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# Cadmium in soybeans and the relevance to human exposure

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## Introduction

Cadmium is considered a human carcinogen by the International Agency for Research on Cancer (IARC, 1993) and the US National Toxicology Program (NTP, 1997). Cadmium contamination of food crops is a persistent issue for both the agricultural industry as well as consumers. This is an issue for agriculture because cadmium can be present in soils naturally or as a result of industrial processes and can contaminate foods that are consumed by humans. Industrial wastewater used for irrigation of agricultural crops can introduce toxic metals, including cadmium, to plant roots. Some fertilizers can introduce metals into agricultural soils. For example, phosphate fertilizers contain cadmium, which can further exacerbate the amount of cadmium available for crops. For these reasons, there have been a number of studies (Benavides et al., 2005; Brown and Jones, 1975; Foy et al., 1978; Ernst et al., 1992; Das et al., 1997; Sanita di Toppi and Gabrielli, 1999; Hall, 2002; Clemens et al., 2002; Choppala et al., 2014; Newbigging et al., 2015) examining metal toxicity in crops. This short review focuses on the routes of exposure of cadmium to humans and the efforts to minimize exposure by using cadmium-excluding soybean cultivars.

## 1. Cadmium toxicity to humans

Piscator (1985) reviewed the main exposures to cadmium in the general population. Other than industrial exposures, the main exposure to cadmium in the general populations is through food (Friberg et al., 1974), with minimal cadmium exposures from air and drinking water (average daily intake ranges from less than 1 μg to 1–2 μg) (Sharett et al., 1982) and cigarette smoking. The Agency for Toxic Substances and Disease Registry recommends a chronic intake of cadmium below 0.1 μg/kg/day to prevent renal toxicity (ATSDR, 2012).

The main concern about cadmium toxicity is chronic exposure. For example, the onset of *itai-itai* disease, or cadmium poisoning, in Japan in the 1950s brought attention to the issue of ingesting crops grown on cadmium-contaminated soils (Kobayashi, 1978). However, Japanese rice farmers only began to show symptoms of cadmium toxicity because of the accumulation of cadmium caused by habitually consuming their own crops which were irrigated with mining wastewater. Although their symptoms did not appear for many years, sufferers of *itai-itai* disease eventually developed osteoporosis and kidney damage. Other symptoms caused by chronic exposure to elevated levels of cadmium include the development of cancer, liver failure, and the suppression of blood cell production (Waalkes, 2000). Although there are studies showing that people who ingested large amounts of cadmium-contaminated shellfish (Sharma et al., 1983; McKenzie-Parnell and Eynon, 1987; Sirot et al., 2008) or cadmium- and zinc-contaminated crops (Strehlow and Barltrop, 1988; Sarasua et al., 1995) exhibited no symptoms of cadmium poisoning,

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chronic exposure to cadmium remains a health concern for its organ toxicity and its carcinogenic effects.

## 2. Global cadmium production

One method to minimize cadmium uptake in soybean crops is to avoid cadmium contaminated soils; however, this is not easily done because of the vast soybean production over limited agricultural land available. For example, the maximum permissible concentration of cadmium in agricultural soils in China is 0.3 mg/kg (CEPA, 1995). However, cadmium concentrations in soils used for agriculture in China range from 0.1–2.6 mg/kg, amounting to an overall national average of 0.43 mg/kg (Wei and Yang, 2010; Liu et al., 2006a,2006b, 2007; Huang et al., 2007; Zhao et al., 2007a,2007b; Li et al., 2009; Li et al, 2008; Yang et al., 2009; Zheng, 2008; Chen and Pu, 2007). Despite this, China remains the largest producer of soybeans in Asia, producing 12.35 million metric tons over 6.8 million hectares of land as of 2014 (USDA Foreign Agricultural Service, 2015).

