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Identification of rice cultivars with low brown rice mixed cadmium and lead contents and their interactions with the micronutrients iron, zinc, nickel and manganese

Bing Li, Xun Wang, Xiaoli Qi, Lu Huang, Zhihong Ye*

State Key Laboratory for Bio-control and Guangdong Key Laboratory of Plant Resources, School of Life Sciences,
Sun Yat-sen University, Guangzhou 510006, China. E-mail: gzlibinggh@126.com

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Abstract

Paddy fields in mining areas are usually co-contaminated by a cocktail of mixed toxic heavy metals (e.g., Cd and Pb in Pb/Zn mines). However, previous studies on rice cultivars screened for effective metal exclusion have mostly focused on individual metals, and have been conducted under pot-trial or hydroponic solution conditions. This study identified rice cultivars with both low Cd and Pb accumulation under Cd- and Pb-contaminated field conditions, and the interactions of the toxic elements Cd and Pb with the micronutrient elements Fe, Zn, Mn and Ni were also studied. Among 32 rice cultivars tested, there were significant differences in Cd (0.06–0.59 mg/kg) and Pb (0.25–3.15 mg/kg) levels in their brown rice, and similar results were also found for the micronutrient elements. Significant decreases in concentrations of Fe and Mn were detected with increasing Cd concentrations and a significant elevation in Fe, Mn and Ni with increasing Pb concentrations. A similar result was also shown by Cd and Ni. Three cultivars were identified with a combination of low brown rice Cd and Pb, high micronutrient and grain yield (Wufengyou 2168, Tianyou 196 and Guinongzhan). Present results suggest that it is possible to breed rice cultivars with low mixed toxic element (Cd, Pb) and high micronutrient contents along with high grain yields, thus ensuring food safety and quality.

Key words: rice (*Oryza sativa* L.); mixed toxic elements; micronutrient; grain yield

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Introduction

Today, an increasing number of paddy fields in many Asian countries have been reported to be contaminated by toxic elements including Cd and Pb. Such contamination is largely due to anthropogenic activities (Rogan et al., 2009; Williams et al., 2009). Rice grown on a paddy field contaminated by toxic elements can accumulate high levels of toxins in grain and this can play an important role in the transfer of these elements into food chains, leading to serious health risks to humans. Exposure to Cd and Pb via the daily rice staple is of concern in some regions, especially in areas where farming and mining coexist (Yang et al., 2004; Bandara et al., 2008).

There is therefore urgency in resolving this potential human health risk. Although phytoremediation has been considered as an effective approach to remove heavy metals from soils, its application is still impractical in most cases because of the time-scale required for it to have an effect (Iskandar et al., 1997; Zaurov et al., 1999) and due to a lack of availability of suitable plant species and unprofitable production during remediation (Pilon-Smits and Freeman, 2006). Accordingly, there is increasing concern about how to produce safe rice from those contaminated paddy fields.

Screening and breeding rice cultivars with low toxic metal accumulation and high tolerance is considered to be the most feasible and effective approach (Grant et al., 2008; Zeng et al., 2008). Previous studies have shown wide variations in the concentration of toxic elements among rice cultivars (Liu et al., 2005; Zeng et al., 2008; Shi et al., 2009) and the published data suggest that some potentially useful cultivars can be employed in rice production on contaminated soils. However, most such studies have been conducted in pot or hydroponic conditions, and have often focused on single toxic metal. Toxic element contamination is often complex, with a mixture of metals present at high concentration in the substrate (An et al., 2004). In recent years, some researchers (Cheng et al., 2006; Zeng et al., 2008) have reported the accumulation of mixed toxic elements by rice cultivars. However, a common cultivar with simultaneously low toxic element accumulation has not yet been reported.

Micronutrient element deficiencies of staple rice grain can also affect human health (Jiang et al., 2008). Hots and Brown (2004) suggested that 3.7 billion people suffer from Fe deficiency and that more than 2 billion suffer

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* Corresponding author. E-mail: lssyzhh@mail.sysu.edu.cn

from Zn deficiency. The global population is estimated to climb to 8.3 billion in 2020. Most of this increase will likely occur in cities of the developing world, where the prevalence of these micronutrient deficiencies and their associated morbidity and mortality is the highest (Zimmermann and Hurrell, 2002). The micronutrient quality of rice should therefore be considered as a rice safety issue. However, when micronutrient elements and toxic elements are in competition, their interaction can limit or reduce micronutrients accumulated in rice grain (Goyer, 1997; Dwivedi et al., 2010). It would therefore be useful to select rice cultivars with low grain mixed toxic elements and high contents of required micronutrient elements for application in paddy fields polluted by a combination of toxic elements.

