Songklanakarin J. Sci. Technol.
42 (2), 447-453, Mar. - Apr. 2020

http://www.sjst.psu.ac.th

Original Article

Variations of grain iron and zinc concentrations among the promising low-grain cadmium rice (*Oryza sativa* L.) cultivars

Anongnat Sriprachote[1*], Kanokporn Manantapong[1], Pornthiwa Kanyawongha[2], Kumiko Ochiai[3], and Toru Matoh[3]

[1] *Department of Soil Science and Environment, Faculty of Agriculture, Khon Kaen University, Mueang, Khon Kaen, 40002 Thailand*

[2] *Department of Plant Production Technology, Faculty of Agricultural Technology, King Mongkut's Institute of Technology Ladkrabang, Lat Krabang, Bangkok, 10520 Thailand*

[3] *Plant Nutrition Laboratory, Division of Applied Life Science, Graduate School of Agriculture, Kyoto University, Sakyo-ku, Kyoto, 606-8502 Japan*

Received: 22 March 2018; Revised: 1 September 2018; Accepted: 28 January 2019

Abstract

We aimed to clarify whether low cadmium (Cd) accumulation in varieties of rice also lower human nutrient uptakes. This trial was setup to explore the correlation between grain-Cd and iron (Fe) and zinc (Zn) among four promising rice cultivars and the prevailing KDML105 and RD6. Their grain Cd (0.10–0.60 mg kg^{-1}) and Zn (17.36–22.61 mg kg^{-1}) contents were significantly different, but not significant for grain Fe (11.17–13.91 mg kg^{-1}). The results revealed significant positive correlations between grain Cd and Zn of the prevailing cultivar (r=0.471). But no correlations between grain Cd and Fe and Zn were observed. The RD15 and KNU2 were identified as the low grain Cd, high grain Fe and Zn compared with the prevailing cultivar. Thus the RD15 and KNU2 led to reduced Cd in rice grain without changing the human essential elements.

Keywords: rice (*Oryza sativa* L.), cadmium, micronutrients, Thailand

1. Introduction

Cadmium (Cd) possesses extreme biological toxicity even at low concentrations. Cd is of special concern because it has relatively high mobility in the soil and environment. The amount of Cd in different locations varies depending on differences in the soil formation, soil management practices, and exposure to sources of pollution. However, the level of Cd in soil appears to be increasing over time. In Thailand, Cd has caused serious problems in rice production. At least 2100 ha of paddy fields in Mae Sot district in Tak Province have been polluted to various degrees (Simmons, Pongsakul, Saiyasipanich, & Klinphoklap, 2005). Rice (*Oryza sativa* L.) is the most important crop in Thailand and in the world. Thus, Cd contaminated rice may pose a major threat to people who consume rice daily. Therefore, the concerns over Cd entering the human food chain are justified.

Many studies have documented wide differences in the accumulation of heavy metals in grains among rice genotypes (Arao & Ae, 2003; Liu *et al.*, 2005; Morishita, Fumoto, Yoshizawa, & Kagawa, 1987; Yu, Wang, Fang, Yuan, & Yang, 2006; Zeng, Mao, Cheng, Wu, & Zhang, 2008). Moreover, it is possible to reduce the amount of Cd accumulated in grains by using genetic improvement. In 2012, Sriprachote, Kanyawongha, Pantuwan, Ochiai, and Matoh (2012b) reported variations in low grain Cd accumulation in Thai rice including RD5, RD15, Khao' Niaw Ubon 1 (KNU1), and Khao' Niaw Ubon 2 (KNU2). However, interactions among

*Corresponding author
Email address: anonsr@kku.ac.th

the coexisting elements at the root surface and within the plants also affect Cd uptake and accumulation. These interactions can occur in different stages of absorption, distribution, and excretion of the microelements and Cd within the crops, as well as during the stage of biological functions of essential elements. The selection of rice genotypes with low Cd accumulation in grain contributes to changes in grain nutrient concentrations.

Micronutrient deficiencies of staple rice grain also have an effect on human health. Hotz and Brown (2004) suggested that 3.7 billion people are suffering from iron (Fe) deficiency and more than 2 billion are suffering from zinc (Zn) deficiency. Therefore, the micronutrient contents and quality of rice should be considered as a safety issue for rice. However, when micronutrients and toxic elements are in competition, their interaction can limit or reduce the accumulation of micronutrients in rice grains. The interactions between Cd and micronutrients, such as copper (Cu), Fe, manganese (Mn), and Zn were reported in crops such as wheat (Zhang, Fukami, & Sekimoto, 2002) and barley (Wu, Zhang, & Yu, 2003). The differences were significant among species and varieties and contradictions also existed between the results of the experiments. Smith and Brennan (1983) reported a synergistic interaction between Cd and Zn, while Cataldo, Garland, and Wildung (1983) observed the antagonistic interaction between Cd and Fe, Zn, Cu, and Mn. Zhang *et al.* (2002) indicated that the effects of Cd on Fe, Zn, Cu and Mn from root uptake and translocation had an impact on wheat genotypes. Therefore, the selected rice cultivars for the Cd-polluted paddy fields in this study were low grain Cd rice with a high level of required micronutrients.

