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Full Length Article

Effects of Nanometer Magnesium Hydroxide on Growth, Cadmium (Cd) Uptake of Chinese Cabbage (*Brassica campestris*) and Soil Cd Form

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Abstract

Pot experiments were conducted to study the effects of different magnesium (Mg) hydroxide dosages (0, 100, 200 and 300 mg·kg^{-1}) of nanometer magnesium hydroxide and ordinary magnesium hydroxide on Chinese cabbage growth, cadmium (Cd) uptake and soil Cd distribution under different Cd pollution levels (1 and 5 mg·kg^{-1}). The results showed that the biomass of Chinese cabbage increased by low amount (100 mg·kg^{-1}) of nanometer magnesium hydroxide, while high amount of nanoparticles caused certain toxic effects on Chinese cabbage. Under low Cd (1 mg·kg^{-1}) stress, compared with the control (CK1), Cd concentration in leaves, petioles and roots of the two Chinese cabbage varieties treated with magnesium hydroxide decreased by 5.4–31.8%, 1.6–6.5%, 15.8–40.8% (Liangqing variety) and 12.1–24.5%, 1.5–12.7%, 5.0–24.9% (Chunxiawang variety). Under high Cd (5 mg·kg^{-1}) stress, compared with the control (CK2), Cd concentration in leaves, petioles and roots of the two Chinese cabbage varieties treated with magnesium hydroxide decreased by 1.6–15.6%, 0.3–21.0%, 14.5–24.9% (Liangqing variety) and 0.1–16.1%, 0.3–19.7%, 13.7–25.0% (Chunxiawang variety). In the 1 and 5 mg·kg^{-1} Cd-contaminated soil, the application of nanometer magnesium hydroxide and ordinary magnesium hydroxide reduced Cd concentration of the ethanol extraction state, deionized water extraction state and sodium chloride extraction state in shoots of the two Chinese cabbage varieties. The exchangeable Cd content in the soil was decreased, and the contents of CAB-Cd, FeMn-Cd, OM-Cd and RES-Cd were increased. Moreover, with the increasing application amount of magnesium hydroxide, the exchangeable Cd content in the soil decreased, while carbonate-bound state and iron-manganese oxidation state Cd contents increased. Cadmium concentration in different parts of Chinese cabbage was significantly or extremely significantly positively correlated with soil exchangeable cadmium content, negatively correlated with soil CAB-Cd, FeMn-Cd, OM-Cd and RES-Cd contents. Under the same amount of magnesium hydroxide, nanometer magnesium hydroxide plays a better role than ordinary magnesium hydroxide in reducing Cd concentrations in Chinese cabbage. © 2020 Friends Science Publishers

Keywords: Cadmium contaminated soil; Cadmium uptake; Correlation; Soil cadmium morphology

Introduction

With the rapid development of industry and agriculture, the continuous development of mines, the arbitrarily discharged cadmium-containing wastewater and the abuse of pesticides and fertilizers, cadmium pollution has spread all over the world (Zou *et al.* 2017). At present, about 10 million hm^2 of cultivated land is polluted in China, and about 12 million tons of food crops are lost each year due to heavy metal pollution in the soil (Teng *et al*. 2010). It is extremely imperative to seek cost effective governance and repair technologies that will not cause secondary pollution. *In situ* chemical immobilization remediation technique is one of the important ways to control heavy metal pollution in soil. By applying a passivator to the soil, mode of occurrence of heavy metals in the soil can be regulated and changed, exchangeable components in the soil and its mobility will be reduced, and then bioavailability of cadmium will be lower. Hence, finding environmentally friendly high-efficiency heavy metal passivator is the research focus.

Magnesium, a main nutrient element of plants, plays an important role in crop growth and development, which can increase crop yield (Loganathan *et al*. 2005; Chwil 2014; Orlovius and McHoul 2015). Kashem and Kawai (2007) showed that the application of magnesium fertilizer reduced the cadmium toxicity of Japanese Brassica spinach and increased the yield of spinach. Moreover, for a higher magnesium concentration, the cadmium concentration in the plant bud was lower, which was probably due to the interaction between magnesium and cadmium in the plant body. Lan *et al.* (2010) also reported that magnesium treatment reduced the absorption of cadmium by wheat, and the ratio of cadmium in seeds and stems was the smallest, which could prevent cadmium migration from plant to grain to some extent. Xie *et al.* (2018) found that the addition of magnesium in soil could effectively reduce effective cadmium content in soil. When the magnesium content increased from 0.06–1.5 mmol·kg^{-1}, the effective cadmium content in soil decreased more gradually. Because Mg^{2+} can replace H^+ on the soil colloid to form Mg $(OH)_2$, there are many active sites on the surface of Mg $(OH)_2$, which has strong monolayer adsorption effect on Cd^{2+}.

Nanometer magnesium hydroxide is a new type of magnesium hydroxide with a particle size in the range of 1–100 nm, which not only increases the input of magnesium, an essential plant element (Yuan *et al*. 2017; Zou *et al*. 2017), but also has large adsorption effect on heavy metals. Its role in water pollution treatment has been reported (Hao *et al.* 2012). After applying nano-magnesium hydroxide, cadmium concentrations of leaves, petioles and roots in Chinese cabbage decreased by 5.3–19.2%, 9.0–28.1% and 3.5–19.3%, respectively, and soil cadmium content decreased by 8.2–41.5% (Liu *et al.* 2018). At the same application rate, cadmium concentrations of leaves, petioles and roots in Chinese cabbage in nanometer magnesium hydroxide treatments were significantly lower than those in ordinary magnesium hydroxide treatments (Liu *et al.* 2018). Although the applications of nano-magnesium hydroxide in the field of environmental protection and fertilizer have been reported, there are few studies at home and abroad on the remediation of heavy metal pollution in soil (Hao *et al.* 2012; Guo 2019). However, the mechanism of soil cadmium pollution remediation by nanometer magnesium hydroxide is still unclear. Pot experiments simulating soil cadmium pollution were conducted to study the effects of different amount of nano-magnesium hydroxide and ordinary magnesium hydroxide on the biomass, cadmium absorption of vegetable, chemical forms and concentrations of cadmium in plant and soil were also studied. By comparative analysis the remediation effect of soil cadmium pollution between nano-magnesium hydroxide and ordinary magnesium hydroxide, its remediation mechanism and reasonable amount of application would be clear, with a view to providing a theoretical basis for the scientific and safety production of vegetable in cadmium contaminated soil.

Materials and Methods

Plant material, soil and cadmium treatments

Experimental material: The test crop was Chinese cabbage (*Brassica peckinensis* L.), and the varieties were Liangqing and Chunxiawang. The test soil was collected from the purple soil base of Southwest University in Beibei District, Chongqing (longitude 106°24′50.66″, latitude 29°48′30.58″). After removing obvious plant residues and stone grains, the soil was screened by 4 mm sieve. The basic physical and chemical properties of soil were 0.77 mg·kg^{-1} for total nitrogen, 53.33 mg·kg^{-1} for alkaline nitrogen, 0.55 g·kg^{-1} for total phosphorus, 17.07 mg·kg^{-1} for available phosphorus, and 21.31 g·kg^{-1} for total potassium, 84.81 mg·kg^{-1} for effective potassium, 13.88 g·kg^{-1} for organic matter, pH 6.50, 30.70 cmol·kg^{-1} for cation exchange capacity (CEC), 0.24 mg·kg^{-1} for total cadmium, with soil effective cadmium < 0.005 mg·kg^{-1}. The tested nanometer magnesium hydroxide (nMg) had a particle size in the range of 82–127 nm and was supplied by Zhengzhou University.