From our previous surveys, paddy fields in the Fankou Pb/Zn mining area in Guangdong Province, China have been shown to be heavily contaminated with Cd and Pb. The aims of present study were firstly to identify rice cultivars with simultaneously low Cd and Pb accumulation (metal exclusion) which could be appropriate for such an area, and secondly, to investigate the interaction of these two toxic metals with the key micronutrient elements Fe, Zn, Mn and Ni.

1 Materials and methods

1.1 Field site

A field trial site was selected and established at a paddy field in the Fankou Pb/Zn mining area (latitude 25°07′06″ and longitude 113°39′12″, altitude 125 m) from April (seed sowing germination) to August 2010 (harvest). Most paddy fields in this area have been contaminated by Pb and Cd from irrigation water polluted with metalliferous mine drainage and processing waste residues from the mine. The average concentrations of Pb and Cd in paddy soil were 2780 and 10.3 mg/kg, respectively, which are 5.6-fold and 10.3-fold of the Third Class (high) standard of the National Environmental Quality Standards for Soil of China (GB15618-1995) (Pb: 500 mg/kg; Cd: 1.0 mg/kg). The paddy soil contained 5.93% total organic carbon (TOC), 1.53 g/kg total N, 0.92 g/kg total P and 4.7 g/kg total K. The soil pH was 6.98 and the texture was made up of 35% sand, 43% silt and 22% clay. Elemental concentrations and properties of the paddy soil are summarized in Table 1. The area has a humid subtropical climate with an average annual temperature of 20°C (ranging from –5 to 40°C) and an average annual rainfall of 1457 mm.

1.2 Plant materials

A selection of 32 rice cultivars consisting of four subgroups: (I) colored rice (6 cultivars); (II) hybrid indica rice (9 cultivars); (III) conventional indica rice (8 cultivars) and (IV) japonica rice (9 cultivars) was used in this study (seeds provided by the Rice Research Institute of the Guangdong Academy of Agricultural Sciences, Guangdong Institute of Eco-environment and Soil Science and South China Agriculture University).

Rice seedlings of different cultivars studied were planted in a randomized complete block design with four blocks. In each, seedlings of each cultivar were planted in a single row of 2 m with 10 duplicate plantings 20 cm apart. Each cultivar row was 20 cm apart. This design was deemed appropriate by other workers (Norton et al., 2009a). At the paddy field, fertilizers were used three times during the field trail. On the day transplanting the seedlings, 200 kg/ha of compound fertilizer (N, P, K) was applied. Ten and 30 days after transplanting, 60 kg/ha of urea and 100 kg/ha of compound fertilizer were applied, respectively. Normal field management was followed according to the cultivation tradition of local farmers. Rice grains of all cultivars studied were ripened in August. The central four plants were eventually harvested and their grains pooled together for Pb, Cd, Fe, Zn, Ni and Mn analysis; the yield is also expressed as the average yield of each plot from the four plants.

1.3 Plant and soil samples preparation and analysis

All rice grains were dehusked and milled to powder in an analytical mill (IKA A11 basic, IKA-Werke GmbH, Germany), and 0.2 g subsamples were weighed into polyethylene tubes. They were acid-digested with HNO_3 (superior grade, Guizhou Chemical, China) at 190°C for 40 min in a microwave oven (MARS-X; CEM, USA). Concentrations of Pb, Fe, Zn, Ni and Mn in the digests were determined by inductively-coupled plasma optical emission spectrometry (ICP-OES; Optima 2000 DV, Perkin Elmer, USA). Concentrations of Cd in the digests were determined by polarized Zeeman atomic absorption spectrophotometry (FAAS; Hitachi Z-2300, Japan). Blanks and an internal standard of poplar leaves (GBW-07604) (China Standard Materials Research Center, Beijing, China) were used for quality control. The elemental recovery rates for the standard material exceeded 90% in all cases.

Soil pH was measured using a pH meter (pH 510, Eutech instruments, Singapore) at a soil: deionized water ratio of 1:2.5 (m/V), and electrical conductivity (EC) measured with a conductivity meter (DDS-11D, China) at a deionized water ratio of 1:5 (m/V). Soil TOC was measured with

Table 1 Physicochemical properties of soil collected from the Fankou paddy field*

pH	TOC (%)	Total N (g/kg)	Total P (g/kg)	Total K (g/kg)	EC (μS/cm)
6.98 ± 0.05	5.93 ± 0.6	1.53 ± 0.19	0.92 ± 0.03	4.7 ± 0.4	524 ± 5.6
Cd (mg/kg)	Pb (mg/kg)	Zn (mg/kg)	Fe (g/kg)	Ni (mg/kg)	Mn (mg/kg)
10.3 ± 1.1	2780 ± 107	4045 ± 71	42.9 ± 0.4	65.4 ± 4.1	2452 ± 192

* Data are expressed as mean ± SE, n = 4.

