Food influence on lead relative bioavailability in contaminated soils: Mechanisms and health implications
Hong-Bo Li, Meng-Ya Li, Di Zhao, Ya-Guang Zhu, Jie Li, Albert L. Juhasz, Xin-Yi Cui, Jun Luo, Lena Q. Ma

GRAPHICAL ABSTRACT

ABSTRACT
To determine the effects of dietary constituents on soil Pb oral bioavailability, Pb relative bioavailability (RBA) in 3 soils contaminated by zinc smelting (ZS), wire-rope production (WR), and metal mining (MM) was measured under fasted and fed states with 9 foods. Under fasted state, Pb-RBA was 84.4 ± 10.3, 82.6 ± 4.70, and 32.3 ± 1.10% for ZS, WR, and MM soils; however, it decreased by 1.3–3.5 fold to 23.9–58.8, 25.6–49.9, and 14.8–24.2% under fed states with foods excluding Pb-RBA with egg in WR soil (97.3 ± 4.46%), and with cabbage and egg in MM soil (40.0 ± 8.62 and 44.4 ± 0.96%). In the presence of foods, egg and pork with significantly higher protein and fat contents leaded to the highest soil Pb-RBA (44.4–97.3%), while Pb-RBA determined with mineral-rich mouse feed was 1.6–7.9 fold lower (9.41–13.5%), suggesting high fat and protein foods tended to increase soil Pb-RBA, while high mineral diets decreased soil Pb-RBA. The increased Pb-RBA of MM soil with cabbage compared to fasted state was due to high organic content in cabbage, which could increase soil Pb solubility by inhibiting Fe and Pb co-precipitation in the intestine. For accurate assessment of health risks of contaminated soils, dietary influence on soil Pb-RBA should be considered.

Keywords:
Contaminated soil
Lead
Relative bioavailability
Food
In vivo mouse bioassay

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1. Introduction

Lead (Pb) is ubiquitous in the environment, causing adverse health effects [1,2]. Among exposure pathways, incidental ingestion of Pb-contaminated soils comprises a sizable proportion of overall daily Pb intake [3–5]. This exposure scenario is more relevant for children due to their prevalence of hand-to-mouth activities. A strong association was documented between children’s blood Pb levels and Pb concentrations in soils [6,7]. However, to accurately assess the health risk of contaminated soils, it is important to determine Pb bioavailability, i.e., the fraction of soil Pb enters the systemic circulation following soil ingestion, which varies considerably among individual soils [8–10].

Using in vivo swine and mouse bioassays, studies have assessed Pb relative bioavailability (RBA, relative to Pb acetate) in contaminated soils [11–14]. For example, Smith et al. [10] measured Pb-RBA in soils using a mouse model via single soil gavage to fasted mice and using area under blood Pb time curve (AUC) as the endpoint. A steady state model with Pb accumulation in the liver, kidneys, or femur as the endpoint was employed with fasted swine by daily administration of dough ball containing Pb-contaminated soil over a 14–15-d period [9,13]. In addition, there were also reports of soil Pb-RBA determination under fed state where soil was amended into animal feed and administered to mice via food consumption over a 10-d period [15,16]. However, previous soil Pb-RBA determinations mainly aimed to assess the ability of in vitro bioaccessibility assays as a surrogate of in vivo assays [17–19]. No study has considered the modulating effects of dietary constituents on soil Pb-RBA determination. Following incidental ingestion, Pb-contaminated soils may encounter with various types of foods in the gastrointestinal tract.

Previous studies have showed that diet strongly influences Pb absorption and accumulation in humans and animals, suggesting nutrients can be used to modulate Pb toxicity [20]. A sharp decrease in Pb absorption from 35–80% to 4.0–8.2% has been observed in humans when Pb is ingested with foods compared to under fasted state [21–23]. In rats, with increasing dietary fat content from 5% to 40% and protein and fat contents compared to pork and egg. Dietary constituents influencing soil Pb-RBA determination. Results of this study have important implications for applying dietary strategies to reduce the health risks associated with incidental soil ingestion.