The results from our previous study revealed the evaluation of a promising low grain Cd accumulation rice. Therefore, the purposes of this study were: i) to identify rice cultivars containing low Cd accumulation which could be appropriate for the Cd-polluted area; ii) to determine the effect of Cd on grain yields; iii) to investigate the interactions of Cd with key micronutrients such as Fe and Zn with respect to their accumulation in rice grains; iv) and to estimate the provisional tolerable weekly intake (PTWI) of Cd through rice consumption. The results are useful for farmers as a mitigation to reduce the amount of Cd in the rice diet in Cd contaminated areas.

2. Materials and Methods

2.1 Study area and plant materials

The study area was previously described in Sriprachote, Kanyawongha, Ochiai, and Matoh (2012a). The experiment was carried out at a paddy field in Pha Te Village, Pratat Phadaeng Subdistrict, Mae Sot District, Tak Province in Thailand during the rice growing season (July to November). The soil texture was loamy soil with 37% sand, 45% silt, and 18% clay. The concentrations of Cd, Fe, and Zn in the diethylenetriaminepentaacetic acid (DTPA) extract were 0.40, 236, and 11.10 mg kg^{-1}, respectively. From the extract of a $HClO_4$-H_2SO_4-HNO_3 acid mixture, the concentrations of Cd, Fe, and Zn were 1.11, 11499, and 84.8 mg kg^{-1}, respectively. The soil pH in a 1:5 extract was 6.43. It also contained a moderate level of organic matter (2.49%), cation exchange capacity (12.44 cmol kg^{-1}) and available phosphorous (8.19 mg kg^{-1}). Mineral concentrations and soil properties are presented in Table 1.

Based on our previous studies (Sriprachote *et al.*, 2012b), six rice cultivars of different types with varying Cd accumulation abilities were used in this experiment. The rice cultivars were Khao Dawk Mali 105 (KDML105) and RD6 (the prevailing cultivars), and RD5, R15, KNU1, and KNU2 which are the promising low Cd accumulation cultivars. The experiment was conducted in randomized complete blocks designed with 3 replications. Rice seeds were soaked in water for 48 h at room temperature (20–25 °C) and germinated in a nursery. After 30 days, three tillers seedlings were transplanted into 3×3 m experimental plots at the spacing of 30 cm intervals. There were approximately 100 hills per plot. Fertilizers (16-8-8) were applied to the plots at 150 kg ha^{-1} one month after the transplanting. During the growing period, normal field management was performed by local farmers following their traditional cultivation methods.

2.2 Plant sample preparation and analysis

The rice was harvested when it had matured. Approximately 10 hills of rice plants were sampled randomly from each plot. The hulls were removed by hand from the raw grains to reveal whole brown rice. All grain samples were dried at 70 °C in an oven for 72 h. A 0.2 g batch of the sampling rice grains from each hill was digested in 4 mL of HNO_3 and $HClO_4$ (60%, 4:1 by volume) solution in a test tube with a block digester. The digestion was filled to 10 mL with 0.1% (v/v) HNO_3. Cadmium, Fe, and Zn in the solution were analyzed using atomic absorption spectrophotometry (Shimadzu AA-6300) equipped with a graphite atomizer. All results were presented in the form of arithmetic means with standard deviations. The analytical data of the means were examined with Tukey HSD test ($P<0.05$). Linear relationships between traits were determined by Pearson analysis using the SPSS statistical package.

Table 1. Physicochemical properties of soil collected from the Pha Te village paddy field.