For comparison, about a third of the world's soybeans is produced in the United States at 108.01 million metric tons over 33.61 million hectares of land (USDA Foreign Agricultural Service, 2015). The second and third largest producers are Brazil and Argentina, producing 94.50 and 60.80 million metric tons over 31.50 and 19.30 million hectares of land, respectively. Holmgren et al. (1993) reviewed the cadmium content in U.S. soil and concluded that the U.S. had a mean of 0.265 mg/kg of dry soil, while cadmium in Brazilian soil samplings ranged from 0.3 to 1.6 mg/kg of dry soil, as estimated by Fadigas et al. (2006).

## 3. Efforts in reducing cadmium in soybeans

The disparity in the high quantity of soybean production and the shortage of low-cadmium containing agricultural soil available translates to a need for soybean producers to develop methods to reduce cadmium in crops when grown on cadmium-contaminated soils. One method is using cadmium-excluding cultivars or low cadmium accumulators (Zhang et al., 2014; Greger and Löfstedt, 2004). Cultivars are agricultural crops specifically grown to enhance desired qualities (properties), such as tolerance to growing in cadmium enriched environments and reduced cadmium uptake (Hernandez-Allica et al., 2008). The selection of these qualities enables the sustainability of crops grown on soil contaminated with cadmium without contamination of the food. Another method is phytoremediation (Sooksawat et al., 2013; Li et al., 2014), where plants with increased cadmium uptake and accumulation are planted in cadmium-enriched soils to remove cadmium from soil. Plants can be genetically modified to incorporate cadmium-binding proteins to improve the efficiency of phytoremediation (Dhankher et al., 2002; Lugon-Moulin et al., 2004). However, more research is necessary to improve this technology and the efficiency of phytoremediation (Murakami and Ae, 2009). Other options to remove cadmium from the soil are being explored, such as using genetically modified bacteria (Valls and de Lorenzo, 2002; Bang et al., 2000a,2000b) or cadmium-biosorbent fungi (Jarosz et al., 2002; Simonovicova et al., 2002) to remediate the soil. Lastly, another solution is to simply avoid using cadmium-enriched wastewater from industrial processes and mining as irrigation; however, using alternative irrigation methods can be too costly.

Despite these efforts to reduce cadmium exposure, it remains necessary to choose low cadmium containing soils for agriculture. However, it is difficult to find soils completely devoid of cadmium because it is naturally present in the environment, and industrial processes that have cadmium byproducts also contribute to its abundance. For this reason, continued efforts to reduce cadmium in crops are still being explored. A recent publication by Zhi et al. (2015) examined the cadmium content in Chinese soybean cultivars grown on soils with low and moderate cadmium contamination.

## 4. Investigating cadmium excluding soybean cultivars

To select effective cadmium-excluding soybean cultivars, Zhi et al. (2015) chose five Chinese soybeans cultivars (Shennong 10, Tiefeng 31, Tiedou 36, Tiefeng 37 and Liaodou 21) as candidates. They collected the soils for testing from the surface layer (0–20 cm) of three different fields. This is in contrast to artificially simulated soils, which are equilibrated for a short period of time, and do not reflect the true metal forms in industrially or naturally contaminated soils (Komarek et al., 2007). Zhi et al. established soils containing a cadmium concentration of 0.15 mg/kg as controls, and considered 0.75 mg/kg and 1.12 mg/kg as low and moderate cadmium-contaminated soils, respectively. The five soybean cultivars were cultivated in open field conditions without additional fertilizers. After 4 months of cultivation, the plants were harvested and separated into roots, stems, leaves, pods, and seeds to analyze cadmium and mineral elements (cadmium, copper, iron, magnesium, manganese, and zinc).

