Short Communication

Selecting for Cadmium Exclusion or Low Accumulation Rice Cultivars in Slight-Moderate Pollution Area under Field Conditions

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Abstract

It is a simple but effective measure to ensure food security by planting rice cultivars with low accumulation ability of heavy metals, especially with Cd-exclusive ones. Eighty-nine pairs of soil and 17 main rice cultivars from the slight-moderate Cd-pollution paddy field in Chengdu Plain were randomly collected. The Cd content in brown rice, Cd enrichment, translocation factors, and rice yield were studied for screening rice cultivars with low Cd uptake and accumulation in a slightly moderate Cd-pollution environment. The results showed that cadmium content in different parts of rice varies in a large range. Cadmium content in brown rice ranged from 0.05 mg·kg^{-1} to 0.48 mg·kg^{-1}, specifically from 0.01 mg·kg^{-1} to 0.19 mg·kg^{-1} in chaff. Among the 17 main rice cultivars, the content of Cd in brown rice of Kyou 817 was 0.46 mg·kg^{-1}, which lay in the highest level, while the Cd content in brown rice of Aiyou 82, Jinyou 527, Gangyou 22, Fuyou 130, IIyou 906, Yixiangyou 1577, Jinyou 725, and Fuyou 838 were lower than national maximum level (0.2 mg·kg^{-1}). Cadmium content in brown rice, chaff, and straw of Aiyou 82 were notably lower than the average value. The Cd content in roots of IIyou 906 reached a relatively high level, but the rest is lower than the average. The enrichment factors of straw in Fuyou 130 and Jinyou 725 (EFs>0.6) were relatively higher than the average. The straw of Fuyou 130, Yixiangyou 1577, and Jinyou 725 had a stronger ability of Cd translocation (translocation factors >0.45, TFs), which exceeded the average. The yield of Aiyou 82 was lower than the average in 90% level, which was remarkably low. In conclusion, IIyou 906 was the most ideal rice cultivar by evaluating the Cd content in brown rice, EFs and TFs in straw, and yield levels. As for Fuyou 130, special attention should be paid to reduce the risk of Cd pollution in straw returning. Gangyou 22, Jinyou 527, and Fuyou 838 presented lower yields or lighter Cd-resistance ability aboveground.

Keywords: cadmium (Cd), rice cultivars, exclusion characteristic, low-Cd accumulation

Introduction

Cadmium (Cd) is a dispensable element for plants and animals, and has a poisonous effect on the human body, even likely to cause pathological changes [1]. Among all the pollution elements, Cd has the strongest translocation ability and can be easily absorbed by plants and accumulated in the food chain causing great harm to humans and animals [2]. In China, 1.46×10^{8} kg agricultural products from the 1.3×10^{5} km^{2} soils are polluted by industry or agricultural pollution every year [2].

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As the main crop, rice yields reached 560 Tg annually around the world, 40% of which was produced and consumed in China [2]. With the fast development of industrialization and urbanization, a large amount of arable soil may be polluted by heavy metals, exhibiting a serious influence on rice production and great harm to human health. Up to now, the overall situation of heavy metal pollution in China's arable soil was generally safe, while some areas had a higher risk of heavy metal pollution [3]. Straw returning was generally regarded as an effective measure to increase production by enhancing soil fertility [4, 5]. It can enhance and maintain soil fertility notably by improving soil organic matters [6-8]. The heavy metals were up-taken in rice from the soil, mainly deposited in the root, and some of it translocated into the stalk and chaff [9]. The stalk and chaff were used by livestock feeding or direct field returning, in which cases the heavy metal Cd enters in the farmland system again. The decomposition and conversion process of the straw has an observable effect on the bioavailability of Cd in the soil [10]. Therefore, how to avoid Cd accumulation in the chaff and stalk, and reduce the translocation of Cd between the underground and aboveground in rice, was an important research project that may provide some insight into reducing Cd pollution in soil and crops.