Treatments: Pot experiment was conducted in No.1 glass greenhouse in College of Resources and Environment, Southwest University, Chongqing from March 1, 2017 to June 6, 2017. There were two cadmium level (1 and 5 mg·kg^{-1}) and three amounts of nanometer magnesium hydroxide and common magnesium hydroxide (0, 150 and 300 mg·kg^{-1}). Each treatment was repeated 3 times and randomly arranged. An opaque gray plastic basin (27 cm in diameter and 17 cm in height) was used to put 5 kg of air-dried soil screened by 4 mm sieve. $CdCl_2 \cdot 2.5\ H_2O$ solution was added to the soil according to the experimental designed cadmium level, which was mixed well and equilibrated in the greenhouse for 3 weeks. During the period, pure water was added to maintain soil water content at 70% of the maximum water holding capacity in the field. After 3 weeks of equilibration, nanometer magnesium hydroxide and ordinary magnesium hydroxide were separately mixed according to the experimental designed application amount. After 5 days of magnesium hydroxide application, Chinese cabbage seedlings with three leaves and one shoot were selected for transplantation, 4 plants per pot. The soil water content was monitored daily by soil moisture meter and water was replenished to maintain the soil water content at 70% of the maximum water holding capacity in the field. The soil base fertilizer was N 180 mg·kg^{-1}, P_2O_5 100 mg·kg^{-1}, K_2O 150 mg·kg^{-1}, and urea, ammonium dihydrogen phosphate and potassium chloride were used as fertilizer sources respectively. Wherein, 40% of N fertilizer was used as base fertilizer, and 60% was used for topdressing twice. Seedlings were harvested 55 days after transplantation.

Analysis of soil physicochemical properties

The soil pH was ascertained in 1:5 (soil: water), and available phosphorus, available potassium and total nitrogen in soil was determined in term of a previously report (Rayment and Higginson 1992). The soil organic matter content was determined on the basis of a previously published method (McCleod 1975).

Analysis of cadmium concentration in soil and plants

Soil containing cadmium was first digested with HNO_3–$HClO_4$ (*v*: *v*=4:1), and its concentration was determined using an atomic absorption spectrophotometer (SIMMA 6000; PerkinElmer, Norwalk, C.T., U.S.A.). The plant samples were first air-dried and ground and the cadmium concentration in the plants was determined using a similar method to that used to quantify the levels of cadmium in the soil. The results were monitored for quality control in following with plant standard reference material (GBW08513) and soil (GBW08303) obtained from the National Institute of Standards and Technology, China. The recovery rates of all the plants and soils were higher than 95%, and the relative standard deviation (RSD) for the precision of the tests was less than 10%.

Determination of cadmium forms in soil and plants

Method proposed by Tessier *et al*. (1979) was used to extract cadmium from soil and plant. Cadmium concentration of each form was determined by atomic absorption spectrophotometry (Perkin Elmer SIMMA 6000, Norwalk, U.S.A.). The detection limit of atomic absorption spectrophotometer was 0.005 mg·kg^{-1}. Soil standard substance (GBW # 08303) and plant reference material (GBW # 08513) from the National Institute of Standards and Technology were used to monitor the quality of the results. Cadmium recovery of all soil samples was higher than 95%, and the accuracy of relative standard deviation (RSD) was within 10%.

Statistical analysis

Three-way analysis of univariate ANOVA and correlation analysis were performed using S.P.S.S. version 21.0package (Acton *et al*. 2009). The variables analyzed separately were cadmium concentration and Cd chemical forms in soil. The level of significance was 0.05.

Results

Biomass

As shown in Table 1, without application of magnesium hydroxide, 1 mg·kg^{-1} cadmium stimulates the growth of leaves of the two Chinese cabbage varieties, Liangqing and Chunxiawang, significantly increasing the petiole and total plant biomass of Liangqing variety, but with a certain inhibitory effect on the roots of Liangqing variety. High cadmium (5 mg·kg^{-1}) inhibits the growth of two Chinese cabbages, and the inhibitory effect on Chunxiawang variety is more obvious. The biomass of leaves, petioles, roots and total plants decreases by 21.0, 31.2, 31.7 and 26.6% as compared with the control (CK).

Under low cadmium (1 mg·kg^{-1}), nanometer magnesium hydroxide and ordinary magnesium hydroxide increase the leaf, petiole and total plant biomass of the two Chinese cabbage varieties, Liangqing and Chunxia, respectively. The increase rate is 11.7–32.0% and 0.4–11.7% (leaf), 6.1–18.1% and 3.0–40.2% (petiole), 8.4–23.1% and 2.4–16.7% (total plant) respectively as compared with the control (CK1) (except for Cd1 + nMg2 treatment of Chunxiawang variety). However, magnesium hydroxide inhibits root growth of the two Chinese cabbages, which decreases by 3.8–14.7% and 27.8–52.1% compared with the control (CK1). Under high cadmium (5 mg·kg^{-1}), magnesium hydroxide significantly increases leaf, petiole, root and total plant biomass of the two Chinese cabbage varieties, Liangqing and Chunxiawang. The increase rate is 14.8–25.9% and 31.3–55.9% (leaf), 8.0–39.0% and 35.3–71.1% (petiole), 12.7–44.5% and 0.4–8.9% (root), 12.6–32.2% and 29.7–56.6% (total plant) as compared with the control (CK2). Compared with low cadmium, the application of ordinary magnesium hydroxide or nanometer magnesium hydroxide under high cadmium (5 mg·kg^{-1}) better promotes Chinese cabbage growth, which is more conducive to the growth of Chinese cabbage roots.

Under low cadmium (1 mg·kg^{-1}), low nanometer magnesium hydroxide treatment brought better growth. Compared with Cd1 + oMg1 treatment, leaves, petiole and total plant biomass of the two Chinese cabbage varieties treated by Cd1 + nMg1 increased by 18.2, 11.2, 13.5% (Liangqing variety) and 8.8, 26.8, 13.9% (Chunxiawang variety), while root biomass decreased by 6.0% (Liangqing variety) and 25.8% (Chunxiawang variety). The growth effect of Chinese cabbage treated with high amount of nanometer magnesium hydroxide was not as good as that treated with common magnesium hydroxide. Under high cadmium (5 mg·kg^{-1}), regardless of low application amount or high application amount of nanometer magnesium hydroxide, good effect was shown on the growth of leaves and petioles of the two Chinese cabbage varieties. Compared with Cd5 + oMg1 treatment, the biomass of leaves, petioles, roots and total plants of the two Chinese cabbage varieties treated with Cd5 + nMg1 increased by 9.7, 27.4, 14.7, 17.4% (Liangqing variety) and 14.6, 8.1. 8.5, 11.4% (Chunxiawang variety), respectively; compared with Cd5 + oMg2 treatment, the biomass of leaves, petioles and total plants of the two Chinese cabbage varieties treated with Cd5 + nMg2 increased by 0.9, 24.0, 9.6% (Liangqing variety) and 13.9, 17.3, 14.3% (Chunxaiwang variety), respectively.

