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Silicon-mediated enhancement of cadmium tolerance in maize (*Zea mays* L.) grown in cadmium contaminated soil

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Abstract

Pot experiments were performed to study the alleviative effects of exogenous silicon (Si) on cadmium (Cd) phytotoxicity in maize grown in an acid soil experimentally contaminated with Cd. Five treatments were investigated in the first trial consisting of a control (neither Cd nor Si added), Cd added at 20 or 40 mg kg^{-1} Cd without or with Si added at 400 mg kg^{-1} Si. A following-up trial was conducted with almost the same treatments as in the first trial except that Si was incorporated at 50 mg kg^{-1} Si. The results showed that Cd treatment significantly decreased shoot and root dry weight, while addition of Si at both levels significantly enhanced biomass. Addition of Si at 400 mg kg^{-1} Si significantly increased soil pH but decreased soil Cd availability, thus reducing Cd concentration in the shoots and roots and total Cd in the shoots. Moreover, more Cd was found to be in the form of specific adsorbed or Fe–Mn oxides-bound fraction in the Si-amended soil. In contrast, soil pH, available Cd and Cd forms were unaffected by addition of Si at 50 mg kg^{-1} Si, but shoot Cd concentration in the Si-amended Cd treatments significantly decreased at both Cd levels used compared to the non-Si-amended Cd treatments. Total Cd in the shoots and roots was considerably and significantly higher in the Si-amended Cd treatments than in the non-Si-amended Cd treatments. The xylem sap significantly increased but Cd concentration in the xylem sap significantly decreased in the Si-amended Cd treatments compared with the non-Si-amended Cd treatments irrespective of Cd and Si levels used. The results suggest that Si-enhanced tolerance to Cd can be attributed not only to Cd immobilization caused by silicate-induced pH rise in the soils but also to Si-mediated detoxification of Cd in the plants.

Keywords: Cadmium; Cadmium uptake; Dry matter yield; Maize; Silicon

1. Introduction

Contamination of the environment with toxic heavy metals due to anthropogenic activities is one of the major global environmental and human health problems.

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Cadmium (Cd) in the soils, for example, derived mainly from industrial processes, mining activities and repeated agricultural use of sewage sludge and phosphate fertilizers, is extremely toxic to living cells even at low concentrations (Sandalio et al., 2001). Cadmium severely inhibits plant growth and even causes plant death by disturbing the uptake of nutrients (Gussarson et al., 1996; Sandalio et al., 2001) and inhibiting photosynthesis via degradation of chlorophyll (Somashekaraiah et al., 1992; Sandalio et al., 2001) and inactivation of enzymes involved in CO_2 fixation (Greger and Ogren, 1991; De Filippis and Ziegler, 1993). It was also reported that Cd toxicity induced oxidative damage characterized by an accumulation of lipid peroxides and oxidized proteins as a result of the inhibition of the antioxidant systems in plants (Sandalio et al., 2001; Vitória et al., 2001).

