Spatial Distribution and Risk Management of Heavy Metal Contamination in Japan

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1. Introduction

Soil pollution and crop contamination by cadmium (Cd) and Arsenic (As) are widely-known and recognized as a global threat to sustainable life and the environment. Various factors contribute to soil pollution, including pollutants factor: sources of pollutants, pollutant pathways, the medium of pollution, and soil factor. Japanese agricultural soils in some region, have been heavily polluted with cadmium (Cd) and various other heavy metals, owing to fast industrialization during the 1960s. The Japanese government urgently enacted the Agricultural Land Soil Pollution Prevention Law in 1970 to cope with the heavy metal pollution, in which Cd, arsenic (As), and copper (Cu) were designated as the targeted hazardous substances for regulation. Cd, in particular, has been recognized as one of the most detrimental elements in Japan, because of the so-called itai-itai disease caused by Cd. Flooded cultivation for 3 weeks before and after ear emergence has been recommended to reduce cadmium (Cd) concentrations in rice grains to below permitted values (0.4 mg kg⁻¹) in some regions of Japan. In 2014, the Codex Alimentarius Commission proposed a maximum permitted concentration for inorganic As in polished rice of 0.2 mg kg⁻¹. However, in contrast to Cd uptake, As uptake by rice plants is markedly increased by flooded cultivation. Thus, there is a tradeoff between As and Cd uptake by rice depending on the type of water management. Promising practical techniques to simultaneously attenuate As and Cd in rice grain are urgently required.

The present study will provide an overview of heavy metal contamination in Japan and state of the art technologies to alleviate Cd and As contamination in soils and crops, which include; (1) breeding of low adsorptive cultivars, (2) phytoremediation of the polluted soil by rice plant, (3) chemical remediation of Cd-polluted soil by soil-washing and, (4) promising methods simultaneously decrease concentrations of As and Cd in rice grains.

2. Concentration of Heavy metal in Japanese soils

The natural abundance levels of some heavy metals in Japanese and world soils are given in the Table 1. The ranges are very wide; there are more than 100 times’ difference in the ratio of the highest value to the lowest. The heavy metal concentration in Japanese soil is similar to that in the world soil. However, some areas are highly polluted by a kind of heavy metals. The pollution of arable soils by heavy metals is primarily caused by wastewater from mines, which has been used for irrigation water to paddy fields and emissions from nonferrous metal refining plants. Human exposure to the heavy metal risk mainly arises from ingestion of the crops grown in polluted soil and from drinking water contaminated with some hazardous heavy metals.

Table 1. Natural abundance of heavy metals in Japanese soil and brown rice (Average: mg kg⁻¹).

<table>
<thead>
<tr>
<th>Substance</th>
<th>Surface Soil</th>
<th>Paddy soils</th>
<th>Brown rice</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Japan(1)</td>
<td>World(2)</td>
<td>Brown rice(3)</td>
</tr>
<tr>
<td>Cr</td>
<td>58 (1.4-233)</td>
<td>63.7 (1-1500)</td>
<td>64 –</td>
</tr>
<tr>
<td>Co</td>
<td>18 (0.2-61.3)</td>
<td>9.62 (0.1-275)</td>
<td>9 –</td>
</tr>
<tr>
<td>Ni</td>
<td>26 (0.2-107.4)</td>
<td>22.92 (0.2-3240)</td>
<td>39 0.19</td>
</tr>
<tr>
<td>Cu</td>
<td>48 (0.9-234.9)</td>
<td>21.61 (1-323)</td>
<td>32 2.9</td>
</tr>
<tr>
<td>Zn</td>
<td>89 (2.5-331)</td>
<td>66.84 (3.770)</td>
<td>99 19</td>
</tr>
<tr>
<td>As</td>
<td>11 (0.4-70)</td>
<td>8.93 (0.07-95)</td>
<td>9 0.16</td>
</tr>
<tr>
<td>Mo</td>
<td>1.3 (0.1-8)</td>
<td>3.10 (0.2-178)</td>
<td>– – –</td>
</tr>
<tr>
<td>Cd</td>
<td>0.3 (0.02-3)</td>
<td>0.48 (0.01-4)</td>
<td>0.45 0.07(4)</td>
</tr>
<tr>
<td>Hg</td>
<td>0.13 (N.D.-5.4)</td>
<td>0.13 (0.004-1.5)</td>
<td>0.32 0.013</td>
</tr>
<tr>
<td>Pb</td>
<td>24 (1-1098)</td>
<td>29.85 (1.5-286)</td>
<td>29 0.19</td>
</tr>
</tbody>
</table>

The values in the parenthesis mean ranges of heavy metal concentrations.

a) Calculated from Yamasaki (2001), detailed data kindly provided.
b) Iimura (1981)
c) Calculated from Kabata-Pendias (2001)
d) MAFF (2002)
3. Promising risk management for Cd contamination in soil and rice