Just like genotype differences in mineral nutrition, the crop's ability in Cd absorbing and accumulating varies evidently among species and populations [6]. Though some crop cultivars possess an over-endurance against high levels of heavy metal pollution, the accumulated heavy metals in their aboveground parts create some hidden ecological risk. During crop production, Cd-resistance crop cultivar was more likely to be planted on a large scale for its resistance ability to keep the heavy metals in soil, and to prevent them from entering the food chain. So its aboveground and edible parts contain relatively low levels of heavy metals [11]. Based on genotype difference, the breeding of Cd-resistance and low-Cd accumulation in the edible part was achieved successfully in sunflower and durum [12], which makes it possible to reduce the harm of Cd in soil and ensure safe agricultural production by a crop's hereditary character. Previous studies showed that in the slightly moderately Cd-polluted area in Chengdu Plain, Cd content in rice varied in a much larger range [13-15]. Thus showed, it may greatly reduce the risk of rice Cd-pollution by selecting Cd-resistance and low-Cd accumulation rice cultivar. Accordingly, research on Cd resistance and low-Cd accumulation rice cultivar selection was made in slightly moderate Cd-polluted areas in Chengdu Plain.

Materials and Methods

Study Area, Sample Collection, and Preparation

Chengdu Plain, located in the western Sichuan basin, is the largest plain in southwestern China, with an area of 8,000 km^2. The study area was in the core of the agricultural and economic region, including Deyang, Guanghan, Xindu, Penzhou, Pixian, Wenjiang, Shuangliu, Chongzhou, Qionglai, and so on. A more detailed description of the study site was reported in previous publications [15, 16]. Results of a previous study showed that the content of Cd in the study area was 2.25 times higher than the geochemical background [15]. More than 40% and about 10% of soil samples were higher than the first and second criteria (GBl5618-1995) level of the National Environmental Quality Standard for Soils (P. R. C) [15].

Table 1. Rice cultivars collected under field conditions in Chengdu Plain*.

Rice cultivar	Rice cultivar	Rice cultivar
Ai You 82 (AY82) (n=4)	Gang You 22 (GY22) (n=8)	Xie You 527 (XY527) (n=3)
Chuan Xiang You 6 (CXY6) (n=3)	Gang You 3551 (GY3551) (n=4)	Yi Xiang You 1577 (YXY1577) (n=4)
IIYou 906 (EY906) (n=9)	Gang You 725 (GY725) (n=7)	Yi Xiang You 3003 (YXY3003) (n=4)
Feng Xiang You Zhan (FXYZ) (n=4)	Jin You527 (JY527) (n=6)	Zhong You 177 (ZY177) (n=3)
Fu You 130 (FY130) (n=6)	Jin You725 (JY725) (n=4)	Zhong You 838 (ZY838) (n=4)
Fu You 838 (FY838) (n=13)	K You 817 (KY817) (n=3)	

*Arabic numeral in brackets indicate the quantity of sample groups.

A total of 89 soil and homologous rice samples were collected for this work, including 17 rice cultivars (Table 1). The selected samples designed by the spatial distribution of total and labile fractions of Cd in soil, distribution, and variation of rice cultivars in Chengdu Plain. Surface soil samples (0~20 cm) were collected, dried by air, ground in a centrifugal ball mill to homogenize, sieved to ≤ 1mm and ≤ 0.149 mm, and stored in a polyethylene container unit.

Seventeen rice cultivars of different types from different sites (Table 1) were collected from the slightly moderate Cd-pollution area in Chengdu Plain. The rice plant was harvested at maturity and pulled from the farmland. The rice grain yield and other information were investigated in the field. The root, straw, and rice grains were separated. The root was washed thoroughly with tap water and deionized water. The root, straw, and grain were oven-dried at 65~70ºC to constant weight. The chaff of the grain was removed with a chaff-removing machine, and the chaff and brown rice were weighed separately. The ovendried samples were ground in a stainless steel grinder to pass through a 60-mesh sieve.

Table 2. Descriptive statistics of Cd concentrations (mg·kg^{-1} dry weight) in different parts of rice*.