Although silicon (Si) has not been considered an essential element for higher plants, it has been well documented that Si can enhance resistance and/or tolerance to Al (Hodson and Evans, 1995; Epstein, 1999; Liang et al., 2001), Mn (Iwasaki et al., 2002a,b; Rogalla and Römheld, 2002) and salt toxicity in plants (Liang, 1999; Yeo et al., 1999; Liang and Ding, 2002; Liang et al., 2003). To date, little information is, however, available on the interactions of Si with Cd (Chen et al., 2000). Addition of 1.7 mM Si had no significant effect on shoot and root dry weight of rice grown hydroponically with 1.0 μM Cd for 6 d, shoot Cd concentration of Si-treated plants, however, was only 51.1% that of Si-deprived ones (Qin and Huang, 1997). Chen et al. (2000) reported that furnace slag was more effective in suppressing Cd uptake by rice and wheat than calcium carbonate or steel sludge. They speculated that the increased pH and available Si arising from the furnace slag contributed to the reduced Cd uptake in plants (Chen et al., 2000). However, convincing evidence is still scant that the reduced Cd uptake is attributable to Si from the furnace slag due to its multi-component. It is generally recognized that pH rise leads to a reduction in Cd availability via Cd immobilization when sodium metasilicate, slag and/or alkaline biosolid are used as Si sources. Nevertheless, mechanisms involved in the Si-enhanced Cd tolerance in plants remain poorly understood. Therefore, pot experiments were performed in this study to investigate the effects of sodium metasilicate incorporated at two contrasting dosages on Cd toxicity of maize (*Zea mays* L.) with respect to plant growth, Cd in the soil, xylem sap and plants grown in an acid soil experimentally contaminated with Cd. The objectives of this paper are (1) to gain better insight into the possible mechanisms involved in Si-mediated detoxification of Cd and (2) to provide both theoretical and practical bases for performing field-scale studies aiming at ameliorating Cd-contaminated soils and environments.

2. Materials and methods

2.1. Experimental conditions and design

First experiment: The soil used for pot experiments was a highly weathered acidic soil (Oxisol) with 4.51 of pH, 12.91 g kg^{-1} of organic matter, 1.40 g kg^{-1} of total N, 0.76 mg kg^{-1} of Olsen-P, 43 mg kg^{-1} of NH_4AC-extractable K and 24.0 g kg^{-1} of NaAC-HAC-extractable Si. The soil was air-dried, crushed to pass a 2 mm sieve and mixed well with 0.25 g kg^{-1} N as urea, 0.15 g kg^{-1} P as KH_2PO_4, and 0.25 g kg^{-1} K as K_2SO_4 and KH_2PO_4. Five treatments with three replicates each were investigated consisting of CK (neither Cd nor Si added), Cd20 and Cd40 (Cd added at 20 and 40 mg kg^{-1} Cd, respectively) without or with Si added at 400 mg kg^{-1} Si (referred to as Si2). Silicon was added as sodium metasilicate ($Na_2SiO_3 \cdot 9H_2O$) and Cd as $CdCl_2 \cdot H_2O$. In order to avoid heterogenous distribution of the Cd added at such a small rate, $CdCl_2 \cdot H_2O$ was dissolved with 50 ml water and then mixed thoroughly with the soil. Finally each 2-l plastic pot filled with 2 kg pretreated soil was watered with tap water daily to keep soil moisture at approximately 90% field water holding capacity for 1 week.

A maize cultivar (*Zea mays* L. cv. Nongda 5108), obtained from China Agricultural University, was used in this experiment. Uniform-sized maize seeds were surface sterilized with 6% H_2O_2 for 10 min, rinsed thoroughly with distilled water, and germinated on moist filter paper for 48 h in an incubator at 25 °C. Five germinated seeds were sown directly into each pot soil. Experiments were conducted in a greenhouse where daily photoperiod was 12 h and the maximum temperature was 35 °C, while the daily minimum temperature at night was adjusted to 25 °C. Tap water (200 ml each time) was used for irrigation when necessary to keep soil moisture at 80% of field water holding capacity. Five days after sowing, each pot was thinned to three seedlings.

Second experiment: This experiment was performed to study the effect of Si on the alleviation of Cd toxicity in maize at such a condition that addition of Si did not significantly change soil pH value. Accordingly, this experiment was conducted under almost the same condition as in the first experiment except that Si was incorporated at 50 mg kg^{-1} Si (referred to as Si1).

2.2. Plant analysis

Fifty-four days (first experiment) and 60 days (second experiment) after sowing plants were harvested and separated into shoots and roots. The shoots were washed thoroughly with tap water and then with distilled water. To remove the ions in the root free space, the roots were washed with 0.5 mM $CaCl_2$ for 30 min and rinsed thoroughly with tap water and finally with distilled water.