Table 2 Grain yield and ranks of 32 rice cultivars used in the Fankou field experiment by subgroup and mean rank of brown rice Cd and Pb

Rice subgroup*	Cultivar	Gain yield (g/plot)[a]	Cd rank[b]	Pb rank	Mean rank
Coloured rice	Suihongnuo	61.1 ± 2.9	27	10	18.5
	Zixiangnuo	26.0 ± 1.3	22	26	24
	Sp345	61.2 ± 5.3	21	28	24.5
	Sp205	35.8 ± 5.9	29	21	25
	Sp161	23.8 ± 1.2	24	29	26.5
	Ruanhongmi	21.5 ± 2.2	23	31	27
Indica-conventional	Guinongzhan	50.9 ± 6.6	11	4	7.5
	Sanhuangzhan 2	33.4 ± 4.7	26	1	13.5
	Texianzhan 13	50.1 ± 2.0	31	7	19
	Choukokoku	36.4 ± 2.9	32	6	19
	Shengtai 1	56.7 ± 5.5	30	11	20.5
	Nanfengnuo	44.9 ± 4.1	15	27	21
	Yuxiangyouzhan	71.5 ± 5.9	13	32	22.5
	Yuexiangzhan	25.4 ± 2.4	28	19	23.5
Japonica	Ribenqing	44.9 ± 1.9	1	13	7
	Zhonghua 11	35.5 ± 3.1	8	14	11
	Nanjing 35	45.7 ± 3.8	2	24	13
	Nanjing 44	44.4 ± 1.9	5	22	13.5
	Laohuangdao	45.8 ± 4.9	12	17	14.5
	Suyunuo	32.7 ± 1.2	14	16	15
	Shennong 265	44.5 ± 2.6	25	5	15
	Zhongdao 097	50.8 ± 3.2	17	15	16
	Yueguang	28.5 ± 1.5	18	25	21.5
Indica-hybrid	Tianyou 196	63.5 ± 6.5	6	3	4.5
	Tianyou 122	66 ± 1.1	3	9	6
	Wufengyou 2168	76 ± 5.9	10	2	6
	Tianyou 998	79.2 ± 5.0	9	8	8.5
	Huayouguangkangzhan	67.5 ± 2.2	7	12	9.5
	Wufengyou 128	94.9 ± 5.9	4	23	13.5
	Huayou 665	87.4 ± 3.9	16	20	18
	Jinyou 402	44.6 ± 3.2	20	18	19
	Shanyou 402	38.3 ± 3.8	19	30	24.5

[a] Data are expressed as mean ± SE, $n = 4$; [b] ranks 1–32 delegate the orders of brown rice Cd and Pb from the lowest to the highest among the 32 rice cultivars.

a total organic carbon analyzer (TOC-VCPH, Shimadzu, Japan), and total N, total P with a Smartchem discrete auto analyzer (Smartchem200, AMS Westco, Italy). Soil samples were digested with an HCl/HNO_3 mixture (3:1, V/V) in the microwave oven, and metal (Pb, Fe, Zn, Ni, Mn, K) concentrations in the digests were again determined by ICP-OES, and concentrations of Cd determined by AAS. Blanks and soil standard material (GBW-07401) were used for quality control. The elemental recovery rates for the standard material exceeded 90%, which is comparable to previous studies using the same standard material (Wang et al., 2011).

1.4 Statistical analysis

All results are presented as arithmetic means with standard errors attached. A statistical comparison of means of plant analytical data was examined with one-way ANOVA in the SPSS statistical package. Correlation analyses for elemental contents were conducted using the Origin 7.5 software package.

2 Results

2.1 Concentrations of Cd, Pb, Fe, Zn, Ni and Mn in brown rice

All 32 cultivars grew successfully to harvestable grain at the Fankou paddy field site. Concentrations of Cd in brown rice ranged from 0.06 to 0.59 mg/kg, with a mean of 0.21 mg/kg (Fig. 1). There was a significant cultivar effect for Cd concentration ($F = 8.7$, $p < 0.001$). The three cultivars with the highest concentration of Cd were Choukokoku, Texianzhan 13 and Shengtai 1, and the three with the lowest Cd, Ribenqing, Nanjing 35 and Tianyou 122. For the four cultivar subgroups, the indica-conventional (mean 0.32 mg/kg) and colored rice (0.29 mg/kg) had significantly higher Cd ($F = 8.2$, $p < 0.001$) than the japonica (0.14 mg/kg) and indica-hybrid (0.12 mg/kg) cultivars.

