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# Dietary exposure to cadmium from six common foods in the United States

Ashish Pokharel [a], Felicia Wu [a,b,*]

[a] Department of Agricultural, Food, and Resource Economics, Michigan State University, East Lansing, MI, USA
[b] Department of Food Science and Human Nutrition, Michigan State University, East Lansing, MI, USA

A R T I C L E I N F O

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A B S T R A C T

Recently, the United States (US) Food and Drug Administration (FDA) launched a Closer to Zero Action Plan to assess the risks of and develop action levels for certain heavy metals in food including cadmium (Cd). The problem of foodborne metal contamination has taken on new urgency, thanks in part to a 2021 US Congressional Report detailing high levels of metals found in infant food. Our risk assessment aids this FDA Action Plan by estimating the American population's Cd exposures in food, by age group and consumption patterns of certain high-risk foods; and by determining circumstances in which exposures exceed tolerable daily intakes developed by policymaking groups in the US and worldwide. We found that the age groups 6–24 months and 24–60 month old are the most highly exposed to Cd in common foodstuffs. American infants and young children of these age groups who regularly consumed rice, spinach, oats, barley, potatoes, and wheat had mean Cd exposures exceeding maximum tolerable intake level was set by the Agency for Toxic Substances and Disease Registry (ATSDR). We have identified age groups at highest potential risk, and therefore of interest for developing food safety policies to improve safety of commercial food for children.

## 1. Introduction

Cadmium (Cd) is a soft, silver-white, naturally occurring metal occurring as cadmium sulfides in the earth's crust and soil; and is a byproduct of mining sulfide ores of other metals such as zinc, lead and copper (ATSDR, 2012). In the environment, Cd can enter the soil, water, and air through metal mining, phosphate fertilizer manufacture and application, fossil fuel combustion, and waste burning and disposal. In agricultural soils, Cd binds with organic soil matter and can be taken up by food and feed crops (ATSDR, 2012; Mench, 1998), accumulate in the edible parts, hence entering the food supply (Paul and Chaney, 2017). In the United States (US), the primary sources of Cd exposure are tobacco (for smokers), leafy green vegetables, cereal grains, potatoes, nuts, and seeds (Mench, 1998; Morrow, 2010). The food and water background intake levels for Cd in the US were estimated at 0.18 μg/kg/day and 0.08 μg/kg/day, respectively, giving a total dietary background level of 0.26 μg/kg/day (Wong et al., 2022).

Chronic exposure to Cd has been associated with diverse health risks. Cd bioaccumulates in the kidneys and has been linked to nephrotoxic and even neurotoxic effects (Noonan et al., 2002; Rigon et al., 2008). Exposure to Cd in heavily polluted areas has been associated with renal dysfunction and consequently an increase in mortality (ATSDR, 2012; Nakagawa et al., 2006). Occupational exposure to Cd has been linked to nephrotoxic effects such as impaired glomerular filtration rate, proteinuria, depressed tubular resorption of solutes such as enzymes and kidney stone formation (ATSDR, 2012; Schaefer et al., 2022). Several studies have reported possible linkages between urinary cadmium and health outcomes such as renal damage, cardiovascular disease, cancer risk and liver disease; controlling for other risk factors such as smoking (Hyder et al., 2013; McElroy et al., 2017; Paschal et al., 2000). A recent systematic review on the effects of oral Cd exposure speculated on increased risk of certain types cancer such as endometrial, cutaneous melanoma, breast, prostrate, bladder, gastric, and pancreatic cancer; and bone conditions such as osteoporosis and decreased bone mineral density in several epidemiological studies (Schaefer et al., 2022).

Because of these health risks, various national and global standard-setting agencies have set oral intake guidelines for Cd. These guidelines have various different names, such as "tolerable daily/weekly/monthly intake" or "minimal risk level," which in all cases refer to a dose considered safe for humans to consume regularly without increasing disease risk over a lifetime. The US Agency for Toxic Substances and Disease Registry (ATSDR) has set a chronic oral minimal risk level (MRL) for cadmium of 0.1 μg/kg bw/day (ATSDR, 2012). To determine the benchmark dose level and consequently the MRL, ATSDR used values from a meta-analysis of seven environmental exposure dose-response

* Corresponding author. Department of Food Science and Human Nutrition, Michigan State University, East Lansing, MI, 48824, USA.
*E-mail address:* fwu@msu.edu (F. Wu).

