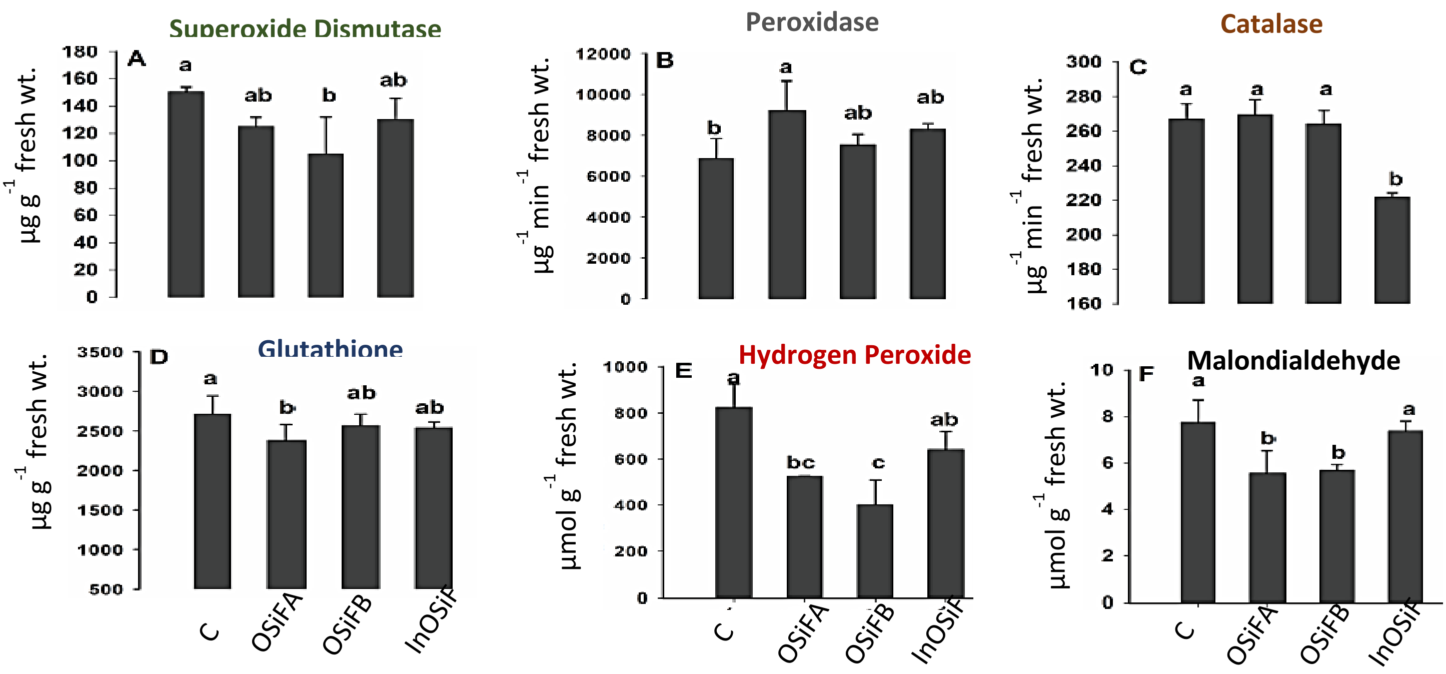
Fig 15 : Effect of Si in alleviating antimony phytotoxicity in giant reed (*Arundo donax* L.) by changing root architechture

The addition of Si to Sb treated plants increased root lignification, perhaps as a defensive response, because the roots of SbSi plants contained more Sb than Sb treated roots. The Si-enhanced lignification of root structures, which is expected to obstruct Sb translocation to the shoot, provides another explanation for the reduced Sb concentration in the shoots of SbSi treated plants.

6.Controlling antioxidant enzymes

Comparative efficacy of organic and inorganic silicon fertilizers on antioxidant response in wheat (*Triticum aestivum* L.)