3.1 Breeding of low adsorptive cultivar
Ishikawa et al. [1] have developed the practical rice showing low-Cd characteristic by using the mutant breeding. “Koshihikari”, the most popular Japanese *japonica* cultivar, were irradiated with accelerated carbon ions from an azimuthally varying field cyclotron. The mutated seeds were self-pollinated and then approximately 3,000 M2 seedlings were screened to obtain the low-Cd mutant lines in the Cd-polluted soil. Three mutants (*lcd-kmt1*, *lcd-kmt2*, and *lcd-kmt3*) were screened showing significantly lower Cd concentration than the Koshihikari (WT). The Cd concentrations in shoots and roots in all *lcd-kmt* were significantly lower than that in WT when those seedlings were treated with Cd in hydroponics. The advanced generation of *lcd-kmt mutants* (M3) and WT were cultivated in the paddy fields that differ in Cd contamination. The Cd concentrations in brown rice of WT were more than 1 mg kg⁻¹, whereas those of all *lcd-kmt mutants* were less than 0.05 mg kg⁻¹. Plant morphology, grain yield, and eating quality for *lcd-kmt mutants* were as good as those of the WT. The gene responsible for low-Cd trait was identified based on gene mapping and the DNA marker was developed for efficient breeding of new rice cultivars.

3.2 Phytoremediation of the polluted soil by rice plant
Murakami et al. [2] conducted the effective phytoextraction using the high-Cd *indica* rice cultivars, “Chokoukoku” for 2-years without irrigation after drainage to enhance availability of soil Cd to rice plant in fields. They demonstrated that the phytoextraction decreased soil Cd content and the grain Cd concentration in subsequently grown *japonica* rice were reduced by 38% and 47%, respectively. In order to achieve commercialization of phytoextraction technology, we have established an integrated mechanized system of harvesting, on-site drying, and packing of Cd-containing rice plants, and developed an efficient system for collecting Cd involving the incineration of the harvesting rice plants. In an effort to improve the phytoextraction, new rice cultivars has been bred, which have some advantages in some agronomic traits such as shattering and lodging susceptibility. To breed new rice cultivars useful for phytoextraction, it is necessary to identify a gene or gene loci associated with high-Cd trait in rice. By the QTL (quantitative trait loci) analysis, Abe et al. [3] identified a major QTL responsible for Cd concentrations in both grains and straw of rice plants using a back cross inbred lines derived from a low- Cd accumulating *japonica* cultivar, Koshiihara and a high- Cd accumulating *indica* cultivar, Jarjan. The Jarjan allele of this QTL was introduced into a “Tachisugata” cultivar resistance to shattering and lodging and producing large biomass through marker-assisted selection.

3.3 Chemical remediation of Cd-polluted soil by soil-washing
Various chemicals were tested for their Cd extraction efficiency by using three paddy soils, selecting ferric chloride (FeCl₃) as a promising chemical for on-site soil washing [4]. The comparison of FeCl₃ extraction ability to that of various iron, manganese, and zinc salts revealed the primary extraction mechanism of FeCl₃ to be proton release coupled with hydroxide generation (hydrolysis). This indicates that proton release from FeCl₃ is controlled by the chemical equilibrium of hydroxide formation, and minimizes the negative effect on soil properties and environment, which are different from hydrochloric acid. Washing with FeCl₃ led to the formation of Cd–chloride complexes, enhancing Cd extraction from the soils. We also developed in situ three-step washing method for Cd-contaminated paddy fields with FeCl₃. The method was comprised of 1) chemically washing the field soil with a FeCl₃ solution; washing the treated soil with water to eliminate residual Cd and FeCl₃; and 3) on-site treatment of wastewater using a portable wastewater treatment system. Concentrations of Cd in the treated water were below Japan’s environmental quality standard. The on-site soil washing confirmed the effectiveness of FeCl₃ for decreasing Cd in soil and rice grains without negative effect on rice yield.

3.4 Promising methods simultaneously decrease concentrations of As and Cd in rice grains
Under anaerobic conditions, Cd precipitates as the barely-soluble sulfide, resulting in a low Cd availability for rice plants. Field experiments showed that flooded cultivation during the entire rice growing period or the latter part of it significantly decreased Cd in rice grains by more than 80%. Flooded cultivation, however, increases As solubility through the reduction of As(V) to As(III) and the reductive dissolution of As-bearing Fe-oxides in soils. As expected, flooded cultivation increased As in rice grains, whereas aerobic cultivation increased Cd [5]. Our strategies for the simultaneous decrease of As and Cd are: ① optimal water management to simultaneously decrease, ② water saving cultivation with low Cd rice cultivar, flooding cultivation with soil amendments for As uptake by rice plant. The state of the art technologies, recently developed in NIAES, will be introduced in the presentation.

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References