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**Abbreviations**

| | |
|---|---|
| ADD | average daily dose |
| ATSDR | Agency for Toxic Substances and Disease Registry |
| B2M | beta-2-microglobulin |
| BW | bodyweight in kg |
| Cd | Cadmium |
| EFSA | European Food Safety Authority |
| EPA | Environmental Protection Agency |
| FCID | Food Commodity Intake Database |
| FDA | Food and Drug Administration |
| JECFA | Joint Expert Committee on Food Additives |
| MRL | minimal risk level |
| PTDI | provisional tolerable daily intake |
| PTMI | provisional tolerable monthly intake |
| PTWI | provisional tolerable weekly intake |
| US | United States |
| TDS | Total Diet Study |
| WWEIA | What We Eat in America |

studies. The studies measured urinary Cd as an indicator of exposure and estimated urinary Cd level corresponding to probabilities of a 10% excess risk of low molecular weight proteinuria (i.e. $UCD_{10}$) to be at 0.5 μg Cd/g creatine urine. The dietary Cd intakes which resulted in the lowest $UCDL_{10}$ value of 0.33 μg/kg bw/day was used and was divided by an uncertainty factor of 3, resulting in a MRL of 0.1 μg/kg bw/day (ATSDR, 2012).

The European Food Safety Authority (EFSA) has set a provisional tolerable weekly intake (PTWI) of 2.5 μg/kg bw/week, corresponding to 0.36 μg/kg bw/day (EFSA, 2011). EFSA derived this PTWI from a benchmark dose level derived from 35 epidemiological studies with urinary Cd levels as exposure and a change in beta-2-microglobulin (B2M) in urine, a biomarker of renal tubular effects, as an outcome. The lower one sided 95% confidence bound for an extra risk of 5% of change in B2M ($BMDL_5$) was used to calculate a critical Cd concentration of 1 μg Cd/g creatinine in urine. A dietary Cd intake value no greater 2.5 μg/kg bw/week was determined to prevent most people from exceeding this urinary Cd concentration after 50 years (EFSA, 2011).

Similarly, the Joint Expert Committee on Food Additives (JECFA) of the Food and Agriculture Organization and the World Health Organization has set a provisional tolerable monthly intake (PTMI) of 25 μg per kg body weight per month (μg/kg bw/month), corresponding to a provisional tolerable daily intake (PTDI) guideline of 0.83 μg/kg bw/day (JECFA, 2011). JECFA used a similar methodology to that of EFSA, relying on estimates derived from the same 35 dose-response studies with urinary Cd levels as exposure and B2M in the urine as an outcome. The critical Cd concentration was determined to be 5.24 μg Cd/g creatinine in urine for the population aged 50 years and over. The dietary Cd exposure which equated to this level in urine was 1.2 μg/kg bw/day, with 95% CI values of 0.8–1.8 μg/kg bw/day. The lower bound value of 95% CI was used the determine the PTMI value of 25 μg/kg bw/month (JECFA, 2011).

Likewise, regulatory agencies in the US, as well as regulatory agencies in other nations and groups of nations, have developed food and water policies for maximum allowable Cd levels. In the US, FDA is currently in the process of forming action levels for Cd in food while US Environmental Protection Agency (EPA) has set standards for Cd in bottled drinking water. Cd regulatory standards in various food items such as cereals, leafy vegetables, and drinking water are reported in Table 1. Of note are that standards for cadmium in drinking water tend to be stricter than those for food, and that only particular foodstuffs have been regulated for Cd – most notably, cereal grains and leafy vegetables. The European Union has set different Cd standards for different foods,

**Table 1**
Cd regulation standards for common food items in various countries.

| | Country/ Region | Food items | Cd standards |
|---|---|---|---|
| 1 | European Union[a] | Leaf vegetables, fresh herbs, leafy brassica | 100 μg/kg |
| | | Cereal grains excluding rice and wheat | 100 μg/kg |
| | | Wheat grains, rice grains | 200 μg/kg |
| | | Processed cereal-based foods and baby foods for infants and young children | 40 μg/kg |
| 2 | USA | Bottled drinking water from US EPA | 5 μg/L |
| 3 | Canada[b] | Drinking water from federal government | 5 μg/L |
| 4 | New Zealand[b] | Leafy vegetables | 100 μg/kg |
| | | Wheat | 100 μg/kg |
| 5 | Sweden[b] | Cereals | 80 μg/kg |
| 6 | Chile[b] | Table mineral water or potable water | 10 μg/L |

[a] COMMISSION REGULATION (EU) No 488/2014 of 12 May 2014 amending Regulation (EC) No 1881/2006 as regards maximum levels of cadmium in foodstuffs https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32014R0488.

[b] Figueroa B E. (2008). Are more restrictive food cadmium standards justifiable health safety measures or opportunistic barriers to trade? An answer from economics and public health. The Science of the total environment, 389(1), 1–9. https://doi.org/10.1016/j.scitotenv.2007.08.015.

Sources

with a stricter standard for foods intended for consumption by infants and young children, and a relatively more relaxed standard for wheat and rice.

More recently, Cd exposure has garnered attention in the United States, as a 2021 report by the US House of Representatives Subcommittee on Economic and Consumer Policy found high levels of Cd and other heavy metals in baby foods available for grocery shelves (US House of Representatives Subcommittee on Economic and Consumer Policy, 2021). Following this Congressional Report, the US Food and Drug Administration (FDA) launched a Closer to Zero Action Plan, to assess the risks and set action levels for Cd, arsenic, lead, and mercury in foods, with a focus on foods commonly consumed by infants and young children; among other goals for improved food safety (FDA, 2023).