The byproducts of peroxidation under stress are hydrogen peroxide **(**H_2O_2)and malondialdehyde (MDA), which can seriously harm the cell membrane system. When compared to the control, both Si fertilisers considerably reduced the amount of H_2O_2 and MDA present in wheat. In comparison to CK and InOSiF, OSiFs considerably reduced their H_2O_2 levels by 36%-51% and 18%-31%, respectively, and their MDA by 27%-28% and 23%-25%, respectively. By balancing the osmotic strength of the cytoplasm and vacuoles and the osmotic intensity of the surrounding environment, Superoxide Dismutase **(**SOD) and Catalase(CAT) together transformed superoxide radicals and H_2O_2 into H_2O and simultaneously produced more Glutathione (GSH) to protect plant cells (Fig : 16).



Mean (n=3) ± SD; $p < 0.05$

CK = Control

OSiFA =Organosilicon fertilizer A

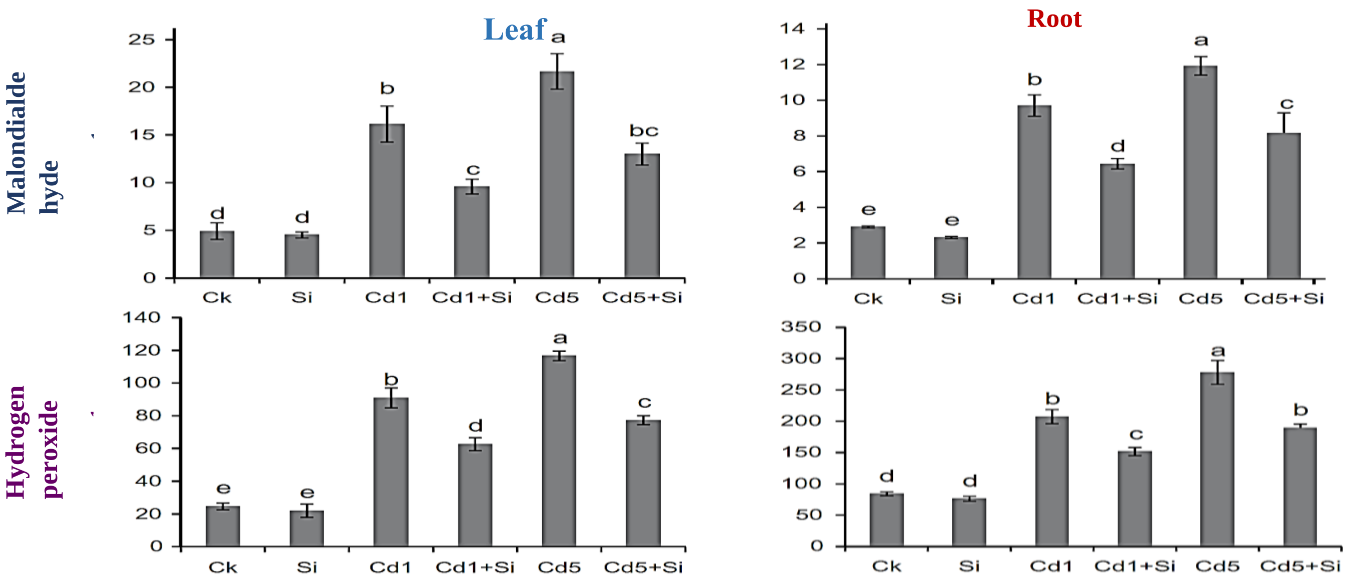
OSiFB = Organosilicon fertilizer B

InOSiF = Sodium silicate with common fertilizer

Fig 16 : Comparative efficacy of organic and inorganic silicon fertilizers on antioxidant response in wheat (*Triticum aestivum* L.)