Soil properties	Values
$pH_{1:5}$	6.43±0.18[a]
$EC_{1:5}$ (µS cm^{-1})	159±32.1
OM (%)	2.49±0.37
P_2O_5 (mg kg^{-1})	8.19±3.50
CEC (cmol kg^{-1})	12.44±1.96
Extractable bases (mg kg^{-1})	
Ca	1265±229
K	70.1±11.1
Mg	127±35.7
DTPA-extractable (mg kg^{-1})	
Cd	0.40±0.27
Fe	236±38.5
Zn	11.1±6.64
Total element (mg kg^{-1})	
Ca	1273±1377
K	9497±2197
Mg	1439±446
Cd	1.11±0.31
Fe	11499±2335
Zn	84.8±39.8

[a] Data are expressed as mean ± SD, *n* = 30

2.3 Provisional tolerable weekly intake (PTWI)

The provisional tolerable weekly intake (PTWI) of toxic metals is dependent on both the metal concentration in rice or meals and the amount of consumption of the respective food. The PTWI of Cd was determined using the following equation:

$$\text{Weekly intake (WI)} = \frac{\text{Weekly Cd intake μg}}{\text{Body weight (BW) kg}}$$

where the weekly intake (WI) of Cd (µg) is a multiple of rice daily intake (kg day^{-1}) within a week (7 days) and rice grain Cd concentration (µg kg^{-1}). It was assumed that the average rice consumption per day was 0.268 kg which was 53.06 kg in BW for females and 58.54 kg in BW for males (National Bureau of Agricultural Commodity and Food Standards [ACFS], 2016). The PTWI were compared with the tolerable daily intake of Cd at 7 µg Cd per kg BW per week, recommended by Codex Alimentarius Commission (CODEX, 2006).

3. Results

3.1 Cadmium, iron, and zinc concentrations in rice grains

All of the six cultivars were grown successfully to the harvesting stage in Mae Sot paddy fields. Generally, the results of this experiment were consistent with the results of our previous research with regards to the differences among the six rice cultivars in Cd concentration. The concentration of Cd in brown rice ranged from 0.10 to 0.60 mg kg^{-1}, with an average of 0.30 mg kg^{-1} (Figure 1a). The cadmium concentrations of the promising low grain Cd cultivars RD5 (0.22 mg kg^{-1}), RD15 (0.10 mg kg^{-1}), KNU1 (0.22 mg kg^{-1}), and KNU2 (0.10 mg kg^{-1}) were significantly lower than those of the prevailing cultivars KDML105 (0.56 mg kg^{-1}) and RD6 (0.60 mg kg^{-1}).

There was no significant effect on Fe concentration in the grains (Figure 1b). An average concentration of Fe was 12.86 mg kg^{-1} that ranged from 11.17 to 13.91 mg kg^{-1}. The Fe concentrations in the grain of the prevailing cultivars were 11.76 mg kg^{-1} for KDML105 and 13.58 mg kg^{-1} for RD6. The results of the four promising low grain Cd cultivars were 13.91 mg kg^{-1} (RD5), 13.24 mg kg^{-1} (RD15), 11.27 mg kg^{-1} (KNU1), and 13.52 mg kg^{-1} (KNU2).

The average Zn concentration in the grain was 20.83 mg kg^{-1} that ranged from 17.36 to 22.61 mg kg^{-1} (Figure 1c). Significant differences in Zn concentration were apparent in six cultivars ($P<0.05$). The highest Zn concentration was detected in the prevailing cultivar RD6 (22.61 mg kg^{-1}). The lowest Zn concentration was detected in the promising low-grain Cd cultivar KNU1 (17.36 mg kg^{-1}). The grain Zn concentrations in the KDML105, RD5, RD15, and KNU2 were similar at 21.65, 20.24, 21.70, and 21.39 mg kg^{-1}, respectively.

3.2 Grain yields and the correlation of Cd grain concentration

The yields of the six rice cultivars ranged from 4.06 to 6.26 kg plot^{-1}, with an average yield of 5.17 kg plot^{-1}