The focus on youth is important, as infants and young children may be more susceptible to adverse effects of Cd exposure (as well as that of other heavy metals) due to higher intakes of food and fluids relative to their bodyweight, and greater potential of metals to affect developing bodies (Spungen, 2019). Various studies have associated Cd exposure with possible adverse effects on neuropsychological function and IQ in children (Chandravanshi et al., 2021; Gustin et al., 2018; Kippler et al., 2012; Wang and Du, 2013). Cd exposure has also been associated with biomarkers of kidney dysfunction in children (Chandravanshi et al., 2021; Rodríguez-López et al., 2020; Sanders et al., 2019). A recent study investigated dietary Cd intake in the US population 2 years and older and the major sources of dietary Cd intake (Kim et al., 2018). Likewise, another study evaluated dietary Cd exposure among children aged 1–6 years in the US (Spungen, 2019). Hence, to our knowledge, only a few studies have investigated dietary Cd exposure in young children and none have investigated exposure in infants 0–6 months of age from commonly consumed food items that are susceptible to high Cd accumulation. This is a gap in evidence as infants less than 6 months of age and young children aged 6–24 months are consumers of commercial baby food products.

Hence, our study aims to fulfill this knowledge gap of dietary Cd exposure in the US population by assessing Cd exposure from two major food items - rice and spinach - in various age groups, including infants and young children, in the US; and evaluating which age groups are more vulnerable to higher Cd exposure. Rice and spinach are commonly consumed foods that take up Cd and other heavy metals readily from soil and rice is a common ingredient used in commercial infant food (Garro-Mellado et al., 2022). Further, we evaluate whether Cd exposure for each of these age groups exceed the guidelines for tolerable intake set by

ATSDR, JECFA and EFSA. As a secondary objective, we calculate the cumulative Cd exposure from six food items commonly used in manufacturing commercial baby food: rice, spinach, oats, barley, potatoes, and wheat (Garro-Mellado et al., 2022). We also report Cd food policies and standards in common food items such as cereals and leafy vegetables in different nations.

## 2. Methods

We conducted a literature search to find studies reporting cadmium levels in rice and spinach: two food crops prone to take up heavy metals, including Cd, in soil. Several studies reported mean/median and maximum Cd levels in rice and spinach (presented in Table 2). For the purposes of this study, we used the Cd levels reported in the *FDA FY 2018-FY 2020 Total Diet Study Elements Report Supplement: Summary of Analytical Results* (TDS) (FDA, 2022) report to calculate the average daily dose (ADD) of Cd. This comprehensive survey analyzed 27 samples each of enriched white rice and raw spinach representing six different regions of the US, with the number of samples from each regions as follows: 4 from the Mid-Atlantic, 5 from the Northeast, 4 from North Central, 5 from the Southeast, 4 from the Southwest, and 5 from the West. We used the mean Cd level reported from these 27 samples across the US over the years 2018–2020.

Daily intake rates of rice and spinach by different age groups were obtained from the *What We Eat in America* (WWEIA) Food Commodity Intake Database (FCID), 2005–2010 (EPA/JIFSAN, 2022). This database was developed by EPA Office of Pesticide Programs to improve the utility of the WWEIA survey for dietary exposure assessment of pesticides. Food commodity intakes are expressed as grams of food consumed per kg bodyweight per day (g/kg bw/day) and were obtained for each of the following age groups: 0–6 months, 6–24 months, 24–60 months, 5–18 years, 18 or more years. In cases where the consumers were not old enough to report estimated average daily intake (infants and young children), consumption estimates were obtained from their caregivers.

To estimate Cd exposure for total rice and spinach intake regardless of the form in which it is processed, the estimated daily amounts of individual food items of which these were the sole/primary ingredients in WWEIA were summed for total daily consumption. For rice, this included aggregating the following foods: white rice, white rice-baby food, brown rice, brown rice-baby food, rice flour, rice flour-baby food, rice bran, rice bran-baby food, and wild rice consumption to give a single value for total rice consumption. Similarly, spinach and spinach-baby food were aggregated to give total spinach consumption. For simplicity, we assumed that the Cd levels in different preparations of rice and spinach are similar to those reported in the TDS study.

We calculated daily exposures to Cd for: 1) the total population, which represents all Americans surveyed by age group, regardless of whether the food was consumed or not (e.g., some Americans do not eat any rice or spinach), and 2) the "Eaters only" sub-population for each age group, which in the WWEIA FCID database represents only the Americans who consumed the food on at least a semi-regular basis (more than one time a week on average) when the food consumption survey was conducted. We included the total population group to generalize the results to the entire US population for policymaking purposes and included "Eaters only" sub-population to generalize the results only to the frequent consumers of food items. The average daily dose (ADD) of Cd from rice or spinach for each age group was calculated by multiplying Cd concentrations in food (from the FDA TDS) by the intake rate per kg bodyweight per day. This is given by the equation:

$$ADD = C \times IR / BW \quad (1)$$

where *ADD* is the average daily dose measured in μg Cd per kg bodyweight per day (μg/kg bw/day), *C* is the cadmium level in rice or spinach measured in μg per kg (μg/kg), *IR* is the daily amount of food consumed measured in kilograms per day, and *BW* is the average bodyweight for a particular age group in the US in kg. We also calculated the upper 95% confidence interval of ADD using sample size and standard error values of food intake levels and Cd levels.