Photo courtesy of Professor Qixing Zhou, MOE Key Laboratory of Pollution Processes and Environmental Criteria, Tianjin Engineering Center of Environmental Diagnosis and Contamination Remediation, College of Environmental Science and Engineering, Nankai University, Tianjin, China

Zhi et al. (2015) found that all five soybean cultivars were able to grow in the presence of low and moderate cadmium contamination. This shows that the plants had substantial cadmium tolerance as no noticeable symptoms of toxicity were observed in them. Tolerance to cadmium is selected in cultivars as it demonstrates the ability to thrive in cadmium-contaminated soils, and therefore paves the way for the selection of cadmium-excluding soybean cultivars – cultivars that grow in cadmium soils but do not uptake cadmium.

The measured cadmium concentrations in soybean seeds were positively correlated with cadmium concentrations in soils. When grown in low cadmium contaminated soil (0.75 mg/kg), the cadmium content in the seeds of cultivars Tiefeng 37 (0.21 mg/kg) and Liaodou 21 (0.23 mg/kg) exceeded the maximum permissible concentration (MPC) value set by the Codex Alimentarius Commission (FAO/WHO, 2001) at 0.2 mg/kg. When grown in moderate cadmium contaminated soil (1.12 mg/kg), the cadmium concentrations in the seeds of all cultivars except Tiefeng 31 (0.19 mg/kg) exceeded the MPC value, which suggested that only the seeds of Tiefeng 31 are safe enough for consumption when grown in moderate cadmium contaminated soil.

However, high cadmium content in agricultural soils is not the sole factor that determines high cadmium content in soybean seeds. Zhi et al. (2015) further evaluated the rate of accumulation and the rate of transfer of cadmium from the root to the seeds by comparing cadmium concentrations in the soil and in the soybean root and seeds. Although they found low rates of transfer of cadmium from the soil and root to the seeds and low potential rates of bioaccumulation, they also found that the absorption efficiency of cadmium correlated positively with pH and organic matter in soils. Soils with moderate cadmium contamination were more acidic and had higher organic matter content than soils with low cadmium contamination. These two properties may affect the rate of cadmium uptake in soybean cultivars.

## 5. Main sources of human exposure to cadmium

The main route of human exposure to cadmium is through ingestion (WHO, 1992). The highest concentration of cadmium in food is found in animal kidneys and shellfish (WHO, 1992; Galal-Gorchev, 1993; Bendell, 2000). However, despite their relatively lower concentrations of cadmium, cereals, roots, and tubers constitute the most cadmium intake on a global scale because these food products are consumed in high quantities (Galal-Gorchev, 1993). The typical cadmium content of cereals, roots, and tubers is 0.02–0.03 mg/kg, but the average consumption is about 700 g/day. This results in an estimated cadmium intake from these sources of 18 μg/day, which makes up 72% of the global dietary cadmium intake. A study by Greger and Löfstedt (2004) found that cadmium content in wheat grain could vary from 30 μg/kg dry weight to 209 μg/kg dry weight in low accumulators. High accumulating cultivars reached as high as 498 μg/kg dry weight. Depending on the species and type of wheat cultivar, and the portion of the plant being analyzed, the amount of cadmium varied.

Between 1980 and 1988, Thailand had the largest weekly dietary intake of cadmium at under 18 μg/kg body weight, followed by Germany at under 6 μg/kg body weight, and Japan, Canada, and the United States all under 4 μg/kg body weight (Galal-Gorchev, 1993). In countries that depend on rice as a staple food, it is estimated that the major source of dietary cadmium intake is rice (Rivai et al., 1990). Yamagata (1978) estimated between 40% and 60% of the exposure of cadmium to people living in Japan is through the consumption of rice, and Suzuki et al. (1988) estimated this value to be 50% for those in Indonesia. Thailand had the highest estimated cadmium content within rice, as much as 584 μg/kg wet weight. Japanese rice ranged from 153 to 468 μg/kg wet weight, Indonesian rice from 92.5 to 564.4 μg/kg dry weight, and rice from India and China had similar values, from 12 to 135 μg/kg dry weight. Lee et al. (2006) conducted a study on the source of dietary cadmium to which the Korean population is exposed. From a diet consisting of rice, fish, breads, and cereals, various vegetables, and stews (including soybean paste soups and stews which were consumed at a weekly intake of 7.8 μg/person and 2.15 μg/person, respectively), the weekly cadmium intake was 1.8 μg/kg body weight. For comparison, the weekly arsenic intake was 4.9 μg/kg body weight. However, Lee et al. (2006) compared these values with the provisional tolerable weekly intakes set by the Joint FAO/WHO Expert Committee on Food Additives (FAO/WHO, 1997; UNEP/FAO/WHO, 1992) and concluded that there was no health risks involved in these metal exposures.