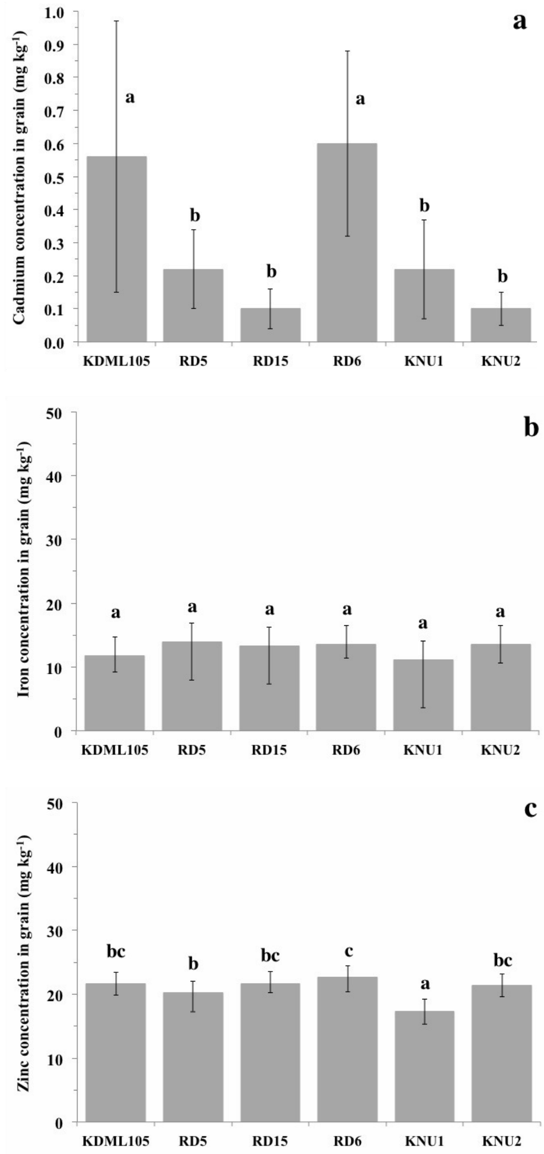

Figure 1. Grain Cd concentrations (a), Fe concentrations in grain (b) and Zn concentrations in grain (c) of 6 rice cultivars grown in a Cd-polluted paddy field. The vertical bars indicate the standard deviation of 30 hills. Any given bar followed by the same letter is not significantly different according to the Tukey HSD test ($P<0.05$).

(Figure 2). The highest yield was from the promising low grain Cd cultivar KNU2 (6.26 kg plot^{-1}) and the lowest yield was from the prevailing cultivar KDML105 (4.06 kg plot^{-1}). There was a negative correlation (r=−0.099) between grain yield and Cd concentration (Figure 3a). However, when the data were grouped into the prevailing cultivar group and the promising cultivar group, a positive correlation (r=0.048) was observed between the amount of Cd and grain yield in the promising low grain Cd cultivars (Figure 3b). Moreover, a negative correlation (r=−0.186) was observed between grain yield and Cd concentration in the prevailing cultivar (Figure 3c). Nevertheless, there was no significant correlation between grain yield and Cd concentration.

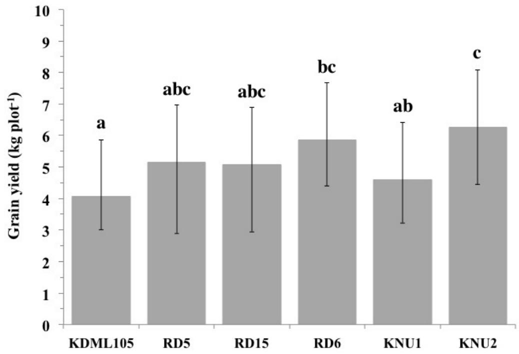

Figure 2. Grain yields of 6 rice cultivars grown in a Cd-polluted paddy field. The vertical bars indicate the standard deviation of 30 hills. Any given bar followed by the same letter is not significantly different according to the Tukey HSD test (P<0.05).

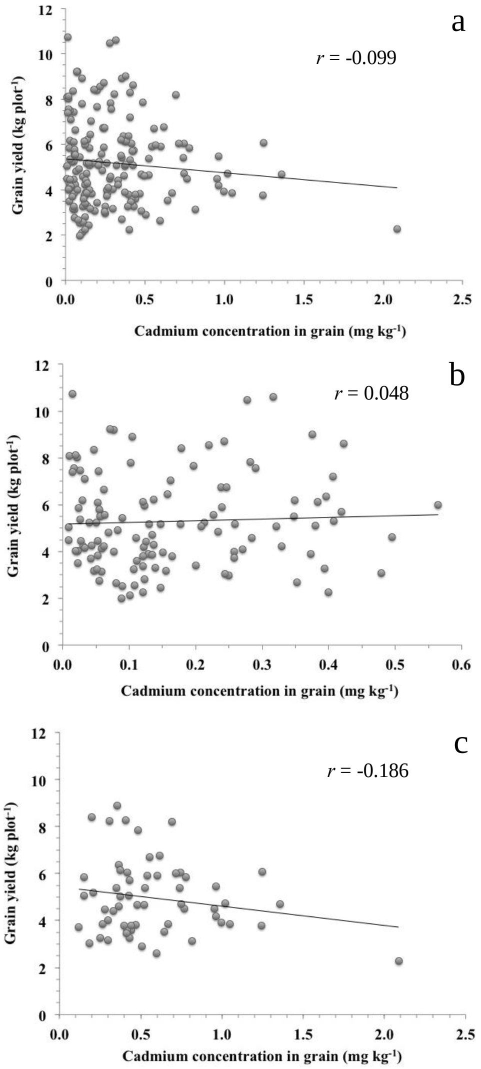

Figure 3. Correlation between grain Cd concentration and grain yield of all data (a), correlation between grain Cd concentration and grain yield in a promising cultivar (b), and correlation between grain Cd concentration and grain yield in a prevailing cultivar (c).