Tissue Cd concentration

It can be seen from Table 2 that, without the application of magnesium hydroxide, the addition of exogenous cadmium causes the cadmium concentration of the two Chinese cabbage varieties, Liangqing and Chunxiawang, to reach 10.180–18.369 mg·kg^{-1}, 10.627–15.140 mg·kg^{-1} (CK1) and 38.265–63.536 mg·kg^{-1}, 34.253–60.612 mg·kg^{-1} (CK2). In general, the cadmium concentration in the leaves and petioles of Liangqing variety is higher than that of Chunxiawang variety under the condition of exogenous cadmium. The application of ordinary magnesium hydroxide and nanometer magnesium hydroxide significantly reduces the cadmium concentration in all parts of Chinese cabbage, which decreases with the increasing application amount.

Table 1: Magnesium hydroxide application on the biomass of Chinese cabbage

Variety	Treatment	Dry weight ($g \cdot pot^{-1}$)			
		Leaf	Petiole	Root	Plant
Liangqing	CK	3.842 ± 0.049d	3.418 ± 0.012e	0.676 ± 0.025a	7.936 ± 0.013e
	CK1	4.047 ± 0.014c	3.626 ± 0.039d	0.625 ± 0.012b	8.298 ± 0.013d
	Cd1 + oMg1	4.520 ± 0.071b	3.849 ± 0.092c	0.629 ± 0.006b	8.998 ± 0.016c
	Cd1 + oMg2	5.222 ± 0.087a	4.068 ± 0.087b	0.602 ± 0.007b	9.891 ± 0.007b
	Cd1 + nMg1	5.341 ± 0.088a	4.281 ± 0.015a	0.592 ± 0.012b	10.214 ± 0.061a
	Cd1 + nMg2	4.582 ± 0.045b	3.940 ± 0.047bc	0.533 ± 0.023c	9.055 ± 0.068c
	CK	3.842 ± 0.049d	3.418 ± 0.012c	0.676 ± 0.025a	7.936 ± 0.013e
	CK2	3.761 ± 0.032d	3.214 ± 0.053d	0.477 ± 0.005d	7.452 ± 0.026f
	Cd5 + oMg1	4.317 ± 0.005c	3.471 ± 0.049c	0.601 ± 0.011b	8.389 ± 0.055d
	Cd5 + oMg2	4.504 ± 0.064b	3.602 ± 0.041b	0.605 ± 0.017b	8.712 ± 0.007c
	Cd5 + nMg1	4.737 ± 0.047a	4.422 ± 0.025a	0.689 ± 0.027a	9.848 ± 0.049a
	Cd5 + nMg2	4.544 ± 0.057b	4.467 ± 0.052a	0.538 ± 0.015c	9.548 ± 0.124b
Chunxiawang	CK	3.784 ± 0.018c	3.528 ± 0.025c	0.930 ± 0.033a	8.242 ± 0.041c
	CK1	3.948 ± 0.077b	3.337 ± 0.024e	0.934 ± 0.010a	8.218 ± 0.063c
	Cd1 + oMg1	4.054 ± 0.095b	3.691 ± 0.039b	0.674 ± 0.020b	8.419 ± 0.154bc
	Cd1 + oMg2	4.275 ± 0.073a	3.749 ± 0.048b	0.550 ± 0.009c	8.575 ± 0.111b
	Cd1 + nMg1	4.410 ± 0.066a	4.678 ± 0.049a	0.500 ± 0.014d	9.588 ± 0.101a
	Cd1 + nMg2	3.965 ± 0.016b	3.437 ± 0.028d	0.447 ± 0.018e	7.849 ± 0.063d
	CK	3.784 ± 0.018c	3.528 ± 0.025b	0.930 ± 0.033a	8.242 ± 0.041c
	CK2	2.989 ± 0.050d	2.427 ± 0.023d	0.635 ± 0.007c	6.051 ± 0.081e
	Cd5 + oMg1	3.925 ± 0.058bc	3.283 ± 0.056c	0.638 ± 0.011c	7.846 ± 0.126d
	Cd5 + oMg2	4.092 ± 0.073b	3.539 ± 0.050b	0.662 ± 0.016bc	8.292 ± 0.140c
	Cd5 + nMg1	4.498 ± 0.115a	3.550 ± 0.019b	0.692 ± 0.012b	8.739 ± 0.145b
	Cd5 + nMg2	4.661 ± 0.060a	4.152 ± 0.045a	0.662 ± 0.018bc	9.475 ± 0.002a
$LSD_{0.05}$	Variety	25.083***	5.499*	48.218***	10.419**
	Cd level	8.291**	8.196**	15.846***	11.185***
	Magnesium hydroxide kinds	43.451***	35.082***	11.563***	40.677***
	Variety × Cd level	1.226	3.368*	0.293	1.914
	Variety × Magnesium hydroxide kinds	0.407	1.159	24.485***	0.007-
	Magnesium hydroxide kinds × Cd level	6.025**	5.344*	46.600***	10.116***
	Variety × Magnesium hydroxide kinds × Cd level	6.291**	1.674	8.669**	2.842

Note: Different lowercase letters indicate significant difference between different magnesium hydroxide treatments under the same Cd pollution level ($P < 0.05$); "*" means $0.01 < P < 0.05$, "**" means $0.001 < P < 0.01$, "***" indicates $P < 0.001$

Table 2: Magnesium hydroxide application on Cd concentration in Chinese cabbage

Variety	Treatment	Cd concentration ($mg \cdot kg^{-1}$)		
		Leaf	Petiole	Root
Liangqing	CK	3.159 ± 0.207d	2.874 ± 0.163d	3.510 ± 0.142d
	CK1	18.369 ± 0.978a	10.180 ± 0.077b	18.329 ± 0.190a
	Cd1 + oMg1	17.381 ± 0.295a	11.149 ± 0.237a	15.435 ± 0.958b
	Cd1 + oMg2	12.807 ± 0.505c	9.966 ± 0.028b	14.182 ± 1.077b
	Cd1 + nMg1	14.332 ± 0.262b	10.018 ± 0.131b	14.882 ± 1.011b
	Cd1 + nMg2	12.537 ± 0.440c	9.523 ± 0.027c	10.858 ± 1.072c
	CK	3.159 ± 0.207d	2.874 ± 0.163d	3.510 ± 0.142e
	CK2	63.536 ± 0.386a	38.265 ± 1.468a	49.641 ± 0.749a
	Cd5 + oMg1	62.496 ± 1.303ab	40.592 ± 0.997a	42.451 ± 0.139b
	Cd5 + oMg2	60.813 ± 0.075b	33.303 ± 1.234b	40.857 ± 0.591c
	Cd5 + nMg1	61.054 ± 0.990b	38.133 ± 1.213a	42.363 ± 0.159b
	Cd5 + nMg2	53.607 ± 0.892c	30.215 ± 0.759c	37.302 ± 0.062d
Chunxiawang	CK	3.780 ± 0.301e	2.724 ± 0.359d	2.705 ± 0.575c
	CK1	15.140 ± 0.191a	10.627 ± 0.228a	12.537 ± 0.678a
	Cd1 + oMg1	13.309 ± 0.159b	10.466 ± 0.356a	11.912 ± 0.195a
	Cd1 + oMg2	11.539 ± 0.346d	9.634 ± 0.245bc	10.893 ± 1.277ab
	Cd1 + nMg1	12.624 ± 0.385c	10.177 ± 0.188ab	11.549 ± 0.049a
	Cd1 + nMg2	11.438 ± 0.096d	9.282 ± 0.088c	9.414 ± 0.576b
	CK	3.780 ± 0.301d	2.724 ± 0.359d	2.705 ± 0.575d
	CK2	54.644 ± 0.048a	34.253 ± 0.489a	60.612 ± 1.838a
	Cd5 + oMg1	54.580 ± 0.643a	34.136 ± 0.214a	52.337 ± 1.832b
	Cd5 + oMg2	50.987 ± 1.643b	31.102 ± 0.559b	46.265 ± 0.197c
	Cd5 + nMg1	51.967 ± 0.082b	31.603 ± 0.658b	46.467 ± 1.537c
	Cd5 + nMg2	45.843 ± 1.269c	27.5056 ± 0.902c	45.430 ± 0.860c
$LSD_{0.05}$	Variety	30.020***	5.425*	5.144*
	Cd level	1937.863***	620.554***	1875.514***
	Magnesium hydroxide kinds	14.305***	4.057*	48.217***
	Variety × Cd level	12.076***	4.199*	47.140***
	Variety × Magnesium hydroxide kinds	0.232	0.056	0.098
	Magnesium hydroxide kinds × Cd level	1.947	2.109	14.324***
	Variety × Magnesium hydroxide kinds × Cd level	0.071	0.031	3.180