Parts of rice	Min.	Max.	Average	S. D.**	C.V(%)***
Brown rice	0.05	0.48	0.20	0.11	55.00
Chaff	0.01	0.19	0.06	0.05	83.33
Straw	0.03	0.51	0.14	0.09	64.29
Root	0.16	0.97	0.49	0.21	42.86

*Data based on the 89 samples, **standard deviation, ***coefficient of variation

Sample Analysis and Data Process

The soil and plant samples were digested within HNO_3-$HClO_4$-HF and HNO_3-H_2O_2 digestion, respectively [17]. The Cd concentrations were determined with an atomic absorption spectrophotometer (AA-6701F+ Graphite Furnace System 6500, SHIMADZU, Japan). Certified standard Cd solution was used to ensure precision of the analytical procedures (GBW07403 for soil; GBW07603 for plant), the certified standard reference material was obtained from the National Research Center for CRM, China.

To compare the relative response of rice cultivars in different Cd exposures, the index of enrichment factors (EFs) and translocation factors (TFs) were calculated. Enrichment factors (EFs) was the ratio of Cd concentration in plant shoot to soil, which indicated the potential of plants accumulating Cd. Lower EFs means lower accumulation potential of heavy metal to plant. Translocation factors (TFs) was the ratio of Cd concentration in shoots to roots, which indicated the capacity of plant transfer Cd. Lower value of TFs showed weak transport potential of heavy metals.

Data were analyzed using SPSS 13.0 for Windows statistical package. T-test was followed by (ANOVA), and significant differences detected between the samples and the average.

Results

Variations in Cd Accumulation and Distributions among Rice Cultivars

The rice Cd content varied in different parts and the variation extent differed. Specifically, the root contained the highest level of Cd, while the chaff had the lowest. The variation coefficient of Cd content in the straw and the chaff varied most dramatically (Table 2). Range of Cd content in root was 0.16 mg·kg^{-1} to 0.97 mg·kg^{-1}, the brown rice was 0.05 mg·kg^{-1} to 0.48 mg·kg^{-1}, the straw was 0.04 mg·kg^{-1} to 0.51 mg·kg^{-1}, and the chaff was 0.01 to 0.19 mg·kg^{-1}.

The frequency distribution of Cd content in brown rice showed that the Cd content of the brown rice planted in the slightly moderate pollution area mainly ranged from 0.05 mg·kg^{-1} to 0.10 mg·kg^{-1} and from 0.20 mg·kg^{-1} to 0.30 mg·kg^{-1}. These two distribution ranges respectively accounted for 31.46% and 35.96% of the investigated samples (Fig. 1). Samples that were over national maximum level (Cd content ≤ 0.20 mg·kg^{-1}) accounted for 53.93% and those higher than 0.30 mg·kg^{-1} accounted for 17.98%.

The Cd content in brown rice between rice cultivars showed (Table 3) that nine of the rice cultivars planted in the Cd excessive farmland (the average of Cd content was 0.39 mg·kg^{-1} in soil, which ranged from 0.23 mg·kg^{-1} to 0.62 mg·kg^{-1}) were out-of-limit (the nation maximum level was 0.2 mg·kg^{-1}). Among those cultivars (Kyou 817, Xieyou 527, Zhongyou 838, Fengxiangyouzhan, and Zhongyou 177), the Cd content in brown rice were over 0.3 mg·kg^{-1}, amounting to serious pollution. Cd content in brown rice of Kyou 817, Xieyou 527, and Fengxiangyouzhan were significantly higher than the average level of that in 17 rice cultivars. There were 8 rice cultivars with low Cd content in brown rice (Aiyou 82, Jinyou527, Gangyou 22, Fuyou 130, IIyou 906, Yixiangyou 1577, Jinyou 725, and Fuyou 838) planted in the area of Cd content ranges from 0.36 mg·kg^{-1} to 0.45 mg·kg^{-1}. Those rice cultivars had a lower Cd content level in brown rice (<0.2 mg·kg^{-1}), which were categorized into cultivars with weak ability of Cd uptake and accumulation. And, specifically, the brown rice Cd content of Aiyou 82, Jinyou 527, and IIyou 906 were notably lower than the average level of all the samples.