2. Materials and methods

2.1. Pb-contaminated soils

Three Pb-contaminated soils were collected from zinc smelting (ZS), wire-rope production (WR), and metal mining (MM) sites in China (Table 1). Soils were air dried and sieved to retrieve the <250 μm size fraction. Total concentrations of Pb, Fe, Mn, Ca, Mg, Cu, Zn, and P in the <250 μm size fraction were determined using ICP-MS (NEXION® 300X, Perkin Elmer, USA) or ICP-OES (Optima 5300DV, PerkinElmer, USA) following triplicate digestion using USEPA Method 3050B. Lead concentrations in ZS, WR, and MM soils were 10.7, 1.02, and 4.16 g kg⁻¹, respectively (Table 1). Detailed description of the elemental concentration is provided in Supplementary Material.

2.2. Foods and mouse feed

Nine common foods, i.e., sugar, polished rice, white wheat flour, ground corn, apple, cabbage, powdered milk, pork, and egg, were purchased from a local market (Table 2), representing different dietary constituents. Following cooked and freeze-dried, foods were analyzed for elements of interest using ICP-MS or ICP-OES following digestion using USEPA Method 3050B. Contents of carbohydrate, protein, fat, and fiber were measured using Chinese National Food Safety Standard Methods GB 5009.5–2010, GB 5009.6–2003, GB 5009.7–2008, and GB 5009.88–2014. Organic acids in foods were measured using high performance liquid chromatography equipped with a UV detector following Milli-Q water extraction [28]. Lead concentrations in the 9 foods were 0.01–0.45 mg kg⁻¹, being >3 orders of magnitude lower than those in soils, suggesting little interference of food Pb on soil Pb-RBA determination. Detailed description of food preparation is shown in Supplementary Material.

Mouse feed was also used when soil Pb-RBA was determined under fed state. Lead concentration in the feed was low at 0.20 mg kg⁻¹ (Table 2). Compared to the foods excluding cabbage, mouse feed was 1–2 orders of magnitude higher in mineral elements, but lower in protein and fat contents compared to pork and egg.

2.3. Pb relative bioavailability assessment under fasted state

A new dosing approach was developed to determine Pb-RBA in soils under fasted state, i.e., repeated daily single gavage of soil suspension to mice over a 10-d period. Female mice (Balb/c) with body weight (bw) of 18–20 g were purchased and housed in polyethylene cages for acclimation with free access to mouse feed and Milli-Q water. Prior to bioassays, the 3 soils were mixed with Milli-Q water to prepare soil suspension containing 35, 60, and 60 mg of ZS, WR, and MM soils in 1.0 g of the suspension. Lower soil mass was used for ZS soil because of its higher Pb concentration than other two soils (Table 1).

Table 1: Elemental concentrations (g kg⁻¹) of 3 Pb-contaminated soils used in this study.