Note: Different lowercase letters indicate significant difference between different magnesium hydroxide treatments under the same Cd pollution level ($P < 0.05$); "*" means $0.01 < P < 0.05$, "**" means $0.001 < P < 0.01$, "***" indicates $P < 0.001$

Under low cadmium (1 $mg \cdot kg^{-1}$), compared with the control (CK1), the cadmium concentration in leaves, petioles and roots of the two Chinese cabbage varieties treated with magnesium hydroxide decreased by 5.4–31.8%, 1.6–6.5% (increased by 9.5% under Cd1 + oMg1 treatment), 15.8–40.8% (Liangqing variety) and 12.1–

24.5%, 1.5–12.7%, 5.0–24.9% (Chunxiawang variety), respectively, among which, cadmium concentration in all parts of the two Chinese cabbage varieties treated with nanometer magnesium hydroxide decreased more significantly, with a respective decrease of 22.0–31.8%, 1.6–6.5%, 18.8–40.8% (Liangqing variety) and 16.6–24.5%, 4.2–12.7%, 7.9–24.9% (Chunxiawang variety) in the leaves, petioles and roots. Under high cadmium (5 $mg\cdot kg^{-1}$), compared with the control (CK2), cadmium concentration in leaves, petioles and roots of the two Chinese cabbage varieties treated with magnesium hydroxide decreased by 1.6–15.6%, 0.3–21.0% (increased by 6.1% under Cd5 + oMg1 treatment), 14.5–24.9% (Liangqing variety) and 0.1–16.1%, 0.3–19.7%, 13.7–25.0% (Chunxiawang variety), respectively. The cadmium concentration in all parts of the two Chinese cabbage varieties treated with nanometer magnesium hydroxide decreased more significantly, with a respective decrease of 3.9–15.6%, 0.3–21.0%, 14.7–24.9% (Liangqing variety) and 4.9–16.1%, 7.7–19.7%, 23.3–25.0% (Chunxiawang variety) in the leaves, petiole and roots. Regardless of high cadmium or low cadmium levels (1 and 5 $mg\cdot kg^{-1}$), the cadmium concentration in all parts of Chinese cabbage decreased with the increasing application amount of nanometer magnesium hydroxide and common magnesium hydroxide. The application of nanometer magnesium hydroxide could reduce more cadmium concentration in various parts of Chinese cabbage under the same application amount.

Plant cadmium form

For shoot of the two Chinese cabbage varieties, Liangqing and Chunxiawang, the concentration and distribution ratio (FDC) of ethanol extracted cadmium (E-Cd), water extracted cadmium (W-Cd), sodium chloride extracted cadmium (NaCl-Cd), acetic acid extracted cadmium (HAC-Cd), hydrochloric acid extracted cadmium (HCl-Cd), residual cadmium (R-Cd) and total extracted cadmium (T-Cd) are shown in Fig. 1. With the increase of cadmium levels, cadmium concentration in shoot of the two Chinese cabbage varieties increases. Under the stress of 1 and 5 $mg\cdot kg^{-1}$Cd, without the use of magnesium hydroxide, the main form of cadmium in the two Chinese cabbages of Liangqing and Chunxiawang is NaCl-Cd, and FDC of cadmium in Chinese cabbage is in the order of NaCl-Cd (47.9–60.8%)>R-Cd (17.4–21.7%)> W-Cd (11.3–21.2%)>E-Cd (5.2–6.1%)>HCl-Cd (1.9–2.5%), HAC-Cd (1.1–2.1%). 1 and 5 $mg\cdot kg^{-1}$Cd increases the concentration of cadmium in the two Chinese cabbage varieties, Liangqing and Chunxiawang, and the total extracted cadmium content is 1.895, 1.668 $mg\cdot kg^{-1}$ (low cadmium 1 $mg\cdot kg^{-1}$) and 5.577, 4.944 $mg\cdot kg^{-1}$ (high cadmium 5 $mg\cdot kg^{-1}$). In particular, it increases NaCl-Cd FDC of the two Chinese cabbage varieties, and reduces R-Cd FDC of Chinese cabbage.

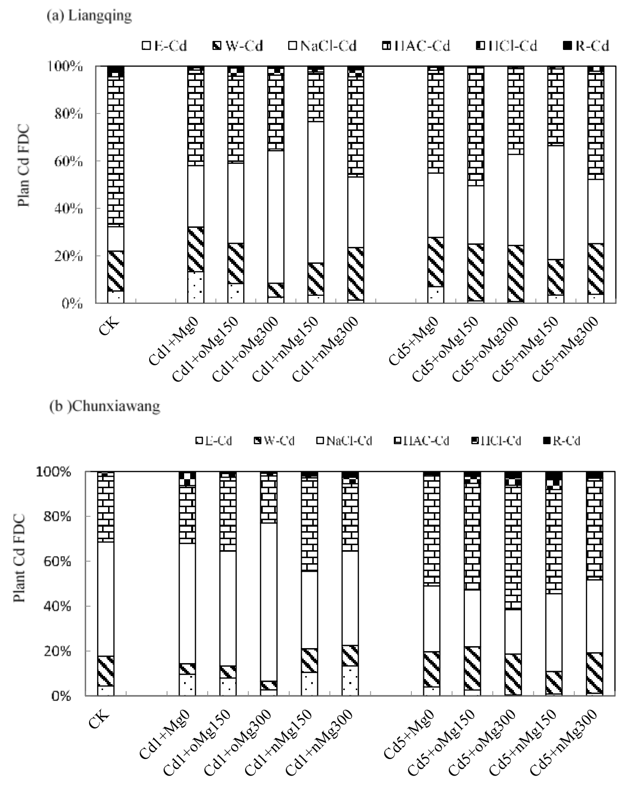

Fig. 1: Magnesium hydroxide application on the morphological distribution ratio (FDC) of Cd in shoot of Chinese cabbage