According to Farooq *et al.* (2013), application of Si lessens Cd toxicity in cotton by lowering the levels of malondialdehyde and hydrogen peroxide and increasing the activity of antioxidant enzymes. Although Cd does not directly produce ROS, it nevertheless triggers an oxidative burst by interfering with the body's defences against free radicals, which boosts MDA levels because lipid peroxidation. This is one of the main mechanisms underpinning the stress that Cd causes in plants (Fig :17).

Alleviation of cadmium toxicity by Si in oxidative stress condition in cotton



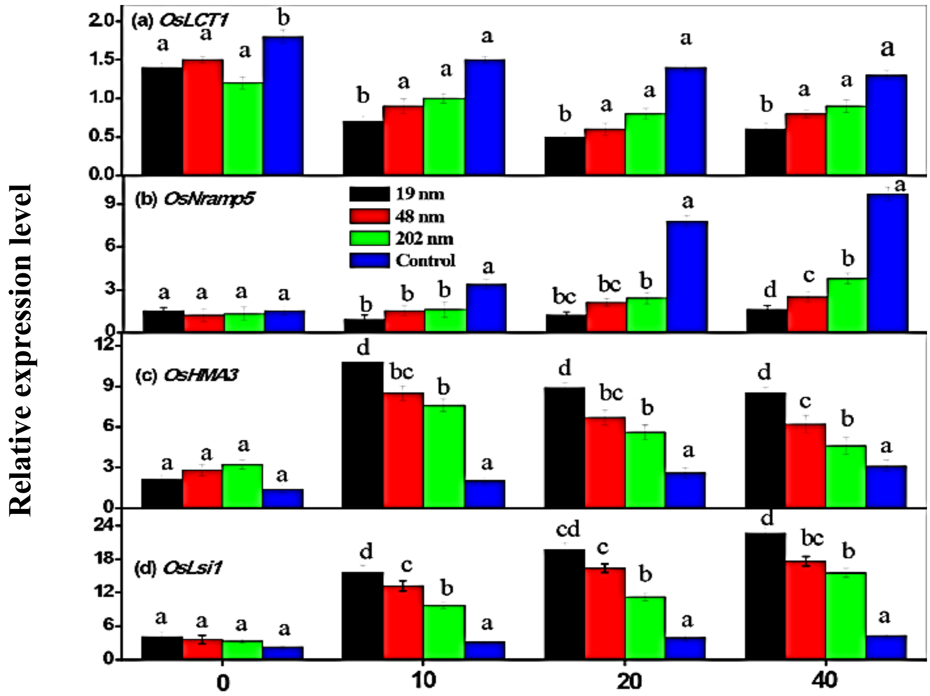
Mean ±SE P≤0.05.

Fig 17 : Alleviation of cadmium toxicity by Si in oxidative stress condition in cotton

7.Up and down-regulation of gene expression responsible for heavy metals and metalloid uptake, accumulation and transportation to plants

Silica nanoparticles alleviate cadmium toxicity in rice cells by genetic expression

According to Cui *et al.* (2017), silicon nanoparticles can lower the absorption of Cd into rice grains and phloem by 16.7% to 64.3% above control by decreasing the expression of the OsLCT1 low affinity cation transporter. SiNPs decreased the expression of the genes for Cd uptake and transport (OsLCT1 and OsNramp5), but they increased the expression of the genes for Cd transport into the vacuole (OsHMA3) and Si uptake (OsLsi1). These findings show that the presence of SiNPs boosted Si absorption capacity by at least 1.87 times and decreased Cd uptake capacity, which jointly reduced the toxicity of Cd in rice (Fig :18).



- Means ± SD ($P < 0.05$).