Concentrations of Pb in brown rice ranged from 0.25 to 3.15 mg/kg, with an average of 1.52 mg/kg (Fig. 1). There was a significant cultivar effect for Pb concentration ($F = 11.2$, $p < 0.001$). The three cultivars with the highest concentrations Pb were Yuxiangyouzhan, Ruanhongmi and Shanyou 402, and the three with the lowest Pb, Tianyou 196, Wufengyou 2168 and Sanhuangzhan 2. For the four cultivar subgroups, the colored rice (mean 2.15 mg/kg) had higher Pb than the japonica (1.58 mg/kg), indica-hybrid (1.30 mg/kg) and indica-conventional (1.25 mg/kg), but there were no significant differences in means.

The mean concentration of brown rice Fe in the cultivars was 19 mg/kg, varying from 0.65 to 50 mg/kg (Fig. 1). Concentration of Fe was strongly affected by cultivar under the Fankou paddy field conditions ($F = 28.5$, $p < 0.001$). It exceeded 30 mg/kg in Laohuangdao (50 mg/kg), Shanyou 402 (48 mg/kg), Yueguang (36 mg/kg) and Sp161 (30

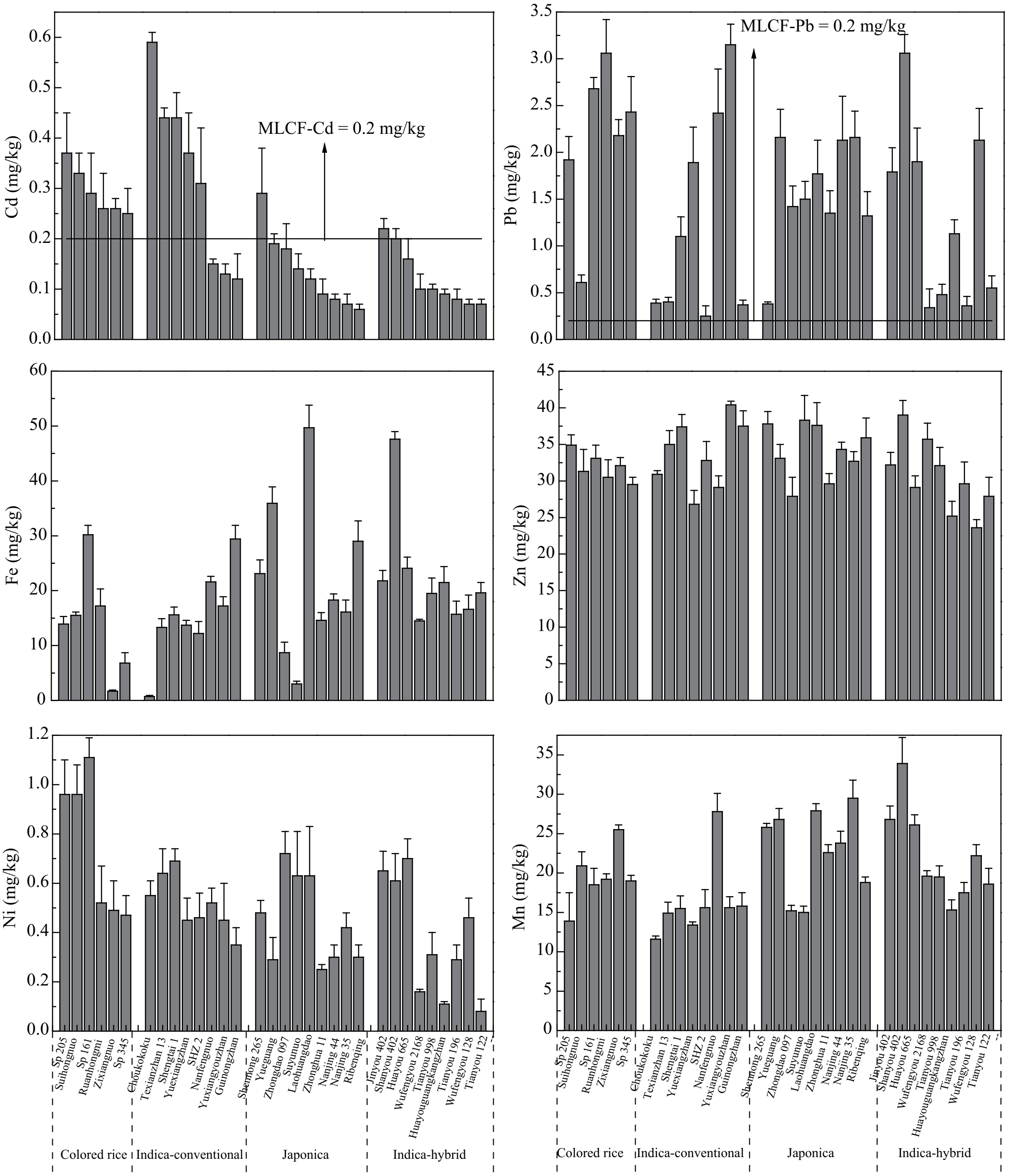

Fig. 1 Concentrations of Cd, Pb, Fe, Zn, Ni and Mn in brown rice of 32 rice cultivars grown at Fankou paddy field contaminated by Cd and Pb (mean ± SE, $n = 4$). MLCF: maximum levels of conlaminants in foods of China.

mg/kg). For the four cultivar subgroups, the indica-hybrid (mean 22 mg/kg) and japonica (22 mg/kg) had higher Fe ($F = 3.2$, $p < 0.05$) than the indica-conventional (15 mg/kg) and colored rice (14 mg/kg) cultivars.