Under the stress of 1 and 5 $mg\cdot kg^{-1}$ Cd, distribution ratio FDC of various forms of cadmium in Chinese cabbage treated by nanometer magnesium hydroxide and ordinary magnesium hydroxide was in the order of NaCl-Cd (42.2–58.6)>R-Cd (20.8–33.3%)> W-Cd (10.6–20.8%)>E-Cd (2.6–7.2%)> HCl-Cd (1.2–3.0%), HAC-Cd (1.0–1.9%). The contents of E-Cd, W-Cd, NaCl-Cd, HAC-Cd and T-Cd in the two Chinese cabbage varieties were significantly decreased ($P < 0.05$), and the reduction was more significant with the increasing application amount of magnesium hydroxide. Under low cadmium (1 $mg\cdot kg^{-1}$), compared to (CK1) added with cadmium but without magnesium hydroxide treatment, nanometer magnesium hydroxide and ordinary magnesium hydroxide treatments made E-Cd, W-Cd, NaCl-Cd, HAC-Cd and T-Cd contents in the two Chinese cabbage varieties decrease by 28.8–50.0%, 20.9–46.2%, 9.0–39.3%, 0.9–28.0%, 6.2–39.0% (Liangqing) and 36.5–75.1%, 7.4–47.8%, 13.1–55.2%, 1.1–35.1%, 10.0–44.7% (Chunxiawang), respectively. Under high cadmium (5 $mg\cdot kg^{-1}$), compared with CK2, nanometer magnesium hydroxide and ordinary magnesium hydroxide treatments made E-Cd, W-Cd, NaCl-Cd, HAC-Cd and T-Cd contents in the two Chinese cabbage varieties decrease by 13.8–56.4%, 28.9–46.3%, 33.0–57.5%, 45.8–71.4%, 25.9–48.8% (Liangqing) and 20.2–35.8%, 16.9–56.4%, 26.3–47.3%, 29.7–71.0%, 20.5–45.5% (Chunxiawang), respectively. Nanometer magnesium hydroxide had better

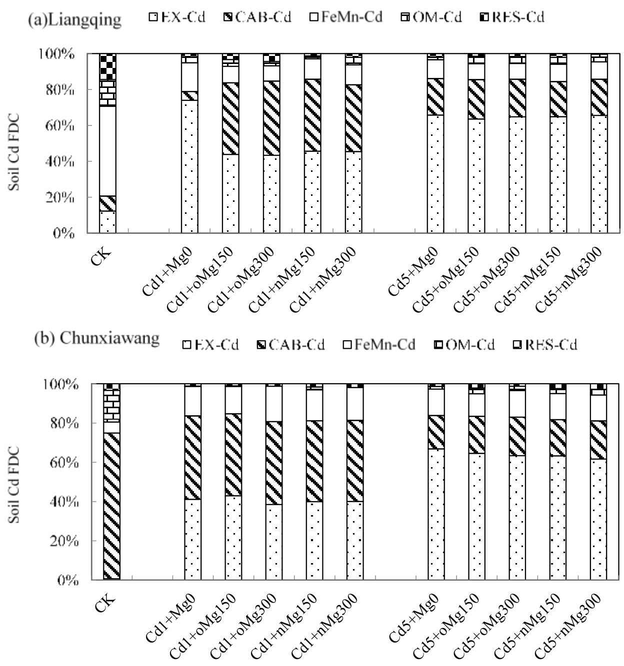

Fig. 2: Magnesium hydroxide application on soil Cd form distribution ratio (FDC)

reduction effect than common magnesium hydroxide. In comparison between the two Chinese cabbage varieties, the cadmium concentration and total extracted cadmium concentration of Liangqing variety were higher than those of Chunxiawang variety.

Soil cadmium form

The morphological content and distribution ratio FDC (referred to as the ratio of certain cadmium content in soil to total cadmium content) of cadmium under each soil treatment are shown in Fig. 2 and Table 3. With the increase of soil cadmium levels, various forms of cadmium contents in soil increase. Without the application of magnesium hydroxide, various forms of cadmium contents in soil for the two Chinese cabbage varieties without cadmium pollution treatment (CK) is significantly lower than that of other treatments ($P < 0.05$), and FDC of cadmium in each form for the two varieties of Liangqing and Chunxiawang is in the order of RES-Cd (46.9%)>FeMn-Cd (26.1%)>EX-Cd (13.7%)> CAB-Cd (8.4%)> OM-Cd (4.9%) and RES-Cd (46.8%) > EX-Cd (22.3%) > FeMn-Cd (15.9%) > CAB-Cd (10.9%) > OM-Cd (4.6%). The addition of exogenous cadmium promotes the conversion of residual cadmium to exchangeable cadmium and carbonate-bound cadmium in the two Chinese cabbage varieties. The total cadmium extraction amount of Liangqing and Chunxiawang is 0.965 mg·kg^{-1}, 0.981 mg·kg^{-1} (under low cadmium treatment 1 mg·kg^{-1}) and 4.909 mg·kg^{-1}, 4.895 mg·kg^{-1} (under high cadmium treatment 5 mg·kg^{-1}). Both of them mainly exist as exchangeable cadmium, with FDC at 37.2–50.6%. The residual cadmium content is decreased, with FDC at 10.0–16.7%. The carbonate-bound cadmium content is increased, with FDC at 16.6–31.6%. Regardless of high cadmium or low cadmium, the two Chinese cabbage varieties demonstrate consistent cadmium distribution ratio order of EX-Cd (37.2–50.6%)> CAB-Cd (16.6–31.6%)> FeMn-Cd (13.8–18.8%)> RES-Cd (10.0–16.7%)> OM-Cd (2.4–7.4%).

In general, compared with the control (added with cadmium but without magnesium hydroxide), exchangeable cadmium FDC showed a downward trend regardless of treatment with nanometer magnesium hydroxide or common magnesium hydroxide, while other cadmium FDCs showed an increasing trend. Moreover, with the increasing application rate of magnesium hydroxide, FDC increase and decrease was more obvious for cadmium in each form. Nanometer magnesium hydroxide showed a better effect in lowering exchangeable cadmium. Under low cadmium (1 mg·kg^{-1}), FDC of each form of cadmium in the two varieties of Liangqing and Chunxiawang treated with magnesium hydroxide was in the order of EX-Cd (29.5–39.7%)>CAB-Cd (21.4–25.6%)>FeMn-Cd (16.4–20.2%)> RES-Cd (15.4–18.1%)> OM-Cd (6.1–7.5%) and EX-Cd (24.9–33.4%)> CAB-Cd (31.3–33.4%)> FeMn-Cd (16.1–21.9%)>RES-Cd (10.1–15.0%)>OM-Cd (7.8–9.4%). Compared with control (CK1), the exchangeable cadmium content of the two varieties of Liangqing and Chunxiawang treated by magnesium hydroxide decreased by 19.1–37.5% and 8.2–32.9%, while the other four forms of cadmium contents increased by 33.1–65.6%, 22.6–57.1%, 5.2–34.5%, 19.5–43.0% (Liangqing variety) and 1.3–6.1%, 16.9–61.8%, 8.2–27.4%, 3.1–51.0% (Chunxiawang variety), respectively. Under high cadmium (5 mg·kg^{-1}), exchangeable cadmium FDC of Liangqing variety was the highest, followed by carbonate-bound and residual cadmium FDC, and organic cadmium FDC was the lowest. Exchangeable cadmium FDC of Chunxiawang variety was the highest, followed by carbonate-bound state and iron-manganese oxidation state cadmium FDC, and organic cadmium FDC was the lowest.