To calculate the cumulative ADD values from six common food items commonly used in commercial baby food manufacturing – rice, spinach, barley, oats, wheat, and potatoes – we used food intake data at the mean level from FCID and mean Cd levels from the TDS study. The exception was barley, for which we used data from Hain's monitoring test report results as TDS study did not have the data (US House of Representatives Subcommittee on Economic and Consumer Policy, 2021).

## 3. Results

### 3.1. Cd levels in rice and spinach

Mean/median and maximum Cd levels found in rice and spinach samples from different studies or reports in the US are presented in Table 2. All studies were conducted since 2013, and several were cited in the US Congressional Report (2021) for high Cd levels found in infant foods.

The median/mean Cd values in rice samples ranged from 6.5 to 18.19 μg/kg, while the maximum Cd values in samples ranged from 23 to 71 μg/kg. Mean Cd levels in spinach were much higher than that of rice, ranging between 117 and 222 μg/kg. In 27 spinach samples taken from 2018 to 2020 across the United States, the highest Cd level found was 400 μg/kg (FDA, 2022). These sample levels found for rice and spinach may be informative for policymakers attempting to set standards for maximum allowable limits of Cd in commonly consumed foodstuffs.

When comparing the Cd levels found in US foods with the oral Cd

**Table 2**
Cadmium concentration levels in rice and spinach from different studies and reports.

| Study/report | Food | Sample size | Cd level (mean or median) | Cd level (maximum) | Notes |
|---|---|---|---|---|---|
| Hain's monitoring test report, 2019[a] | Rice flour | NA | 18.19 μg/kg | NA | Values from ingredient test report. Rice flour was used as a premix for baby food. Cd concentration was the hypothetical level in finished product. |
| Shi et al. (2020) | Polished rice | 18 | 17.05 μg/kg | 31.80 μg/kg | Locally produced, market rice, purchased from retailers. |
| Tatahmentan et al. (2020) | White rice | 28 | 6.50 μg/kg | 71 μg/kg | Samples from rice grown in California, Texas, Louisiana. |
| Meharg et al. (2013) | Rice | 21 | 17 μg/kg | 40 μg/kg | |
| FDA, 2022 | Enriched cooked white rice | 27 | 6.50 μg/kg | 23 μg/kg | Samples from 2018 to 2022 FDA's Total Diet Study |
| Beech-Nut's monitoring test report, 2019[a] | Spinach puree | NA | 143 μg/kg | NA | Values from ingredient test report of 7/10/2019 |
| Spungen (2019) | Boiled spinach | NA | 117 μg/kg | NA | Samples from 2014 to 2016 FDA's Total Diet Study |
| FDA, 2022 | Raw spinach | 27 | 222 μg/kg | 400 μg/kg | Samples from 2018 to 2022 FDA's Total Diet Study |

Note: "NA" represents data unavailability.
[a] Refers to data obtained from US House of Representatives Subcommittee on Economic and Consumer Policy, 2021 report "Baby Foods Are Tainted with Dangerous Levels of Arsenic, Lead, Cadmium, and Mercury."

standards set by different regulatory agencies: mean Cd levels in spinach from the FDA's TDS study were higher than those in leafy vegetables in European Union and New Zealand. Mean Cd levels in rice from the TDS study were lower than the regulatory standards from various countries. Hence, if the FDA sets Cd action levels similar to those in the EU and New Zealand, there may be a future challenge for some US spinach producers to achieve those action levels, in the absence of interventions.

### 3.2. Daily intake of rice and spinach

Mean rice and spinach intake level and their 95% confidence intervals for the total population and the "Eaters only" sub-population are reported in Table 3.

The FCID provides data separately not just by age group, but by all Americans within the age group surveyed ("Total population" columns in Table 2) as well as those subsets of Americans who consumed the food on a regular basis ("Eaters only" sub-population columns). In the total population, the mean rice intake ranged from 0.24 to 0.81 g/kg bw/day. The intake per body weight was higher in younger age groups of 0–6 months, 6–24 months, and 24–60 months age when compared to the older age groups. Rice was widely consumed with 40% and 85–90% of people consuming it for 0–6 months and all other age groups respectively. Spinach intake was low with consumption between 3 and 15% of the people across all age groups with mean intake ranging from 0.02 to 0.06 g/kg bw/day. In the "Eaters only" sub-population, the mean rice intake ranged from 0.26 to 1.36 g/kg bw/day. Likewise, the mean spinach intake ranged from 0.29 to 80 g/kg bw/day with the intake per bodyweight highest for 24–60 months age group.