In addition, the Cd average content in chaff was generally low, which varied from 0.02 mg·kg^{-1} to 0.17 mg·kg^{-1}. The Cd content in straw ranged from 0.04 mg·kg^{-1} to 0.29 mg·kg^{-1}, and that was significant among the rice cultivars. The roots had the strongest ability of Cd enrichment, and the Cd content ranged from 0.25 mg·kg^{-1} to 0.83 mg·kg^{-1}. The Cd content in roots of Fuyou 130, Yixiangyou 3003, and Zhongyou 838 were over 0.60 mg·kg^{-1}.

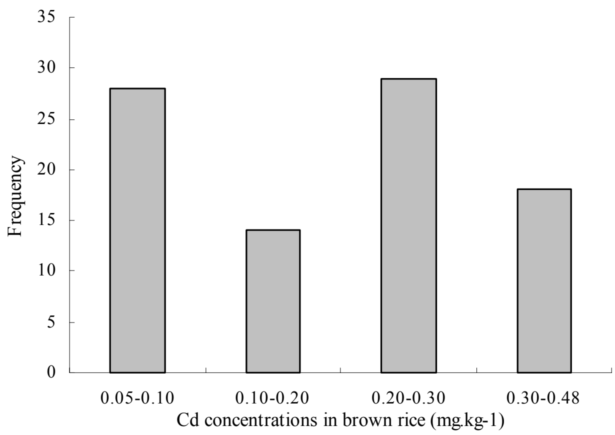

Fig. 1. Frequency of the Cd concentrations in brown rice.

Table 3. Cadmium (Cd) concentrations (mg·kg^{-1}) in the rice cultivars#.

Rice Cultivars	Brown rice	Chaff	Straw	Root
Ai You 82	0.08±0.04**	0.03±0.01**	0.06±0.02**	0.40±0.03**
Chuan Xiang You 6	0.23±0.05	0.02±0.01*	0.04±0.01**	0.34±0.13
II You 906	0.15±0.07*	0.03±0.02**	0.09±0.03**	0.44±0.21
Feng Xiang You Zhan	0.30±0.04**	0.04±0.02	0.16±0.09	0.52±0.15
Fu You 130	0.13±0.07	0.07±0.05	0.24±0.13	0.60±0.22
Fu You 838	0.19±0.08	0.07±0.06	0.13±0.06	0.49±0.20
Gang You 22	0.13±0.07*	0.06±0.03	0.13±0.06	0.43±0.19
Gang You 3551	0.23±0.12	0.07±0.05	0.12±0.06	0.51±0.26
Gang You 725	0.21±0.10	0.06±0.03	0.12±0.05	0.43±0.16
Jin You527	0.11±0.07*	0.05±0.02	0.17±0.10	0.59±0.21
Jin You725	0.19±0.10	0.10±0.03	0.29±0.17	0.57±0.21
K You 817	0.46±0.01**	0.02±0.01**	0.05±0.01**	0.34±0.08**
Xie You 527	0.36±0.01**	0.17±0.01**	0.17±0.02	0.55±0.19
Yi Xiang You 1577	0.15±0.07	0.11±0.07	0.09±0.03*	0.25±0.10*
Yi Xiang You 3003	0.21±0.12	0.07±0.04	0.22±0.18	0.83±0.06**
Zhong You 177	0.30±0.05	0.03±0.02	0.15±0.04	0.38±0.16
Zhong You 838	0.33±0.17	0.03±0.02*	0.15±0.09	0.66±0.26

All data are the means± standard deviation.
** and * significant difference at 0.01 and 0.05 levels by one sample T-test, compared to average, respectively. The same as follow.

In a word, the Cd contents in brown rice, chaff, straw, and root of Aiyou 82 were notably lower than the other rice cultivars planted in the same region. Except for the root, the other parts of IIyou 906 absorbed lower or much lower Cd compared with the average level. As for Kyou 817, the Cd content in brown rice was notably higher than the average level in the region, and the other parts were lower than the other rice cultivars. The Cd content of brown rice and chaff in Xieyou 527 were remarkably higher than the other cultivars. The Cd content of straw and root in Yixiangyou 1577 was notably lower than the average, while the Cd content of root in Yixiangyou 3003 was dramatically over the average level.