The mean brown rice Zn concentration was 33 mg/kg, ranging from 24 to 40 mg/kg (Fig. 1). A significant difference in Zn concentration was apparent in the 32 cultivars ($F = 4.2$, $p < 0.001$). Concentrations of Zn in 22 of the 32 cultivars exceeded 30 mg/kg; the five cultivars with the highest were Yuxiangyouzhan, Shanyou 402, Suyunuo, Shennong 265 and Laohuangdao. There was no significant difference among the four cultivar subgroups.

Concentrations of Ni in brown rice ranged from 0.08 to 1.11 mg/kg, with an average of 0.50 mg/kg (Fig. 1). There was a significant cultivar effect for Ni concentration ($F = 5.8$, $p < 0.001$). For the four cultivar subgroups, the colored rice (mean 0.75 mg/kg) had higher ($F = 4.2$, $p < 0.05$) Ni than the indica-conventional (0.51 mg/kg), japonica (0.45 mg/kg) and indica-hybrid (0.38 mg/kg) selections.

Concentrations of Mn ranged from 12 to 34 mg/kg, with a mean of 20 mg/kg (Fig. 1). Concentrations of Mn were strongly affected by cultivar under the Fankou paddy field conditions (F = 11.8, $p < 0.001$). For the four cultivar subgroups, the japonica (mean 23 mg/kg) and indica-hybrid (22 mg/kg) had only slightly higher Mn (F = 2.8, $p < 0.05$) than the colored rice (19 mg/kg) and indica-conventional cultivars (16 mg/kg).

2.2 Grain yield and correlation with brown rice concentration of Cd and Pb

The grain yield of the cultivars ranged between 21.5 and 94.9 g/plot with a mean yield of 49.6 g/plot (Table 2). There was a significant cultivar effect for grain yields (F = 12.6, $p < 0.001$); the five cultivars with the highest grain yields were Wufengyou 128, Huayou 665, Tianyou 998, Wufengyou 2168 and Yuxiangyouzhan. For the four subgroups, the indica-hybrid (mean 68.6 g/plot) had higher yield than the others did. There was a negative correlation between grain yield and Cd concentration ($r = -0.34$, $p < 0.001$), and a similar result was detected between grain yield and Pb concentration ($r = -0.23$, $p < 0.01$).

2.3 Relationships between brown rice concentrations of Cd and Pb and the micronutrient elements Fe, Zn, Ni and Mn

As shown in Fig. 2, there were significant positive correlations between brown rice concentrations of Pb and Fe ($p < 0.05$), Pb and Mn ($p < 0.0001$), Pb and Ni ($p < 0.05$), Cd and Ni ($p < 0.0001$), and a negative correlation between concentrations of Cd and Fe ($p < 0.01$), Cd and Mn ($p < 0.001$). Nevertheless, there was no significant correlation between Zn and Pb, or Cd. When taken as a whole group, there was no correlation between Cd and Pb. However, when the data were grouped into four subgroups, a positive correlation ($p < 0.05$) was observed between Cd and Pb in indica-hybrid, a negative correlation between Cd and Pb in indica-conventional ($p < 0.01$) and japonica ($p < 0.05$) (Fig. 3a) cultivars.

3 Discussion

In recent years, a number of studies have reported screens of rice cultivars with low toxic metal accumulation and high tolerance to produce safe rice from slightly and moderately contaminated paddy fields (Liu et al., 2003a; Grant et al., 2008). The present study shows that there was a wide range in the concentration of brown rice Cd between the cultivars with a 9.8-fold range. Among the 32 cultivars studied, brown rice Cd of 13 cultivars exceeded the permissable limit (0.2 mg/kg) of the maximum levels of contaminants in foods of China (MLCF, GB2762-2005). Concentrations of Cd in the paddy field reached up to 10.3 mg/kg, however, the brown rice Cd levels of 19 cultivars are considered safe for human consumption. Our previous study showed that concentrations of brown rice Cd in 17 of the 20 rice cultivars exceeded 0.2 mg/kg when cultivated in a paddy field (soil Cd = 1.2 mg/kg) at Shangba village near the Dabaoshan multi-metal mine (Guangdong, China) (Wang et al., 2011). The results suggest that it is possible to screen rice cultivars with low Cd from paddy fields polluted by Cd. Brown rice Pb in all 32 cultivars exceeded 0.2 mg/kg (MLCF for Pb < 0.2 mg/kg). The main reason may be that the paddy field has been seriously polluted by Pb in the Fankou Pb/Zn mining area for many years, resulting in the concentration of paddy soil Pb being 2780 mg/kg (Table 1). However, there is a 12.6-fold range in Pb between the cultivars, the lowest being 0.25 mg/kg, which is close to the MLCF value for Pb. Our data provide a possible selection of some cultivars accumulating low concentrations of Pb in rice grain suitable for slightly and moderately contaminated paddy fields. For the subgroups, the colored rice had the highest concentrations of both Cd and Pb (Fig. 3b). Williams et al. (2005) had reported that colored rice cultivars accumulate much higher As than white rice under paddy field conditions. These observations suggest that colored rice cultivars should be not cultivated in paddy fields polluted by toxic elements.