### 3.3. Average daily doses of cadmium from rice and spinach in the US population

Fig. 1 presents the ADD results with the upper 95% confidence interval. In this Figure, we also compare the ADD values to ATSDR's chronic oral MRL of 0.1 μg/kg bw/day. (Of the agencies that had set maximum tolerable intakes for Cd, ATSDR has the strictest standard.) For the total population, ADD from both rice and spinach were below ATSDR's chronic oral MRL. On the contrary, for the "Eaters only" sub-population, ADD from spinach for 0–6 months, 6–24 months and 24–60 months age group were higher than ATSDR's chronic oral MRL. None of the ADD values exceeded EFSA's provisional tolerable daily intake level of 0.36 μg/kg bw/day, with the highest ADD value being 0.31 μg/kg bw/day which is the upper bound of the 95% CI from spinach in the "Eaters only" sub-population.

Perhaps most noteworthy: when actual consumption rates of rice and spinach are compared in Table 2, Americans as a whole consume far more rice than spinach daily by weight. However, as Fig. 1 shows, cadmium exposure nonetheless is much higher from spinach than from rice; particularly among those who report eating spinach on a regular basis. Table 2 shows that among "Eaters only," the weights of rice and spinach consumed are much closer; however, cadmium levels in spinach are much higher than those found in rice in the US, also shown in Table 1.

### 3.4. Cumulative ADD from six food items

Fig. 2 shows the cumulative ADD from six food items by age group for both the total US population and "Eaters only" sub-population: rice, spinach, oats, barley, potatoes, and wheat.

For the total population, the cumulative ADD from six food items exceeded ATSDR's chronic oral MRL with values of 0.15, 0.17, 0.10 and 0.10 μg/kg bw/day for 6–24 months, 24–60 months, 5–18 years, and 18 years-and-above age groups, respectively. It is likely that the 0–6 month age group did not have cumulative Cd exposures exceeding the ATSDR MRL, because often babies in the United States are not introduced to some of these foods at such a young age. Similarly, for the "Eaters only" sub-population the cumulative ADD values exceeded the ATSDR level for all age groups with values of 0.20, 0.29, 0.35, 0.19 and 0.18 μg/kg bw/day for 0–6 months, 6–24 months, 24–60 months, 5–18 years, and 18 or more years age groups respectively. None of the age groups exceed the EFSA and JECFA tolerable intake level. For comparison (Spungen, 2019), had estimated the mean Cd exposures in US children aged 1–6 years to be ranging from 0.38 to 0.44 μg/kg bw/day with major source of Cd being grains, mixed food and vegetables. Similarly, Kim et al., 2018 had estimated the mean dietary Cd exposure for the US population to be 0.54 μg/kg bw/week, corresponding to about 0.08 μg/kg bw/day, while the mean dietary Cd exposure for US children aged 2–10 years was estimated to be 0.94 μg/kg bw/week, corresponding to about 0.13 μg/kg bw/day.

## 4. Discussion

When policies are created to improve food safety by setting maximum tolerable levels of contaminants in particular foods, it is important to remember that humans' diets are rarely monotonic, particularly in high-income nations such as the United States. Therefore, the total potential exposures to a contaminant from multiple foodstuffs must be taken into account when considering health risks and thereby risk-based food policies. We have shown that in several age groups the cumulative exposure from just six common food ingredients exceeds Cd guidelines set by various agencies, raising concern that cumulative Cd exposure from all foods consumed by the US population may be at a much higher level.

Cadmium, one of the heavy metals of focus in the FDA Closer to Zero

**Table 3**
Intake levels of rice and spinach for total population and "Eaters only" sub-population.

| | Total population | | | | "Eaters only" sub-population | | |
|---|---|---|---|---|---|---|---|
| Age group | n | % who report eating the food | Mean intake (g/kg bw/day) | 95% CI | n | Mean intake (g/kg bw/day) | 95% CI |
| **Rice Consumption** | | | | | | | |
| 0–6 months | 602 | 39 | 0.52 | (0.38, 0.66) | 217 | 1.36 | (1.03, 1.69) |
| 6–24 months | 1316 | 90 | 0.81 | (0.69, 0.93) | 1153 | 0.90 | (0.76, 1.04) |
| 24–60 months | 1718 | 88 | 0.55 | (0.45, 0.65) | 1529 | 0.62 | (0.52, 0.72) |
| 5–18 years | 6327 | 87 | 0.25 | (0.21, 0.29) | 5554 | 0.28 | (0.24, 0.32) |
| 18 or more years | 14,710 | 90 | 0.24 | (0.22, 0.26) | 13,084 | 0.26 | (0.24, 0.28) |
| **Spinach Consumption** | | | | | | | |
| 0–6 months | 602 | 3 | 0.02 | (0.00, 0.04) | 19 | 0.56 | (0.40, 0.72) |
| 6–24 months | 1316 | 9 | 0.05 | (0.03, 0.07) | 95 | 0.60 | (0.44, 0.76) |
| 24–60 months | 1718 | 7 | 0.06 | (0.00, 0.12) | 90 | 0.80 | (0.23, 1.37) |
| 5–18 years | 6327 | 6 | 0.02 | (0.01, 0.03)[a] | 338 | 0.39 | (0.31, 0.47) |
| 18 or more years | 14,710 | 15 | 0.04 | 0.2 (0.03, 0.05) | 1904 | 0.29 | (0.25, 0.33) |