Characteristic of Cd Enrichment and Translocation in Straw

The enrichment factors (EFs) of the 17 rice cultivars varied most dramatically, ranging from 0.09 to 0.70 (Fig. 2). The rice cultivars with EFs above 0.4 were Jinyou 725, Fuyou 130, Yixiangyou 3003, Zhongyou 177, and Xieyou 527, and the straws of Jinyou 725 and Fuyou 130 had the apparent enrichment ability in EFs above 0.6. The rice cultivars with relatively low EFs were Kyou 817, Aiyou 82, and Chuanxiangyou 6, the Cd contents in straw were lower than 20% of Cd content in soil. The translocation factors (TFs) of the 17 cultivars were all lower than 0.5, and the average level was 0.32. YixiangyYou 1577, Fuyou 130, Yixiangyou 3003, Jinyou 725, and Zhongyou 177 had relative stronger translocation ability of Cd in the root and the EFs were 0.4~0.5. The rice cultivars with a weaker translocation ability for Cd in the root included K You 817, Chuanxiangyou 6, Aiyou 82, and IIyou 906. The TFs were below 0.25.

Grain Yield Analysis

The grain yields of Yixiangyou 3003, Aiyou 82, and Chuanxiangyou 6 were 95% lower than the average level of 8,420 kg·hm^{-2} in the region (Fig. 3). The grain yields of Aiyou 82 and Yixiangyou 3003 were both notably lower than the average, which were difficult to be planted on a large scale. There was a little gap (around 5%) of the grain yield among Fengxianyouzhan, Zhongyou 838, Fuyou 838, and Kyou 817, relative to the average yield in the area. The grain yield of the other 10 rice cultivars were higher than the average grain yield, and the grain yield of Fuyou 130, Gangyou 22, and Jinyou 527 yield were higher than the average level significantly. The grain yield of Fuyou 130 was 1.14 times of the average grain yield level (8,420 kg·hm^{-2}) in the region, which was the highest yield.

Discussion

In China, about 20 million hectares in arable soil, which accounts for 1/6 of the total amount of arable soil, were under the threat of pollution by heavy metals. 89% of the soil in Guangdong had been polluted in different degrees, about 77% of which had been slightly polluted [18]. According to the research of Zhen et al., 10% of the 91 polished rice samples collected in China reached the out-of-limit Cd [19]. In recent years some studies have concentrated on the genotype difference of crops, including rice for the uptake and accumulation of heavy metals and the uptake and accumulation of physiology features [20-25]. More importance had been attached to safe agricultural production on the slightly moderately polluted soil. In this situation, it can be deemed as a feasible and effective measure to select and breed crop cultivars with low-accumulation or high-endurance in heavy metals.

The evaluation indicators in selecting and breeding low-uptake/enrichment crop cultivars include the effectiveness of soil heavy metal, endurance to heavy metal, and difference among varieties. The evaluation can be conducted in the field environment or by pot/water culture experiment. Field research or field experiment was often regarded as the important method in the study of the ecological scopes of environmental pollution, for it is easy to carry out and fit real-life production. This study showed that, in the slight-moderate Cd-pollution areas (soil Cd content was 0.23 $mg\cdot kg^{-1}$ to 0.62 $mg\cdot kg^{-1}$), Cd content in different parts of rice from the highest to the lowest were as follows: root>>brown rice>straw>chaff. Different rice cultivars performed significant variation in the uptake and accumulation