<table>
<thead>
<tr>
<th>Soil</th>
<th>Fe</th>
<th>Mn</th>
<th>Ca</th>
<th>Mg</th>
<th>Pb</th>
<th>Ca</th>
<th>Zn</th>
<th>Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZS</td>
<td>49.0 ± 12.6</td>
<td>0.75 ± 0.18</td>
<td>93.2 ± 32.7</td>
<td>27.5 ± 9.58</td>
<td>0.47 ± 182</td>
<td>0.18 ± 0.06</td>
<td>10.6 ± 3.69</td>
<td>10.7 ± 0.10</td>
</tr>
<tr>
<td>WR</td>
<td>26.1 ± 1.29</td>
<td>0.55 ± 0.03</td>
<td>31.5 ± 0.84</td>
<td>9.82 ± 0.30</td>
<td>1.49 ± 0.08</td>
<td>0.02 ± 0.00</td>
<td>0.75 ± 0.01</td>
<td>1.02 ± 0.02</td>
</tr>
<tr>
<td>MM</td>
<td>128 ± 1.13</td>
<td>11.9 ± 0.28</td>
<td>7.04 ± 0.11</td>
<td>5.87 ± 0.16</td>
<td>1.06 ± 0.01</td>
<td>0.52 ± 0.01</td>
<td>2.63 ± 0.01</td>
<td>4.16 ± 0.08</td>
</tr>
</tbody>
</table>
Following 1 week of acclimation, mice were fasted overnight, weighed, and then randomly assigned to different dose groups with 3 separate mice in one group for each treatment. To establish the linear dose response curve, 3 dosing groups receiving ~6.25, 12.5, and 25.0 μg g\(^{-1}\) bw d\(^{-1}\) Pb were conducted for Pb(AC)\(_2\) treatment. At 9:00 am of each day, 1.0 mL of 125, 250, or 500 mg L\(^{-1}\) Pb(AC)\(_2\) was administered to 3 separate mice, respectively. For soils, one dose level was used by daily administering 1.0 g of soil suspension to 3 mice via gavage at 9:00 am. Lead dose levels were ~2.93, 11.4, and 17.7 μg g\(^{-1}\) bw d\(^{-1}\) Pb for WR, MM, and ZS soils, respectively. In addition, 3 control mice receiving 1.0 mL of Milli-Q water daily at 9:00 am were included to determine background Pb accumulation in mouse tissues.

On each day, following gavage at 9:00 am, mice were kept fasted until 17:00 pm when mouse feed was supplied to the mice. At 21:00 pm, the feed was removed and mice were fasted overnight again for gavage at 9:00 am next day (Fig. S1). The 8 h difference between Pb dose and feeding would minimize the influence of feed consumption on Pb absorption, maintaining the fasted state in mice. In addition, the 4-h feeding daily would maintain the nutritional status of mice, allowing repeated gavaged dose during the 10-d period.

At the end of exposure, mice were weighed and sacrificed to collect liver samples. The tissues were immediately stored at ~80 °C before being freeze-dried. Lead concentration in the liver was determined using ICP-MS following digestion using USEPA Method 3050B. Initially, a linear response of Pb accumulation in the liver with Pb dose under fasted state was established for Pb(AC)\(_2\) (Fig. 1), then Pb-RBA in soils under fasted state was determined as the ratio of the dose-normalized Pb accumulation in the liver following 10-d soil gavage to that following 10-d Pb(AC)\(_2\) gavage (Eq. 1).

\[
Pb-\text{RBA(\%)} = \left( \frac{\text{liver Pb dose soild\text{-fasted}}}{\text{liver Pb dose Pb acetate-fasted}} \right) \times \left( \frac{\text{liver Pb dose soil-fasted}}{\text{liver Pb dose Pb acetate-fasted}} \right) \times 100\%
\]

where, liver Pb\(_{\text{soild\text{-fasted}}}^{\text{liver}}\) and liver Pb\(_{\text{Pb acetate-fasted}}^{\text{liver}}\) are Pb concentrations in liver after 10-d gavaged doses of soil and Pb acetate to fasted mice; and Pb dose\(_{\text{soild\text{-fasted}}}^{\text{soil}}\) and Pb dose\(_{\text{Pb acetate-fasted}}^{\text{soil}}\) are the gavaged Pb doses of soil and Pb acetate to fasted mice.

### 2.4. Pb relative bioavailability assessment under fed state with foods

Soil Pb-RBA under fed state with different foods was determined using a steady state dosing approach via diet consumption over a 10-d period [29, 30]. Initially, diets were prepared by mixing each food with mouse feed at 50% each, which was amended with the Pb-contaminated soils (Table 3). In addition to the diets prepared with 50% food and 50% mouse feed, soil-amended diets were also prepared using 100% mouse feed (Table 3). To assess the influences of foods on Pb absorption under fed states, Pb(AC)\(_2\)-amended diets were also prepared at both 50% food and 50% mouse feed and 100% mouse feed. Detailed description of the diet preparation is provided in Supplementary Material.