Another source of cadmium is the consumption of tobacco products. About 49% of adult males living in China smoke cigarettes (compared to a worldwide range of 9% to 67%), which can add to the overall exposure from consuming cadmium-contaminated food (World Bank, 2015). The tobacco plant can accumulate cadmium in its leaves (Lugon-Moulin et al., 2004). Although it is difficult to compare concentrations in tobacco leaves as they depend on the genetics of each particular plant and on its growing conditions (climate, soil, and fertilization and irrigation methods), it is estimated that the cadmium content of tobacco leaves ranges from 0.5 μg/g to 5.0 μg/g (Lugon-Moulin et al., 2004, 2006). However, it is difficult to compare this value to the amount of cadmium present and ingested in food, as there are many compounding factors. Cadmium may have different bioavailabilities depending on the route of exposure, *e.g.*, ingestion *vs.* inhalation, and the amount consumed of either cadmium-contaminated food or tobacco products differs among individuals.

## 6. Conclusions and recommendations

Humans are inevitably exposed to cadmium because of the variety of cadmium sources (Mead, 2000). The bioavailability of cadmium – for both human absorption after ingestion and for agricultural plant roots for uptake from soil – depends on the environmental conditions. For example, pH, organic matter content, and other elements, such as zinc, manganese, and selenium, present in soil alongside cadmium can affect the uptake of cadmium by plants (Chaney, 2012; Roberts, 2014). One of the major efforts in minimizing human exposure to cadmium is to reduce the cadmium content in food crops. A method is using cadmium excluding cultivars for food crops, which would then also reduce the levels of exposure to consumers; however, as Zhi et al. (2015) showed, it is not always effective.

When Zhi et al. (2015) accounted for the yield of seed biomass, all the cultivars except Tiedou 36 were considered cadmium-excluding cultivars. However, their evaluation of cadmium in seeds indicated that the cultivars were not able to exclude cadmium for safe consumption according to the current recommendations. Further avenues of research should be explored to lower the rate of uptake, bioaccumulation, and transfer from roots to seeds. One approach could be through the selection of soybean cultivars that would reduce the absorption of cadmium from soil to root or the transfer of cadmium from root to seed.

The observations of Zhi et al. (2015) suggest that reducing the uptake of cadmium in soybeans by optimizing pH values and organic matter content in soils may be a potential strategy to reduce cadmium in soybean seeds. Zhi et al. (2015) also showed that the presence of cadmium in soils also increases the uptake of zinc and iron in soybeans, and decreases the concentration of manganese in seeds. This may be because both cadmium and zinc may share similar physical properties or uptake transporters. The mechanisms of the interactions between cadmium and other mineral nutrient elements are complicated and further studies are needed to make appropriate recommendations on cadmium in agricultural soils.

The study by Zhi et al. (2015) demonstrates that even cadmium excluding soybean cultivars, crops specifically chosen to have low cadmium uptake, when grown on low to moderate cadmium contaminated soil, can still retain cadmium concentrations above the recommended limit of 0.2 mg/kg. Therefore, the agricultural industry should choose cadmium-excluding soybean cultivars carefully depending on the soil on which they will be grown. More research is needed to explore other options of reducing human exposure to cadmium through food and to improve the cadmium exclusion of cultivars.

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