Compared with the control (CK2), nanometer magnesium hydroxide treatment reduced exchangeable cadmium content in soil for the two Chinese cabbage varieties by 10.1–27.4%, while the other four forms of cadmium content increased by 6.4–18.1%, 0.0–34.6%, 12.9–105.0%, 11.4–49.4%, respectively. Compared with the control (CK2) without magnesium hydroxide addition, ordinary magnesium hydroxide treatment reduced the exchangeable and iron-manganese oxidation state cadmium content in soil by 4.3–21.0% and 7.6–15.2%, respectively for Liangqing variety, while cadmium content of the other three forms increased by 16.0–22.6%, 12.2–12.9%, and 5.7–37.3%, respectively. The change of cadmium content in soil was consistent between ordinary magnesium hydroxide treatment and nanometer magnesium hydroxide treatment for Chunxiawang variety. The soil exchangeable cadmium content decreased by 12.4–20.5%, while the other four

Table 3: Magnesium Hydroxide Application on soil Cd forms

Variety	Treatment	Cd content (mg·kg^{-1})					
		EX-Cd	CAB-Cd	FeMn-Cd	OM-Cd	RES-Cd	Total-Cd
Liangqing	CK	0.031±0.001e	0.019±0.001e	0.059±0.002e	0.011±0.001e	0.106±0.001e	0.226±0.002d
	CK1	0.488±0.004a	0.160±0.007d	0.133±0.004d	0.058±0.004d	0.128±0.004d	0.965±0.007c
	Cd1 + oMg1	0.395±0.007b	0.213±0.004c	0.163±0.004c	0.071±0.005ab	0.153±0.004c	0.994±0.002b
	Cd1 + oMg2	0.335±0.007c	0.235±0.004b	0.193±0.007b	0.069±0.002bc	0.183±0.007a	1.014±0.002ab
	Cd1 + nMg1	0.336±0.005c	0.244±0.005b	0.193±0.007b	0.061±0.002cd	0.168±0.004b	1.001±0.009b
	Cd1 + nMg2	0.305±0.007d	0.265±0.007a	0.209±0.009a	0.078±0.004a	0.179±0.005a	1.035±0.021a
	CK	0.031±0.001d	0.019±0.001f	0.059±0.002d	0.011±0.001d	0.106±0.001f	0.226±0.002b
	CK2	2.100±0.035a	0.938±0.011e	0.794±0.023b	0.295±0.007c	0.783±0.004e	4.909±0.012a
	Cd5 + oMg1	2.009±0.140ab	1.088±0.011b	0.673±0.018c	0.333±0.018b	0.828±0.007d	4.929±0.136a
	Cd5 + oMg2	1.658±0.071c	1.150±0.035a	0.734±0.037bc	0.331±0.002b	1.075±0.004b	4.948±0.138a
	Cd5 + nMg1	1.888±0.053b	0.998±0.004d	0.794±0.044b	0.333±0.007b	0.888±0.004c	4.899±0.005a
	Cd5 + nMg2	1.525±0.042c	1.048±0.007c	0.889±0.019a	0.363±0.007a	1.170±0.007a	4.994±0.083a
Chunxiawang	CK	0.049±0.002f	0.024±0.002b	0.035±0.001e	0.010±0.001e	0.103±0.004c	0.220±0.007b
	CK1	0.365±0.004a	0.310±0.007a	0.136±0.002d	0.073±0.004d	0.098±0.004c	0.981±0.019a
	Cd1 + oMg1	0.335±0.007b	0.314±0.002a	0.171±0.002b	0.081±0.002bc	0.101±0.002c	1.003±0.007a
	Cd1 + oMg2	0.275±0.007d	0.328±0.014a	0.220±0.007a	0.079±0.002c	0.103±0.007c	1.004±0.019a
	Cd1 + nMg1	0.305±0.007c	0.321±0.009a	0.159±0.002c	0.086±0.002b	0.116±0.002b	0.988±0.018a
	Cd1 + nMg2	0.245±0.007e	0.329±0.002a	0.171±0.002b	0.093±0.004a	0.148±0.004a	0.985±0.004a
	CK	0.049±0.002e	0.024±0.002d	0.035±0.001d	0.010±0.001d	0.103±0.004e	0.220±0.007e
	CK2	2.070±0.049a	1.006±0.023c	0.885±0.014c	0.119±0.002c	0.815±0.007d	4.895±0.018d
	Cd5 + oMg1	1.813±0.042b	1.096±0.016b	1.066±0.051b	0.210±0.004b	0.876±0.005c	5.061±0.002b
	Cd5 + oMg2	1.645±0.042cd	1.150±0.007ab	1.218±0.039a	0.241±0.009a	0.828±0.011d	5.081±0.009b
	Cd5 + nMg1	1.675±0.000c	1.098±0.018b	1.096±0.044b	0.211±0.009b	0.908±0.004b	4.988±0.021c
	Cd5 + nMg2	1.555±0.081d	1.188±0.042a	1.191±0.041a	0.244±0.009a	0.938±0.007a	5.115±0.004a
$LSD_{0.05}$	Variety	2.212	44.752***	55.899***	120.927***	4.318*	3.292
	Cd level	1017.123***	4175.121***	1369.352***	1287.434***	562.486***	32451.781***
	Magnesium hydroxide kinds	17.415***	32.020***	13.290***	47.502***	6.496**	5.402*
	Variety × Cd level	0.249	7.087**	44.754***	200.446***	0.035	2.909
	Variety × Magnesium hydroxide kinds	0.016	3.891*	11.418***	5.914**	1.045	1.160
	Magnesium hydroxide kinds × Cd level	4.994*	11.151***	4.474*	24.399***	2.578	1.587
	Variety × Magnesium hydroxide kinds × Cd level	0.322	7.312**	9.195**	6.930**	0.561	2.192

Note: Different lowercase letters indicate the significant difference between different magnesium hydroxide treatments under the same Cd pollution level ($P < 0.05$); "*" means $0.01 < P < 0.05$, "**" means $0.001 < P < 0.01$, "***" indicates $P < 0.001$

forms of cadmium contents increased by 8.9–14.3%, 20.5–37.6%, 76.5–102.5%, 1.6–7.5%. Regardless of high cadmium or low cadmium, with the increasing application amount of magnesium hydroxide, the exchangeable cadmium content of the soil decreased, while the carbonate bound state and iron-manganese oxidation state cadmium contents increased. Where, under low cadmium (1 mg·kg^{-1}), the exchangeable cadmium content of Cd1 + oMg2 treatment was 15.2 and 17.9% lower than that of Cd1 + oMg1 treatment for the two varieties of Liangqing and Chunxiawang, and exchangeable cadmium content of Cd1 + nMg2 treatment was 9.2 and 19.7% lower than that of Cd1 + nMg1 treatment. Under high cadmium (5 mg·kg^{-1}), the exchangeable cadmium content of Cd5 + oMg2 treatment was 17.5 and 9.3% lower than that of Cd5 + oMg1 treatment for the two varieties of Liangqing and Chunxiawang, and exchangeable cadmium content of Cd5 + nMg2 treatment was 19.2 and 7.2% lower than that of Cd5 + nMg1 treatment. In the case of same application amount of magnesium hydroxide, nanometer magnesium hydroxide has a better effect in reducing exchangeable cadmium content in the soil.