Paddy fields, especially in mining areas, are often contaminated by a cocktail of toxic elements (An et al., 2004; Zeng et al., 2008) and so require an effective way to screen rice cultivars which can exclude these metals and metalloids. A previous study found rice cultivars Chunjiang 026, Chunjiang 11 and Hu 97-98 had low Cd, whilst Jia 02-5, Jia C1 and Dan K15 had low Pb concentrations when grown in three contaminated soils (Zeng et al., 2008). However, a common cultivar with simultaneously low grain Cd and Pb had not been reported. In this study, the 32 rice cultivars have been ordered by mean rank of Cd and Pb concentrations (Table 2), so revealing some potentially useful cultivars. The five cultivars with the lowest Cd and Pb were Tianyou 196, Tianyou 122, Wufengyou 2168, Ribenqing and Guinongzhan. However, Tianyou 122 and Ribenqing should be rejected because of their higher concentration of Pb (the concentration of Cd is deemed 'safe' from 1 to 19 Cd rank score). The three cultivars (Tianyou 196, Wufengyou 2168 and Guinongzhan) are therefore suggested for use in future breeding programs for paddy fields contaminated by Cd and Pb.

Norton et al. (2009b) concluded that grain toxic elements (e.g., As) have a strong positive correlation with grain yield (Norton et al., 2009b). The consequences of the strong positive correlation between grain toxic elements concentration and grain yield could be very detrimental to human health, as cultivars which produce higher grain yields are more likely to be grown by farmers and therefore toxic element loadings in rice grain for human consumption would be high. In the present study, when Cd and Pb concentrations and the grain yield were compared, a negative correlation was observed between Cd and grain yield. A similar result also emerged between Pb and grain yield. For the three cultivars with both low Cd and Pb, their grain yields (Tianyou 196 = 63.5 g/plot, Wufengyou 2168 = 76 g/plot and Guinongzhan = 50.9 g/plot) were higher than the mean grain yield (49.6 g/plot) of the 32 rice cultivars. The results indicate that it is possible to screen and/or breed rice cultivars with reduced toxic element accumulation and still maintain a high grain yield. Further trials are however required under different contaminated conditions in other rice growing regions.