As shown in Figure 4a., considering all of the data, there were significant positive correlations between the grain concentrations of Cd and Zn (r=0.364, P<0.01), and negative correlations between the grain concentrations of Cd and Fe (r=−0.065) (Figure 4a). However, when the data were grouped into the prevailing and the promising groups, a significant positive correlation (r=0. 471, P<0.01) was detected between the Cd and Zn concentrations in the prevailing cultivars (Figure 4b). On the other hand, there was no correlation

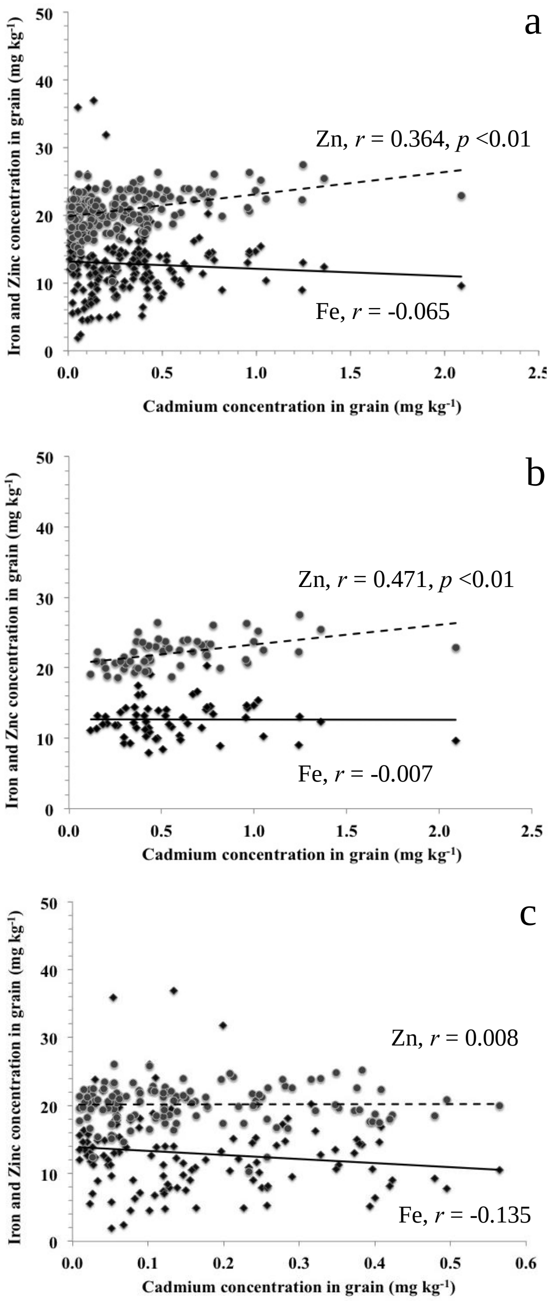

Figure 4. Correlation between grain Cd concentrations and Fe (diamond) and Zn (circle) of all data (a), correlation between grain concentrations of Cd and micronutrient in a prevailing cultivar (b), and correlation between grain concentrations of Cd and micronutrient in a promising cultivar (c).

between the Cd and Fe con-centrations in the grains (r=−0.007) in the prevailing cultivars. Nevertheless, there were no correlations between the grain Cd concentration and Fe (r=−0.135) and Zn (r=0.008) in the promising cultivars (Figure 4c).

3.3 Dietary intake of Cd

The estimated WI values of Cd for adults in the Cd-polluted area through consumption of rice are presented in Table 2. The highest WI of Cd through rice consumption was from the prevailing cultivar RD6 (21.21 and 19.23 μg Cd per BW per week for females and males, respectively). Meanwhile, the lowest WI of Cd was through consumption of the promising cultivar RD15 and KNU2 (3.54 and 3.20 μg Cd per BW per week for females and males, respectively). The calculated PTWI of Cd in rice of the promising cultivars (RD15 and KNU2) was low compared to the FAO/WHO tolerable daily intakes (7 μg Cd per BW per week). The results indicated that the estimated WI values of Cd based on rice grain intake alone exceeded the PTWI value of 7 μg Cd per BW per week, except for two promising cultivars RD15 and KNU2.

Table 2. Estimated weekly intake (WI) of Cd values (μg Cd per kg BW per week) based on rice grain Cd concentrations.