Correlation between plant cadmium and soil cadmium

The correlation between cadmium concentration in various parts of Chinese cabbage and various forms of cadmium concentration in soil is shown in Table 4. Under low cadmium (1 mg·kg^{-1}), except that there is no significant correlation ($P > 0.05$) between petiole cadmium content and soil EX-Cd content in Liangqing variety, the correlation between cadmium concentration in various parts of the two Chinese cabbage varieties and soil EX-Cd content reaches a very significant level ($P < 0.01$). Under high cadmium (5 mg·kg^{-1}), the correlation between cadmium concentration in various parts of the two Chinese cabbage varieties and EX-Cd content in soil reaches a significant level ($P < 0.05$). Except that cadmium content in the leaves of Chunxiawang variety is significantly correlated with soil EX-Cd content, that of other parts is extremely significantly correlated with soil EX-Cd content ($P < 0.01$). The correlation between the other four forms of cadmium in soil and cadmium concentration in different parts of Chinese cabbage is related to the Chinese cabbage variety and cadmium concentration. Under low cadmium (1 mg·kg^{-1}), there is a significant negative correlation between cadmium concentration in leaves and roots of Liangqing variety and soil CAG-Cd, FeMn-Cd, RES-Cd and Total-Cd contents ($P < 0.01$); There is also a significant negative correlation between soil OM-Cd content and cadmium concentration in roots of Liangqing variety. Under low cadmium (1 mg·kg^{-1}), there is a significant negative correlation between cadmium

Table 4: Correlation coefficient between Cd concentration in various parts of Chinese cabbage and Cd content in soil

Variety	Soil Cd form	Cd1			Cd5		
		Leaf	Petiole	Root	Leaf	Petiole	Root
Liangqing	EX-Cd	0.914**	0.450	0.865**	0.853**	0.913**	0.849**
	CAB-Cd	-0.874**	-0.447	-0.898**	-0.202	-0.295	-0.626
	FeMn-Cd	-0.932**	-0.540	-0.908**	-0.732*	-0.637*	-0.241
	OM-Cd	-0.515	-0.138	-0.811**	-0.802**	-0.583	-0.933**
	RES-Cd	-0.942**	-0.458	-0.790**	-0.859**	-0.932**	-0.843**
	Total-Cd	-0.853**	-0.496	-0.960**	-0.356	-0.254	-0.305
Chunxiawang	EX-Cd	0.937**	0.941**	0.876**	0.747*	0.787**	0.932**
	CAB-Cd	-0.752*	-0.642*	-0.531	-0.772**	-0.775**	-0.852**
	FeMn-Cd	-0.745*	-0.565	-0.389	-0.659*	-0.707*	-0.875**
	OM-Cd	-0.704*	-0.594	-0.743*	-0.657*	-0.679*	-0.927**
	RES-Cd	-0.614	-0.732*	-0.834**	-0.643*	-0.667*	-0.629
	Total-Cd	-0.278	0.056	0.066	-0.660*	-0.671*	-0.773**

Note: ** indicates a significant correlation at the 0.01 level (bilateral); * indicates a significant correlation at the 0.05 level (bilateral)

concentration in leaves and petioles of Chunxiawang variety and soil CAB-Cd ($P < 0.05$). The cadmium content in leaves is significantly negatively correlated with soil FeMn-Cd ($P < 0.05$). There is a significant negative correlation between cadmium concentration in leaves and roots and soil OM-Cd content ($P < 0.05$). The correlation between soil RES-Cd content and cadmium concentration in petioles and roots reaches a significant level ($P < 0.05$), and that with cadmium concentration in root reaches a very significant level ($P < 0.01$). Under high cadmium (5 mg·kg^{-1}), there is a significant negative correlation between soil FeMn-Cd content and cadmium concentration in leaves and petioles of Liangqing variety ($P < 0.05$). The correlation between soil OM-Cd content and cadmium concentration in leaves and roots reaches a very significant level ($P < 0.01$). Soil RES-Cd content is significantly negatively correlated with cadmium concentration in leaves, petioles and roots ($P < 0.01$). Under high cadmium (5 mg·kg^{-1}), there is a significant or extremely significant correlation between cadmium concentration in the leaves, petiole and roots of Chunxiawang variety and various forms of cadmium content in soil (except that the correlation between soil RES-Cd content and cadmium concentration in roots does not reach a significant level), and the correlation with soil CAB-Cd, FeMn-Cd, OM-Cd, RES-Cd and Total-Cd contents is negative.

Discussion

Cadmium (Cd) is a non-essential element in plant growth and development, and when cadmium reaches a certain concentration, it not only affects the normal growth of plants, but also has strong biological toxicity (Tan *et al*. 2017). Cadmium effect on plant growth mainly demonstrates hormesis effect, while the critical concentration of cadmium toxicity on plant growth is related to soil type and plant species (Yang *et al*. 2019). Peng *et al.* (2019) showed that low concentrations of cadmium (≤10 μg·L^{-1}) treatment promoted rice growth, but did not reach significant levels; when cadmium concentration was higher than 10 μg·L^{-1}, there was inhibition effect, and the inhibition was more obvious when cadmium concentration was higher. Wang *et al.* (2019) showed that when the mass concentration of cadmium was 5 mg·L^{-1}, the growth of celery seedlings was not significantly different from that of the control; when the mass concentration of cadmium in nutrient solution was ≥ 10 mg·L^{-1}, the plant growth was inhibited. In this experiment, without the application of magnesium hydroxide, leaf biomass of the two Chinese cabbages increased under low cadmium (1 mg·kg^{-1}) stress, while root biomass decreased. The reason may be that the root system is a plant absorption organ, so the root system is more severely poisoned by soil cadmium (Tan *et al*. 2017). High cadmium (5 mg·kg^{-1}) inhibited the growth of various parts of Chinese cabbage, indicating that 5 mg·kg^{-1} exogenous cadmium has obvious toxic effects on the growth of Chinese cabbage. This is basically consistent with the results of Guo *et al.* (2018). Compared with the two Chinese cabbage varieties tested, a greater cadmium toxic effect was found on Chunxiawang variety. The reason may be different vegetable varieties with different cadmium resistance (Zou 2017).

This experiment found that the application of nanometer magnesium hydroxide and ordinary magnesium hydroxide promoted shoot growth of the two varieties, thereby increasing the total plant biomass. Regardless of low cadmium or high cadmium, leaf and petiole biomass of Chinese cabbage treated with ordinary magnesium hydroxide increased with increasing application amount. Under low cadmium (1 mg·kg^{-1}), Chinese cabbage treated with low amount of nanometer magnesium hydroxide showed better growth. However, the biomass of leaf and petiole of Chinese cabbage decreased with the increasing application amount of nanometer magnesium hydroxide, but they were higher than that without magnesium hydroxide application. The reason may be that nanometer magnesium hydroxide has a small grain size, a large specific surface area, and a strong adsorption capacity (Zhang *et al.* 2002) which increases the adsorption of cadmium in soil and reduces the toxic effect on the plant under high cadmium conditions. Yuan *et al.* (2017) studied the nutritional effects of low potassium combined with nanometer magnesium hydroxide on Chinese cabbage. The yield increase effect of low potassium combined with nanometer magnesium hydroxide on Chinese cabbage reached a significant level, but low amount treatment of nanometer magnesium hydroxide had better yield increase effect than high amount treatment of nanometer magnesium hydroxide. The results of this study are similar to ours. It maybe nanoparticles have toxic effects on plants, it interferes with biochemical metabolism of cells and affects plant growth (Zhang *et al*. 2013). Therefore, application of nanometer magnesium hydroxide should be controlled in a reasonable amount.