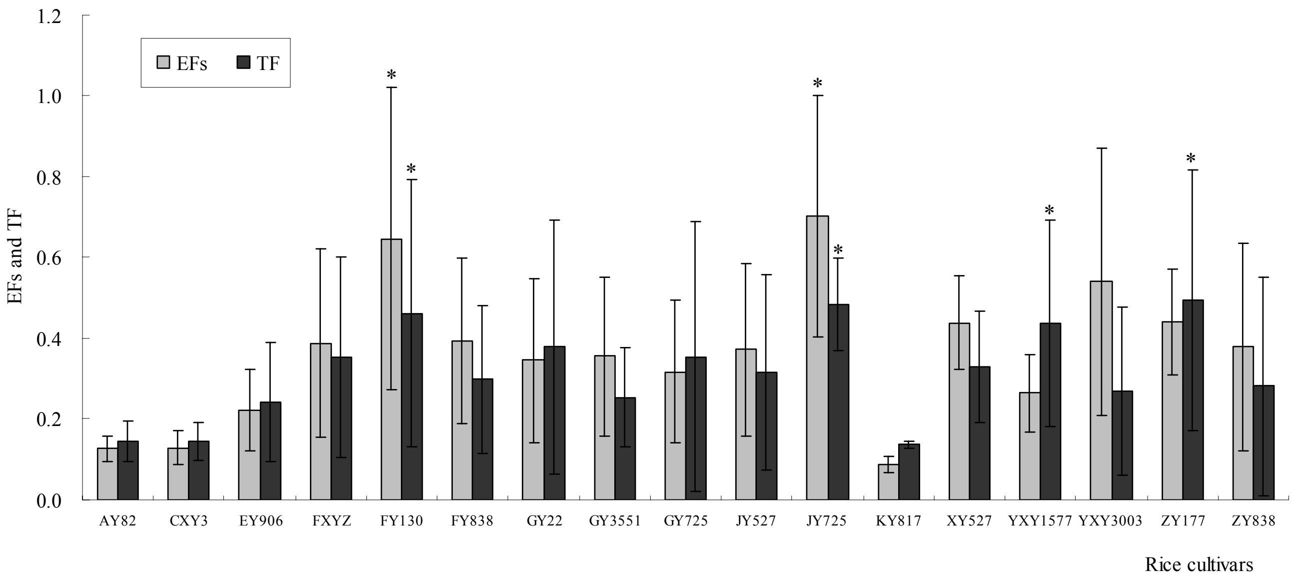

Fig. 2. EFs and TF of 17 rice cultivars selected in the slight-moderate pollution of Cd.

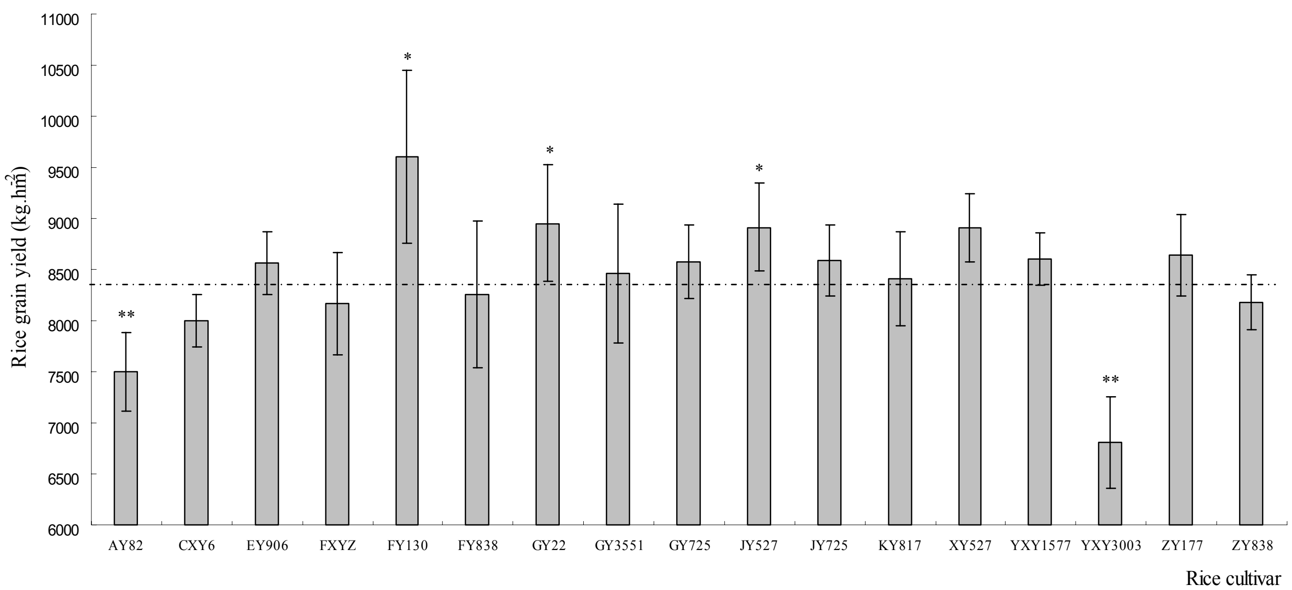

Fig. 3. Rice grain yield of different cultivars ($kg\cdot hm^{-2}$). Values are means ± S.D. of rice cultivars.