Rice cultivar	Gender[a]	
	Female	Male
RD5	7.79	7.05
RD15	3.54	3.20
KNU1	7.79	7.05
KNU2	3.54	3.20
KDML105	19.80	17.95
RD6	21.21	19.23

[a] Average consumption of rice among a 65-year-old population at 0.268 kg per day: 53.06 kg in BW for female and 58.54 kg in BW for male (ACFS, 2016).

4. Discussion and Conclusions

The concern over safe agricultural products with low heavy metal contents that can be cultivated in slightly and moderately contaminated soils has been increasing. Our previous study revealed that specific rice cultivars (RD5, RD15, KNU1, and KNU2) had significantly lower Cd concentrations than the prevailing cultivars (KDML105 and RD6) when grown in the contaminated paddy fields (Sriprachote *et al.*, 2012b). In the current study, six rice cultivars were grown in the soil with DTPA-extracted Cd content of 0.40 mg kg^{-1}. The results showed that the Cd levels in the grains from rice plants grown in soil even slightly polluted by Cd could be greater than the limit set by CODEX which is 0.4 mg Cd kg^{-1} grain (CODEX, 2006). However, the current results indicated that the grain Cd concentrations in the promising cultivars (RD5, RD15, KNU1, and KNU2) were significantly lower than the prevailing cultivars (KDML105 and RD6). Among the six cultivars, grain Cd concentrations of the prevailing cultivars exceeded the permissible limit of 0.4 mg kg^{-1} (CODEX, 2006). However, grain Cd concentration in all of the promising cultivars was still below the permissible limit, whereas the Cd concentration in the prevailing cultivars was 3.6-fold higher than the promising cultivars. The results suggest the possibility of reducing grain Cd accumulation if the promising cultivars were planted in the Cd-polluted fields with the potential risk of excess Cd concentration.

Norton *et al.* (2009) concluded that grain toxic elements had a strong positive correlation with the yields. Wang (2002) indicated that rice had a strong physiological tolerance to Cd, but Bingham, Page, and Strong (1980) reported that the effect of Cd on the yield of rice varied significantly with soil pH. In the present study, the comparison between the Cd concentration and the grain yields revealed an unrelated correlation (r=−0.099). For the promising cultivars, their grain yields (RD5 = 5.15 kg $plot^{-1}$, RD15 = 5.09 kg $plot^{-1}$, KNU1 = 4.61 kg $plot^{-1}$ and KNU2 = 6.26 kg $plot^{-1}$) were found to have either the same amount or higher than the average grain yield (5.17 kg $plot^{-1}$). In this study, there were remarkable differences among the rice cultivars in terms of their sensitivity to Cd in the formation of grain yield. The promising cultivars were strongly tolerant to Cd-polluted soils (r=0.048), while the prevailing cultivars were sensitive to the soil (r=−0.186). Therefore, grain yields and rice growth appeared to be variety dependent rather than the Cd accumulation in the grains. In addition, some rice cultivars, such as RD15 and KNU2, showed little or no decrease in grain yield when grown in the Cd-polluted paddy fields and contained a very low concentration of Cd in brown rice. Moreover, the estimated weekly Cd intake through rice consumption showed that RD15 and KNU2 could reduce the values of Cd intake (3.54 and 3.20 μg Cd per kg BW per week for female and male, respectively) to lower than the FAO/WHO limit (7 μg Cd per kg BW per week). This study may provide an alternative method to select appropriate rice cultivars for cultivation in Cd-polluted paddy fields.

Humans require at least 23 mineral nutrients for growth and development. The demand for most nutrients can be supplemented by consuming cereals, particularly rice since it is a staple crop. Saenchai, Prom-U-thai, Jamjod, Dell, and Rerkasem (2012) analyzed 15 Thai rice cultivars. The study showed significant differences in Fe (10.2 mg kg^{-1}) and Zn (28.7 mg kg^{-1}) concentrations in the grain. Similar results in rice and other staple crops were also reported (Graham, Senadhira, Beede, Iglesias, and Monasterio, 1999; Jiang *et al.*, 20 08; Yang, Ye, Shi, Zhu, and Graham, 1998). In this study, the average concentrations of Fe and Zn of the brown grain in the promising cultivars were 12.86 and 20.83 mg kg^{-1}, respectively, and there were differences among the rice cultivars. The results showed that the Zn concentration in grain (20.83 mg kg^{-1}) was less than the normal value of Zn (28.7 mg kg^{-1}) in Thai rice, but the grain Fe concentration (12.86 mg kg^{-1}) was still higher than the normal value (10.2 mg kg^{-1}) of Fe concentration in Thai rice. These results further indicated that an effective approach is to screen and select appropriate rice cultivars to improve the nutritional status of the grain. However, considering the grain micronutrient status together with Cd loadings, it showed that the Cd loadings could limit the mineral nutrient accumulation in grain. The interaction between Cd and micronutrients during the uptake and distribution of the crops is a public concern. This is because the amount of metal is closely associated with the quality of nutrition and the safety of the rice.