The addition of exogenous cadmium significantly increased the cadmium concentration in various parts of the two Chinese cabbage varieties. With the increase of soil cadmium levels, the cadmium concentration in various parts of the two Chinese cabbage varieties increased significantly. This is consistent with the research results of Song (2015). With the increase of cadmium levels, the cadmium concentration in both roots and stems of rice seedlings increased significantly. The application of nanometer magnesium hydroxide and ordinary magnesium hydroxide reduced the cadmium concentration in various parts of Chinese cabbage, showing a downward trend with the increase of application amount. The reason may be that magnesium can competitively inhibit the absorption of cadmium. In addition, magnesium ions promote the synthesis of chlorophyll precursors, thereby increasing plant resistance and reducing cadmium enrichment in plants (Song 2015). This experiment found that application of nanometer magnesium hydroxide could more significantly reduce the cadmium concentration in various parts of Chinese cabbage. The reason may be that nano-sized particles have a small particle size, a large specific surface area, a large ratio of surface atoms, and an uneven atomic step, which increases the contact surface of the reaction (Su and Tang 2015) thereby adsorbing cadmium in the soil to a greater extent and reducing the its migration to the plant body. Comparison of the two Chinese cabbage varieties reveals that cadmium concentration of leaves and petioles of Liangqing variety was higher than that of Chunxiawang variety regardless of high cadmium or low cadmium conditions, indicating that cadmium enrichment ability of Liangqing variety is stronger under cadmium pollution. The reason may be different varieties of vegetables with different cadmium absorption ability (Zou 2017). In cadmium-contaminated soil, planting low cadmium uptake crop varieties can reduce cadmium concentration in edible parts, and improving the safety and quality of agricultural products.

Huang (2012) reported that in the leaves and petioles of Chinese cabbage, cadmium mainly existed as sodium chloride extraction state and deionized water extraction state, and cadmium in the roots mainly existed in the forms of sodium chloride extraction state and acetic acid extraction state. Our experiment found that cadmium in shoots of the two Chinese cabbage varieties mainly existed in the form of sodium chloride extraction state, followed by residual state and deionized state, and the contents of acetic acid and hydrochloric acid were the least. The reason may be that pectate, protein-bound or adsorbed heavy metals can be extracted from sodium chloride solution (Zou 2017), while cadmium has a strong affinity for sulfhydryl groups in proteins or other organic compounds, and there is also affinity for other side chains of protein. As a result, cadmium is often bound with proteins in crop body (Braude *et al.* 1981; Niu 2012) which reduces toxicity to plants. The application of nanometer magnesium hydroxide and ordinary magnesium hydroxide significantly reduced the distribution ratio of sodium chloride extracted form of Chinese cabbage, increased the distribution ratio of residual cadmium, and reduced the ethanol extraction state, deionized water extraction state, sodium chloride extraction state and total extracted cadmium content as a whole. This result is similar to that of Sun *et al.* (2013). It indicated that nanometer magnesium hydroxide and ordinary magnesium hydroxide could promote the conversion of cadmium with strong activity to poorly soluble cadmium in Chinese cabbage, thus reducing the toxic effect of cadmium on plant growth (Mao *et al.* 2015). These results are also consistent with our biomass results.

The activity, biotoxicity and mobility of heavy metals in soil vary with their occurrence patterns. Exchangeable heavy metals are located at the exchange sites of active components such as cosmid minerals or humus, which have a greater impact on availability or activity of plants. Organically bound states are usually not directly involved in the supply of plants, while carbonate bound state is absorbed to the carbonate surface, or exists as co-precipitation (Alva *et al*. 2000; Li *et al*. 2001). In this experiment, cadmium concentration in various parts of the two Chinese cabbage varieties was significantly or extremely significantly positively correlated with exchangeable cadmium content in soil, and negatively correlated with the contents of CAB-Cd, FeMn-Cd, OM-Cd and RES-Cd in soil. It indicted that the most important contribution to the cadmium content of Chinese cabbage is soil exchangeable cadmium. This is inconsistent with the results of Li *et al.* (2015). This may be related to cabbage variety, soil type and soil modifier type (Xie *et al*. 2014; Xin *et al*. 2017).

The form that can be absorbed and utilized by plants is mainly exchangeable. The non-residual heavy metals can also be absorbed by plants under certain conditions, and they will display certain differences due to different soil types and plant species (Mao *et al*. 2015; Xin *et al*. 2017). In our experiments, soil exchangeable cadmium FDC reduced by both nanometer magnesium hydroxide and ordinary magnesium hydroxide, while CAB-Cd, FeMn-Cd, OM-Cd and RES-Cd FDC increased. Furthermore, with the increase of magnesium hydroxide application, the content of exchangeable cadmium in soil with high availability decreased significantly, and the carbonate binding state and iron-manganese oxidation state with poor availability increased, which was beneficial to reduce cadmium toxicity on plant and cadmium absorption by plant (Xie *et al*. 2014). Compared with the two-magnesium hydroxide, nano-magnesium hydroxide had a better effect on the reduction of soil exchangeable cadmium, due to its greater adsorption ability. Compared with two varieties of Chinese cabbage, lower content of exchangeable cadmium was observed in rhizosphere soil of Chunxiawang variety. It further proved that cadmium pollution risk of agricultural products could be reduced by the proper redistribution of crop varieties in cadmium contaminated soil.

Conclusion

Both nanometer magnesium hydroxide and ordinary magnesium hydroxide decreased the toxicity of soil cadmium to Chinese cabbage, and promoted the growth of Chinese cabbage. Low amount of nanometer magnesium hydroxide (100 $mg \cdot kg^{-1}$) was more conducive to the growth of Chinese cabbage, while high amounts of magnesium nanoparticles caused certain toxic effects on Chinese cabbage. On cadmium-contaminated soil, the application of nanometer magnesium hydroxide and ordinary magnesium hydroxide reduced cadmium concentration in all parts of Chinese cabbage, and cadmium concentration of Chinese cabbage decreased with the increasing application amount. With the increasing application amount of magnesium hydroxide, exchangeable cadmium content of the soil is decreased, while carbonate-bound state and the iron-manganese oxidation state cadmium contents are increased. Cd concentration in different parts of Chinese cabbage was significantly or extremely significantly positively correlated with soil exchangeable cadmium content, but negatively correlated with CAB-Cd, FeMn-Cd, OM-Cd and RES-Cd content in soil. Regardless of high cadmium or low cadmium, cadmium concentration in leaves and petioles of Chinese cabbage was higher in Liangqing variety than in Chunxiawang variety, and Liangqing variety had stronger cadmium enrichment ability. Under the same amount of magnesium hydroxide, nanometer magnesium hydroxide plays a better role than ordinary magnesium hydroxide in reducing cadmium in various parts of Chinese cabbage.

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