of Cd. Eight rice cultivars, including Aiyou 82, Jinyou 527, Gangyou 22, Fuyou 130, IIyou 906, Yixiangyou 1577, and Jinyou 725, had lower Cd content in brown rice than the maximum-standards (<0.20 mg·kg^{-1}), which satisfied the National Limit Standard of Contaminants in Food. Therefore, those 8 rice cultivars were qualified to be planted in the slightly moderate Cd-pollution environment.

The enrichment factors (EFs) reflect to some extent of the crop's potential enrichment ability in heavy metals. A high EF indicated the large accumulation of heavy metals and potential biological cluster [26, 27]. The translocation factor (TF) was often used to indicate the crop's ability to translocate heavy metals. The EFs and the TFs can be employed as major quantitative indicators in screening heavy metal-resistant crop varieties for lower pollution risk [11, 26-28]. In this research, the Cd enrichment and translocation ability in straw was relatively poor. Specifically, the EFs and TFs of Kyou 817, Aiyou 82, Chuanxiangyou 6, IIyou 906, and Gangyou 3551 were lower than the average level (EFs<0.36, TF<0.32) in the region that qualified them to be planted in Chengdu Plain. Under general circumstances, biomass was one of the important indicators in screening crops with heavy metal hyperaccumulation ability. The agronomy trait of rice, esp. the yield, was a major consideration for rice cultivar popularization. Based on the actual situation in rice planting, the average output was employed as the indicator in the optimization and popularization in rice cultivars. So, screening out low heavy metal-uptake and accumulation rice cultivar with relative high yield was the precondition for ensuring appropriate rice production and harmless to personal health. The study indicated that the yields of Jinyou 527, Gangyou 22, IIyou 906, Yixiangyou 1577, and Jinyou 725 exceeded the average output of 8,420 kg·hm^{-2} in the study area. What's more, the Cd content in brown rice was lower than 0.2 mg·kg^{-1} (the National Limit Standard of Contaminants in Food), so that those rice cultivars may be taken as alternatives for popularization.

The heavy metal uptake and accumulation abilities of crops were influenced by environmental conditions and genotype differences. According to the report by Grant et al., Cd-accumulation ability of the durum wheat with Cd-resistance, low Cd-accumulation was controlled by one single gene [12]. Their study showed that OsHMA3 could make the rice retain the Cd taken up within its root cells [29]. So we can make contributions to agricultural production by inserting those key genes, which can control Cd uptake and accumulation in crops.

Conclusion

In the slightly-moderate Cd-pollution paddy soil in Chengdu Plain, 89 pairs of soil-rice samples of 17 main cultivars were studied. The results indicated that the Cd content in all of the brown rice was little higher than the limit level in China (<0.2 mg·kg^{-1}). Over 50% of the rice cultivars were polluted by cadmium, the Cd content of brown rice in Kyou 817, Xieyou 527, and Zhongyou 838 exceeded dramatically, to be over 0.3 mg·kg^{-1}. The Cd contents of brown rice in Aiyou 82, Jinyou 527, Gangyou 22, Fuyou130, IIyou 906, Yixiangyou 1577, and Jinyou 725 were lower than the limit level of 0.2 mg·kg^{-1}.

In a word, considering the Cd content in brow rice, relative Cd-enrichment/translocation factors, and grain yield, IIyou 906 has proven to be the best choice in popularization. The Fuyou 130 showed lower Cd content in brown rice, but its EFs (EFs=0.65) and TFs (TF=0.46) were both relatively higher, and the risk of Cd pollution during the straw returning should be given more attention in paddy soil.

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