Man requires at least 23 mineral nutrient elements for

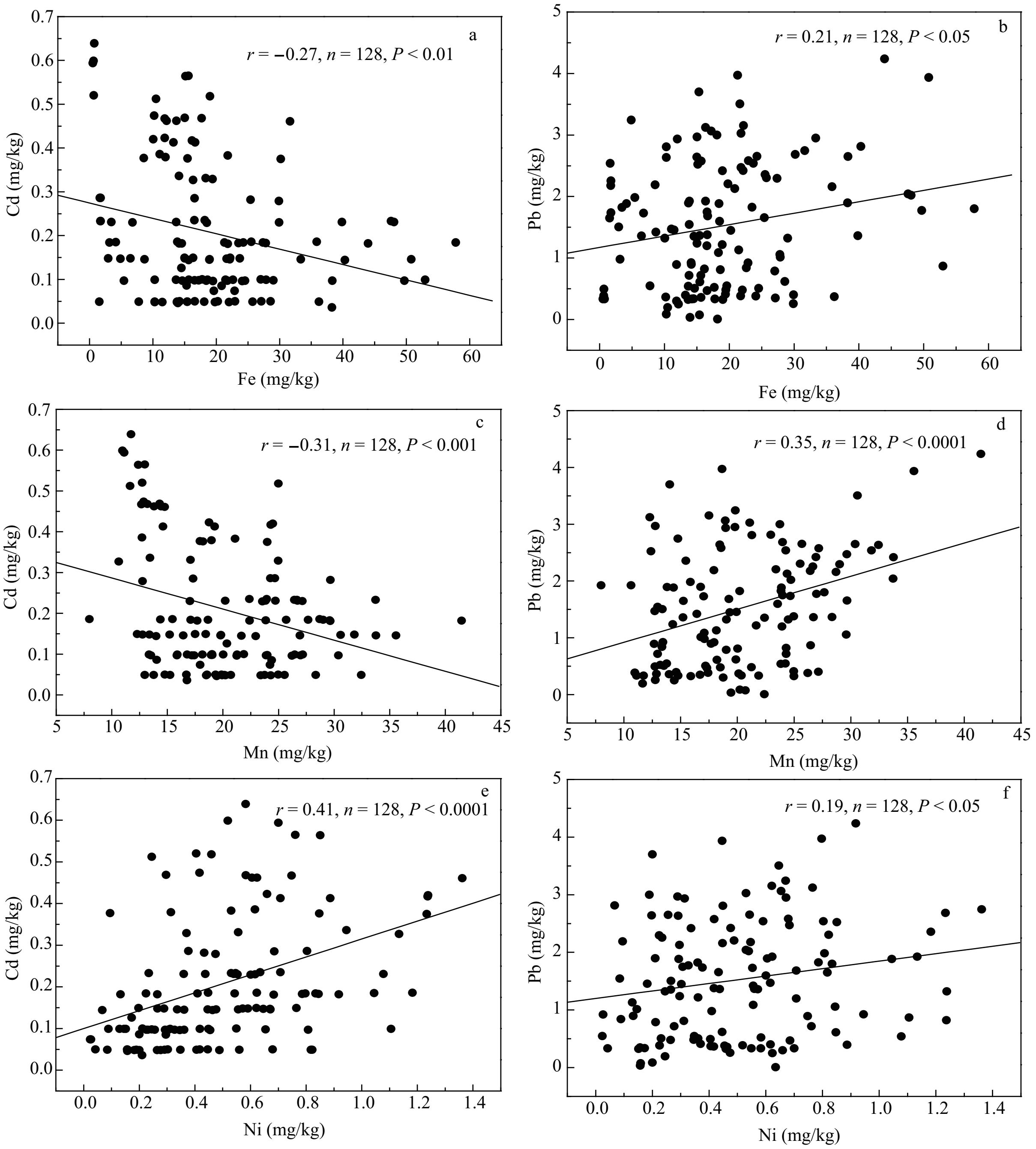

Fig. 2 Correlations between brown rice toxic elements (Cd, Pb) and mineral nutrition elements (Fe, Mn, Ni).

normal growth and development, and the demand is for most nutrients to be supplied by cereals, particularly rice, due to its staple role (Welch and Graham, 2004). In the present study, mean concentrations of Fe, Zn, Ni and Mn were 19, 33, 0.50 and 20 mg/kg, respectively, and there were significant differences among the rice cultivars. Yang et al. (1998) analyzed 285 rice samples and showed that there are significant differences in grain Fe and Zn concentrations. Similar results in rice and other food crops were also reported by Graham et al. (1999). These results further indicate that an effective approach is to screen and breed rice cultivars to improve the nutritional status of the grain. However, when considering the micronutrient status of grain together with toxic element loadings, it has been shown that the toxic elements can limit mineral nutrient accumulation in the grain (Goyer, 1997; Dwivedi et al., 2010). This interaction is thus of public concern. The interaction between Cd/Pb and nutrient elements has been demonstrated with significant differences among species and varieties (Burzynski, 1987), but contradictions are apparent between the results of different studies. For example, Smith and Brennan (1983) reported a synergistic interaction between Cd and Zn, whereas Cataldo et al. (1983) observed an antagonistic interaction between Cd and Fe, Zn, Cu, Mn. Our present results showed that there were no significant relationships between Cd and Zn, Pb and Zn in brown rice. Zinc concentration (4045 mg/kg) in the paddy soil studied was much higher than in normal/uncontaminated soil (⩽ 500 mg/kg) in China. However, the mean concentration of Zn in the brown rice