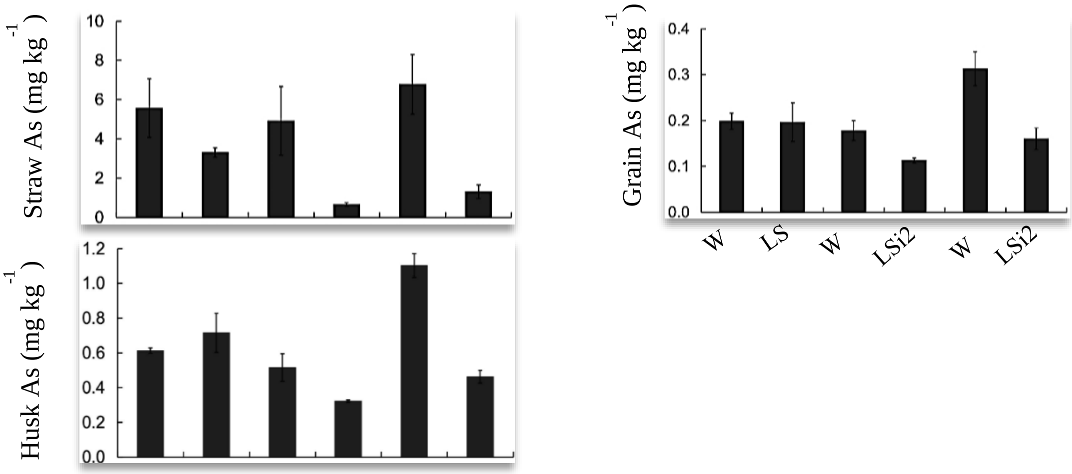
Cd^{2+} concentrations (10, 20 and 40 µm)

1.0 mM SiNPs (19 nm, 48nm, and 202 nm)

Fig 18 : Silica nanoparticles alleviate cadmium toxicity in rice cells by genetic expression

Effect of silicon transporters on heavy metals uptake, accumulation, and transportation by rice

Three mutant cultivars of rice were grown in a field experiment on soil with a background level of total As (5.3 mg/kg) to study the involvement of the Lsi1 and Lsi2 transporters in the accumulation of As in rice. Ma *et al.* (2008). As concentrations in straw were lower in all three mutants than in the wild type, with the two lsi2 mutants having concentrations that were just 13–19% of the equivalent wild-type rice. In contrast, the grain As concentration in both lsi2 mutants was considerably (P 0.01) lower than that of wild-type rice, being 63% and 51% of the corresponding wild-type rice, respectively (Fig : 19).



means ± SD (n = 3).

Fig 19 : Effect of silicon transporters on heavy metals uptake, accumulation, and transportation by rice

- **<u>Conclusions</u>**

✓ In order to reduce the threats to the environment and human health caused by acidic soil contaminated with several metals, fly ash and steel slag application may be a viable option.

✓ Si application changes soil pH , microbial community etc which reduce the available form of heavy metals and metalloid

✓ Si application enhance formation of phytochelatins, oranic and inorganic ions which can form complex with heavy metals and metalloid and reduce their availability in plants

✓ Most SiNPs alleviate heavy metals and metalloid toxicity by accumulated on the cell walls and bind them to prevent entering into the cell.

✓ Si application enhanced root lignification as a defence reaction restrict the heavy metals and metalloid translocation to the shoot

✓ Applying Si lowering reduces the uptake and buildup of metalloids and heavy metals via decreasing ROS damage through improved antioxidant enzyme activity.

✓ Si application can reduce plant heavy metals and metalloid uptake by stimulating the Si transporter (OsLsi1); and inhibiting the heavy metal transporters.

- **Future prospects**

✓ To assess the viability of Si application for the cleanup of metal-contaminated soils, extensive field tests are needed.

✓ To clarify the potential coexistence of Si and Cd in phytoliths of shoots or in the endodermis of roots, additional research is necessary.

✓ More research should be done on the Si-NPs dispersion and plant migration, as well as the potential impact of microbial communities in the soil's rhizosphere.

✓ The precise mode of action and underlying mechanism of Si-mediated regulation of antioxidant enzymes in plants under abiotic stress conditions require further study at the transcriptome level.

✓ Finding the allelic differences in LSi1 and LSi2 that prefer uptake of silicon over arsenite requires additional research.

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