Cadmium is phytotoxic and may lead to changes in concentration and composition of plant nutrients. The interactions of Cd and metal nutrients, such as Fe, Zn, Cu, and Mn were identified in some crops, such as wheat (Zhang *et al.,* 2002), barley (Wu *et al.,* 2003) and rice (Cheng, Yao, Zhang, & Tao, 2009). The results of this study showed that Cd had a positive, significant effect on Zn accumulation (r=0.364, P<0.01) in grains. In contrast, it had negative effects on Fe accumulation (r=−0.065). Furthermore, the prevailing cultivars had higher increases in Fe and Zn accumulations in rice grains due to Cd presence than the promising cultivars. The Zn concentration was also significantly correlated with the Cd concentration in the grain (r=0.471, P<0.01). The results implied that some synergistic interaction existed in absorption and translocation between Cd and Zn for the prevailing cultivars, but not for the promising cultivars. Moraghan (1993) reported a synergistic interaction between Cd and Zn. However, there were also contradictory reports on the relationship between Cd and Zn. Many reports concluded that Cd addition caused a decrease in Zn concentrations in corns and tomatoes (Mahler, Bingham, Page, & Ryan, 1982; Root, Miller, & Koeppe, 1975), barley (Wu *et al.,* 2003), and rice (Cheng *et al.,* 2009). However, in these studies, the concentrations of Fe in the rice grains were stable. Our studies also showed that Cd accumulation could not influence the accumulation of Fe and Zn in rice grains for the promising cultivars. The present results identified some rice cultivars (RD15 and KNU2) with reduced Cd but high in Fe and Zn. This study suggested a possible way to culture rice on Cd-polluted paddy fields. It also ensured rice safety and offered a way to solve the nutrient deficiency problems.

Acknowledgements

This research was supported by a grant from the Ministry of Agriculture, Forestry, and Fisheries of Japan (Molecular cloning and characterization of agronomically important genes of rice IPG0007) and a grant from the Japan Society for the Promotion of Science (Grant-in-Aid for Scientific Research [B] 23405021).

References

Arao, T., & Ae, N. (2003). Genetic variations in cadmium levels of rice grain. *Soil Science and Plant Nutrition, 49*(4), 473–479.

Bingham, F. T., Page, A. L., & Strong, J. E. (1980). Yield and cadmium content of rice grain in relation to addition rates of cadmium, copper, nickel with sewage sludge and liming. *Soil Science, 130,* 32-38.

Cataldo, D. A., Garland, T. R., & Wildung, R. E. (1983). Cadmium uptake kinetics in intact soybean plant. *Plant Physiology, 73,* 844–848.

Cheng, W. D., Yao, H. G., Zhang, H. M., & Tao, X. H. (2009). Influences of cadmium on grain mineral nutrient contents of two rice genotypes differing in grain cadmium accumulation. *Rice Science, 16*(2), 151–156. doi:10.1016/S1672-6308(08)60072-4

Codex Alimentarius Commission. (2006). Joint FAO/WHO Food Standards Programme Codex Alimentarius Commission Report of the 29th Session. Retrieved from http://www.codexalimentarius.net/web/archives.jsp?year=06

Graham, R., Senadhira, D., Beede, S., Iglesias, C., & Monasterio, I. (1999). Breeding for micronutrient density in edible portions of stable food crops: conventional approaches. *Field Crops Research, 60,* 57–80.

Hotz, C., & Brown, K. H. (2004). International zinc nutrition consultative group (IZiNCG) technical document No. 1. Assessment of the risk of zinc deficiency in populations and options for its control. *Food and Nutrition Bulletin, 25*, S94–S203.

Jiang, S. L., Wu, J. G., Thang, N. B., Feng, Y., Yang, X. E., & Shi, C. H. (2008). Genotypic variation of mineral elements contents in rice (*Oryza sativa* L.). *European Food Research and Technology, 228*, 115–122. doi:10.1007/s00217-008-0914-y

Liu, J., Zhu, Q., Zhang, Z., Xu, J., Yang, J., & Wong, M. H. (2005). Variations in cadmium accumulation among rice cultivars and types and the selection of cultivars for reducing cadmium in the diet. *Journal of Science of Food and Agriculture, 85*, 147–153. doi:10.1002/jsfa.1973

Mahler, R. J., Bingham, F. T., Page, A. L., & Ryan, J. A. (1982). Cadmium enriched sewage sludge application to acid and calcareous soils: Effect on soil and nutrition of lettuce, corn, tomato and swiss chard. *Journal of Environmental Quality, 11*(4), 694–700.