Note.
[a] Indicates that values were reported to be less than the given value. Data Source: EPA/JIFSAN (U.S. Environmental Protection Agency/Joint Institute for Food Safety and Applied Nutrition) (2021). What we eat in America- Food Commodity Intake Database. https://fcid.foodrisk.org/percentiles.php.

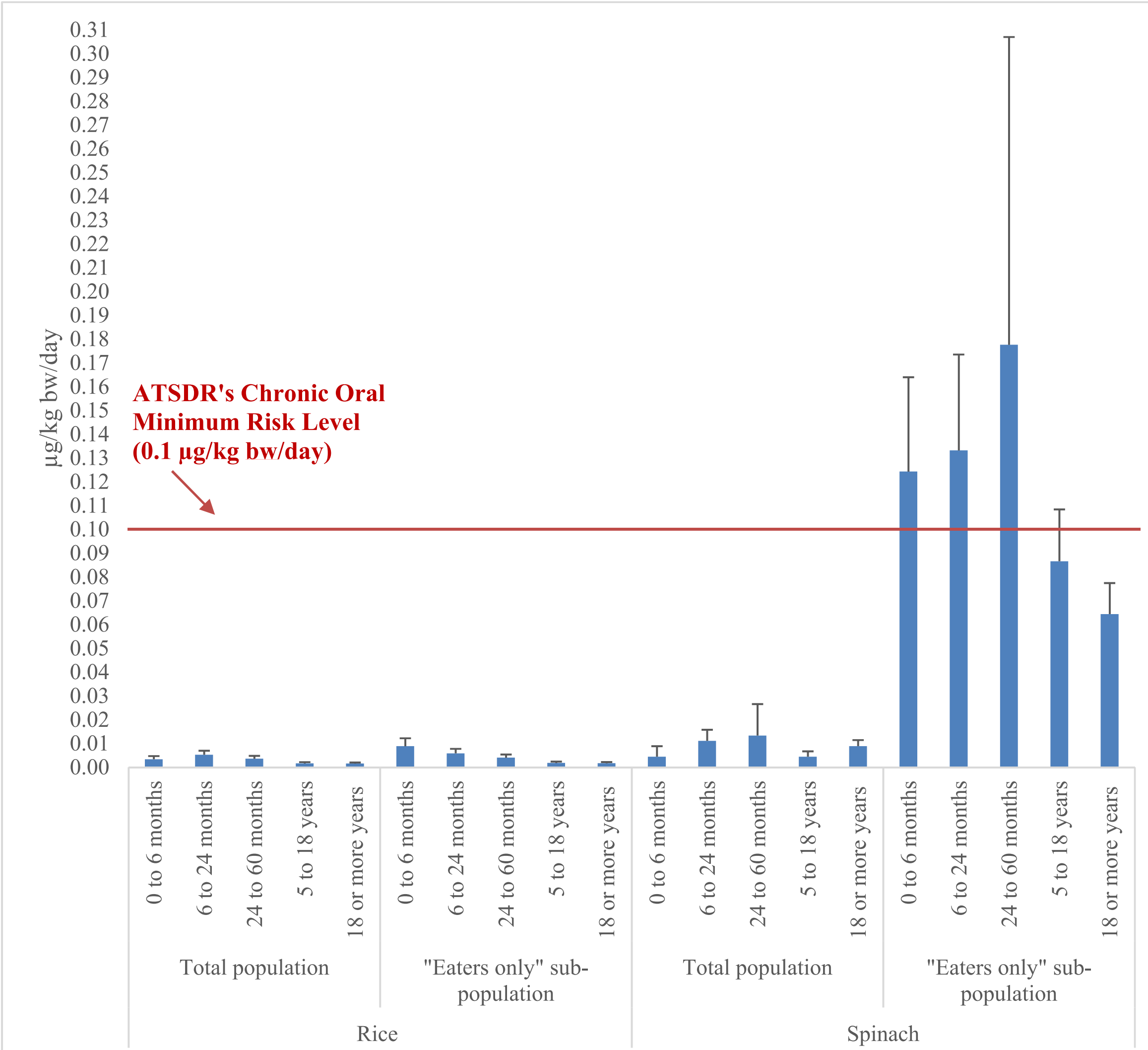


**Fig. 1.** Average daily dose to cadmium by age group in the United States, with upper 95% CI, from rice and spinach consumption.