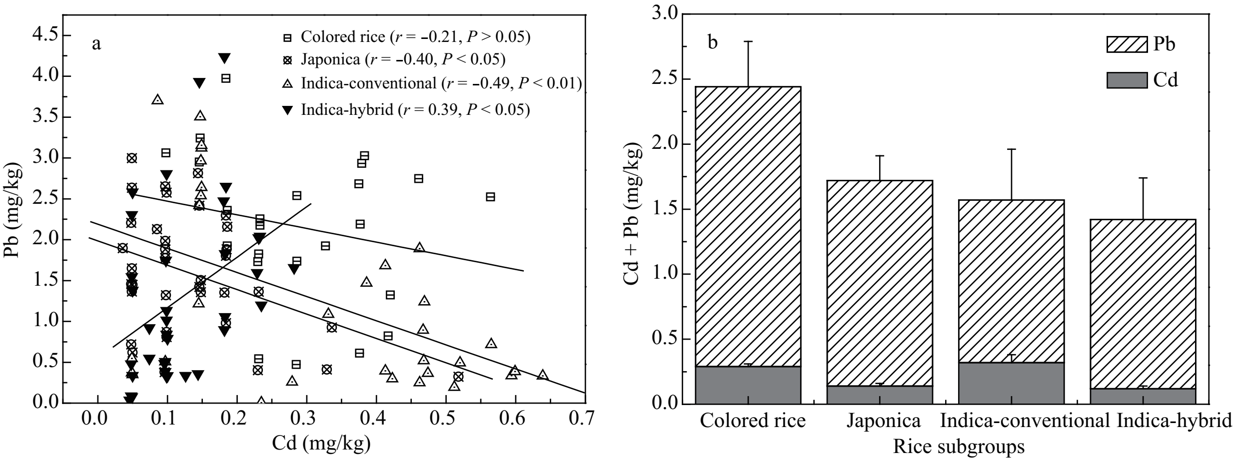

Fig. 3 Correlations between brown rice Cd and Pb (a) and concentrations of Cd and Pb (b) in different rice subgroups grown at Fankou paddy field contaminated by Cd and Pb.

was only 33 mg/kg, still under the permissable limits (50 mg/kg) of Zn in cereals of China (NY 861-2004) and the results (58.4 mg/kg Zn in brown rice under normal soil conditions) reported by Graham et al. (1999). Our results suggest that the interactions of multiple (toxic) elements may have a negative effect on Zn uptake by rice. The present results also show a significant decrease in concentrations of Fe and Mn with increased Cd concentration, suggesting that brown rice is neither safe nor nutritionally desirable for local residents if they select the cultivars with high toxic elements. Furthermore, a significant elevation in micronutrient elements (Fe, Mn and Ni) in brown rice occurred with increasing Pb concentrations. A similar effect was also found between Cd and Ni. These results suggest it would be very detrimental to human health if rice cultivars are selected only for high mineral nutrition. Concentrations of Fe, Zn, Mn and Ni in the three cultivars (Wufengyou 2168, Tianyou 196 and Guinongzhan, Fig. 1), which were identified to use in paddy fields polluted by Cd and Pb in our study area, were higher than or close to the global mean concentration (Zimmermann and Hurrell, 2002; Adomako et al., 2011). Moreover, concentrations of Fe, Zn and Mn in the grains of rice cultivars are stabilized (Norton et al., 2010). The present results indicate that some rice cultivars with reduced toxic elements but high micronutrient elements can be identified.

When the cultivars tested were considered as four subgroups, the order of brown rice Cd and Pb concentration was colored rice > japonica > indica-conventional > indica-hybrid (Fig. 3b). In previous studies, some results have shown that differences existed among the cultivars for Cd uptake and distribution in rice plants, but the differences were not necessarily related to rice genotypes (Liu et al., 2003b), that there is no consistent difference in grain Cd concentration between normal and hybrid cultivars (Yu et al., 2006), and that there is no difference in Cd, Cu and Zn concentrations between conventional rice and hybrid rice (Yin et al., 2010). However, the other results indicated that hybrid rice cultivars have greater abilities in Cd accumulation than normal cultivars (Wu et al., 1999). Grain Pb concentration of hybrid rice was shown to be higher than japonica (Liu et al., 2003b), and conventional and glutinous rice have a stronger ability to accumulate Fe, Cu, Zn, Pb and Cd than hybrid rice (Liu et al., 2010). Thus, some researchers suggest the selection by rice types for Cd content is not appropriate (Xu et al., 2009). Unfortunately, these conclusions were based on data from screens conducted in pot-trials or hydroponics, and focused on contaminated soil with a single toxic element. The physicochemical properties of the soils play important roles in determining the uptake of heavy metals by rice (Zeng et al., 2010), and synergy or antagonism of elements also influences their uptake and translocation in plants. In the present study, whereas a negative correlation between Cd and Pb in indica-conventional and japonica was shown, a positive correlation was observed between these two metals in indica-hybrid rice cultivars. These results indicated the possibility of screening rice cultivars with simultaneously low Cd and Pb. More cultivars should be used in future research, especially hybrid rice because of its high grain yields, and in different districts, to confirm the findings of our present study.

4 Conclusions

The trials reported at one contaminated paddy site here indicated that the accumulation of toxic elements (Cd, Pb) and micronutrient elements (Fe, Zn, Ni, Mn) by brown rice does show useful variation among the 32 rice cultivars tested. The grain yields and micronutrient elements were influenced by Cd and Pb, but three cultivars (Wufengyou 2168, Tianyou 196 and Guinongzhan) with low Cd and Pb, higher micronutrient contents and high grain yields have been flagged. The study suggests a possible way to enable rice culture on paddy fields polluted by combined toxic elements (Cd and Pb) and to ensure rice safety.

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