Moraghan, J. T. (1993). Accumulation of cadmium and selected elements in flax seed grown on a calcareous soil. *Plant Soil, 150*(1), 61–68. doi:10.1007/BF779176

Morishita, T., Fumoto, N., Yoshizawa, T., & Kagawa, K. (1987). Varietal differences in cadmium levels of rice grains of japonica, indica, javanica and hybrid varieties produced in the same plot of a field. *Soil Science and Plant Nutrition, 33*, 629 – 637.

National Bureau of Agricultural Commodity and Food Standards. (2016). Food consumption data of Thailand. Retrieved from http://www.acfs.go.th/document/download_document/FCDT.pdf

Norton, G. J., Islam, M. R., Deacon, C. M., Zhao, F. J., Stroud, J. L., McGrath, S. P., Meharg, A. A. (2009). Identification of low inorganic and total grain arsenic rice cultivars from Bangladesh. *Environmental Science and Technology, 43*(15), 6070–6075. doi:10.1021/es901121j

Root, R. A., Miller, R. J., & Koeppe, D. E. (1975). Uptake of cadmium: Its toxicity, and effect on iron ratio in hydroponically grown corn. *Journal of Environmental Quality, 4*(4), 473–476.

Saenchai, C., Prom-u-thai, C., Jamjod, S., Dell, B., & Rerkasem, B. (2012). Genotypic variation in milling depression of iron and zinc concentration in rice grain. *Plant Soil, 361*(1), 271–278. doi:10.1007/s11104-012-1228-1

Simmons, R. W., Pongsakul, P., Saiyasipanich, D., & Klinphoklap, S. (2005). Elevated levels of cadmium and zinc in paddy soils and elevated levels of cadmium in rice grain downstream of zinc mineralized area in Thailand: Implication for public health. *Environmental Geochemistry and Health, 27*, 501–511. doi:10.1007/s10653-005-7857-z

Smith, G. C., & Brennan, E. G. (1983). Cadmium-zinc interrelationships in tomato plants. *Physiology and Bio-chemistry, 73*(6), 879-882.

Sriprachote, A., Kanyawongha, P., Ochiai, K., & Matoh, T. (2012a). Current situation of cadmium-polluted soil, rice and soybean in the Mae Sot District, Tak Province, Thailand. *Soil Science and Plant Nutrition, 58*(3), 349–359. doi:10.1080/00380768.2012.686435

Sriprachote, A., Kanyawongha, P., Pantuwan, G., Ochiai, K., & Matoh, T. (2012b). Evaluation of Thai rice cultivars with low-grain cadmium. *Soil Science and Plant Nutrition*, *58*(5), 568–572. doi:10.1080/00380768.2012.715070

Wang, K. R. (2002). Tolerance of cultivated plants to cadmium and their utilization in polluted farmland soils. *Acta Biotechnology*, *22*, 189–198. doi:10.1002/1521-3846(200205)

Wu, F. B., Zhang, G. P., & Yu, J. S. (2003). The interaction of Cd and four microelements in uptake and translocation in barley and as affected by genotypes. *Communications in Soil Science and Plant Analysis, 34*, 2003–2020. doi:10.1081/css-120023233

Yang, X., Ye, Z. Q., Shi, C. H., Zhu, M. L., & Graham, R. D. (1998). Genotypic differences in concentrations of iron, manganese, copper, and zinc in polished rice grains. *Journal of Plant Nutrition*, *21*(7), 1453–1462. doi:10.1080/01904169809365495

Yu, H., Wang, J., Fang, W., Yuan, J., & Yang, Z. (2006). Cadmium accumulation in different rice cultivars and screening for pollution-safe cultivars of rice. *Science of the Total Environment*, *370*, 302–309. doi:10.1016/j.scitotenv.2006.06.013

Zeng, F., Mao, Y., Cheng, W., Wu, F., & Zhang, G. (2008). Genotypic and environmental variation in chromium, cadmium and lead concentrations in rice. *Environmental Pollution*, *153*(2), 309–314. doi:10.1016/j.envpol.2007.08.022

Zhang, G. P., Fukami, M., & Sekimoto, H. (2002). Influence of cadmium on mineral concentrations and yield components in wheat genotypes differing in Cd tolerance at seedling stage. *Field Crops Research, 77*, 93–98.