Action Plan, is a contaminant of several commonly consumed foods in the US. Rice and spinach are two such foods that a large proportion of Americans consume throughout the course of their lives, starting often in infancy; for example, in the forms of rice-based infant cereals and pureed spinach. The median/mean Cd levels in US rice found in different studies and monitoring reports did not exceed the EU's standard of 40 μg/kg in baby food or 200 μg/kg in rice. But the Cd levels in US spinach were much higher, with all reported values greater than 100 μg/kg. This may be because leafy vegetables such as spinach are known to accumulate Cd in the edible portion, whereas polishing rice may remove much of the Cd; and factors such as soil Cd concentration, pH, and organic matter influence soil Cd phytoavailability for different crops (Paul and Chaney, 2017).

This current study estimates foodborne cadmium exposures, with their upper 95% CI, using representative samples of food intake in US population and food items in the US, for multiple different age ranges of Americans. This gives a balanced picture of the possible range of ADD values that one may expect in the US population. The differentiation of ADD values by age groups help in identifying the most vulnerable age group helping policy-makers to identify the appropriate measures to reduce exposure among the most vulnerable age groups. The combined Cd exposure from six common food items used in commercial baby food and commonly consumed by Americans throughout the lifespan – rice, spinach, wheat, potato, barley, and oats – was higher, as expected; especially for the 6-24-month and 24-60-month age groups. Among American children aged 24–60 months who consumed these foods on a regular basis, the average daily dose exceeded the ATSDR MRL and were close to EFSA's tolerable intake level.

However, when evaluating the total Cd intake and ADD values, we advise caution in extrapolating to particular health effects. Most ingested Cd passes through the gastrointestinal tract without being absorbed, and it is estimated that only about 1–10% of the total Cd is absorbed in the intestines by binding with transporters protein such as metallothionein (ATSDR, 2012). Iron levels in the body seem to play a role in Cd absorption, as higher iron stores have been associated with lower Cd absorption (ATSDR, 2012).

Nonetheless, the higher Cd exposures found in the 6–24 and 24–60 months age groups, especially for the "Eaters only" sub-population, is concerning; as these groups represent collectively a vulnerable population undergoing rapid physical and cognitive development, and consuming higher intake of food relative to their body weight. As described earlier, various studies have associated cadmium exposure with adverse outcomes in child health. When comparing our estimated combined Cd exposures from six foodstuffs in our study with Cd exposures estimated in previous studies, the ADD values were comparable to that of the most recent JECFA monograph on Cd; which found mean dietary exposure in infant 6–12 months to be about 0.3 μg/kg bw/day (derived from a value of 9.4 μg/kg bw/month) and for children of 2

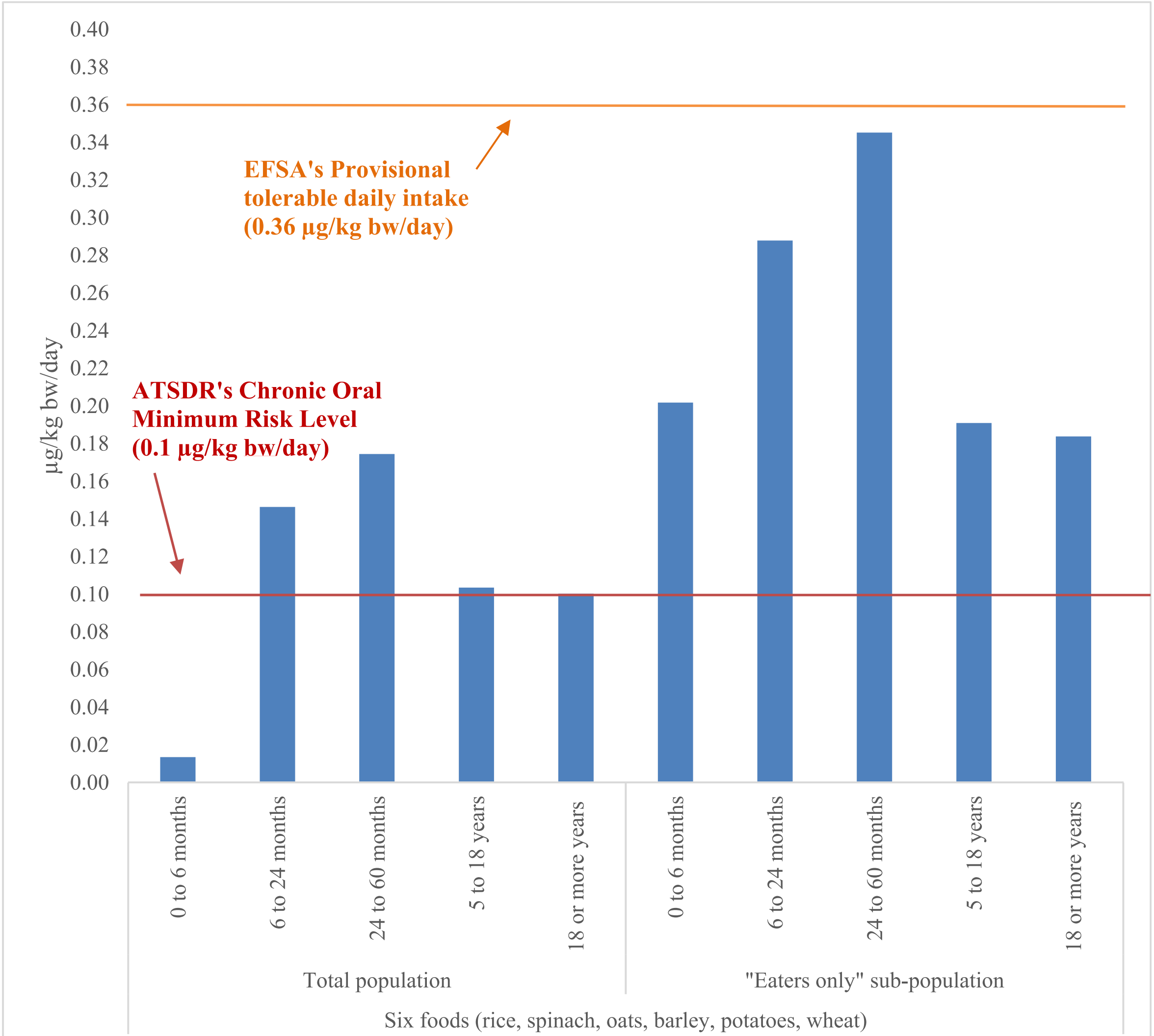


**Fig. 2.** Cumulative average daily dose to cadmium from six common food items in the United States.

years to be about 0.4 µg/kg bw/day (derived from a value of 12.9 µg/kg bw/month) in the US (JECFA, 2011).

Our study has some limitations. The number of samples of rice and spinach tested for Cd, although nationally representative, were small. The food intake data of Americans by age group were from 2005 to 2010 as reported in the FCID database, as intake data in such detail for more recent years were unavailable; although we do not have reason to believe that American diets have changed substantially since that time period. For cumulative ADD values from six different food items, we were not able to calculate the upper 95% CI level for cumulative ADD due to methodological complexity and lack of individual-level data in the FCID database.

There is also the consideration that food and chemical policy groups around the world – in the case of cadmium, JECFA, EFSA, and ATSDR – have set different tolerable daily/weekly/monthly intakes for cadmium (the dose expected to be safe for human exposure), for a variety of reasons: (1) different toxicological or epidemiological studies chosen to derive a safe dose, (2) different uncertainty factors used to extrapolate a safe human dose, and (3) different assumptions about an appropriate health endpoint to target. The estimation of daily vs. weekly vs. monthly tolerable intake introduces further sources of variability. Because at the moment, it is not possible to state that one policy group's estimated tolerable intake of Cd is more valid than another's, we are limited in not being able to conclusively state that one group of Americans will likely develop disease from current Cd exposures. Rather, we can only compare in a relative sense which groups are at highest risk, based on the dietary exposures we calculated. At present, the group that appears at highest risk is the population of young American children, ages 24–60 months, due to relatively high intakes of foods likely to be contaminated with cadmium and less bodyweight over which to distribute the cadmium intake.

The last is a potentially important finding, as the original focus of the 2021 US Congressional Report was on heavy metals in infant food. Indeed, the 6–24 month age category in the US does have estimated Cd exposures exceeding the strictest tolerable intake level, set by ATSDR. Our risk assessment suggests, however, that it may be equally if not more important to focus on the foods that young children 24–60 months old (2–5 years of age) consume in high amounts – because predicted cadmium exposure is highest for this age group in the United States.

In summary, our findings confirm the challenge in setting appropriate standards for cadmium in individual food items, due to the possibility of Cd exposure from multiple foods. At the mean food intake and mean Cd levels, the cumulative exposure from just six food items, commonly used in commercial baby food manufacturing, exceeded ATSDR's chronic oral MRL values for the 6–24 and 24–60 month age groups; and the group estimated to have highest dietary Cd exposure was Americans aged 24–60 months. However, exposures to Cd from individual foods such as rice and spinach are generally low at mean levels of food intake for the total US population – below all tolerable intakes set by regulatory agencies. Thus, in addition to setting action levels for individual foodstuffs, it may also make sense for policymakers to set Cd standards for finished food products such as pureed infant foods of mixed ingredients; as exposure to Cd may come from multiple different ingredients with highly diverse Cd levels.

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## CRediT authorship contribution statement

**Ashish Pokharel:** Data curation, Formal analysis, Writing – original draft, Visualization. **Felicia Wu:** Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition.

## Declaration of competing interest

The authors declare that they have no financial interests that could have influenced the work reported in this paper.

## Data availability

Data will be made available on request.

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