Following preparation, ~5 g/mouse of each diet was fed to mice daily ad libitum at 9:00 am, with each treatment having 3 mice. At the end of 10 d exposure, mice were fasted overnight, weighed, and sacrificed to collect liver samples. Food consumption was determined by the difference in total amounts of food supplied and remained. Average daily diet consumption rate was 3–4 g. Lead dose level was calculated as the product of daily food consumption and Pb concentration in diet divided by the average of pre- and post-exposure mice bw. Lead dose levels were ~13, 4, and 7 μg g\(^{-1}\) bw d\(^{-1}\) for ZS, WR, and MM soils, respectively, while it was ~6 μg g\(^{-1}\) bw d\(^{-1}\) for Pb(AC)\(_2\). Liver samples were processed and analyzed similarly to fasted state experiments. Soil Pb-RBA under fed state with foods was calculated by dividing the dose-normalized Pb accumulation in liver following consumption of soil-amended diets to that following repeated gavaged doses of Pb(AC)\(_2\) to
dose-normalized liver Pb accumulation following daily gavaged doses of Pb(AC)2 to fasted mice) was used to calculate Pb-RBA under both fasted and fed states to facilitate assessing the influence of dietary constituents on soil Pb-RBA.

2.5. Sequential gavage of Pb with specific food constituents

To verify the increased soil Pb-RBA with high fat and protein diet, pure wheat starch, wheat fiber, soybean protein powder, and corn oil were used to determine the influences of dietary constituents on Pb absorption from ingested Pb(AC)2 and ZS soil. The other two soils were not included as we observed similar dietary influences for different soils. At 9:00 am each day over a 10-d period, 3 separate mice received a single gavage dose of 0.5 mL of 1 g L⁻¹ Pb(AC)2 or 0.5 mL soil suspension containing ~0.09 g ZS soil, which was followed by sequential single gavage of 0.5 mL of food solutions containing ~0.15 g starch, fiber, or protein, or 0.5 mL corn oil. Following the gavage, mice were kept fasted until 17:00 pm when mouse feed was supplied to the mice. At 21:00 pm, the feed was removed and mice were fasted overnight again for gavage at 9:00 am next day. At the end of 10-d exposure, liver were collected and analyzed for Pb accumulation.

2.6. QA/QC and statistical analyses

For QA/QC, a certified soil reference material SRM NIST 2711a (1400 ± 10 mg kg⁻¹ Pb, National Institute of Standards and Technology) was included. Measurement of the SRM yielded a mean Pb concentration of 1173 ± 21 mg kg⁻¹ (n = 3, recovery of 84%), within the range of acid-extractable concentration of 1100–1400 mg kg⁻¹. During Pb determination using ICP-MS, duplicate analyses, and spike and check samples (10 μg Pb L⁻¹) were included, providing mean deviation between duplicate samples of 0.7% and spike and check recoveries of 98.0 and 99.1% (n = 30). Significant difference in Pb-RBA between treatments was assessed using Fisher’s least-significant difference (LSD) (p = 0.05).

3. Results and discussion

3.1. In vivo Pb dose response and Pb-RBA under fasted state

Prior to assessing soil Pb-RBA under fasted state, in vivo Pb dose response was assessed for the new dosing approach, i.e., repeated daily single gavage of soil suspension over a 10-d period. A strong linear correlation was observed between Pb accumulation in the liver and Pb dose level (R² = 0.98) over a Pb dose range of 6–30 μg g⁻¹ bw d⁻¹ as Pb(AC)2 (Fig. 1A), suggesting the suitability of the newly-developed dosing approach to determine soil Pb-RBA under fasted state. This approach was similar to fasted swine models using daily administration of a dough ball containing Pb-contaminated soils for 14–15 d [9,13].

Previous studies have used a single gavage dose and area under muscle blood Pb time curve (AUC) as the endpoint to determine soil Pb-RBA under fasted state [10,14,31]. Compared to the mouse blood AUC

![Graph](https://via.placeholder.com/150)

**Fig. 1.** Linear response of Pb accumulation in mouse liver with Pb dose level following Pb acetate dosage under fasted state (A), and dose normalized Pb accumulation in mouse liver following Pb acetate dosage under fasted and fed states with food matrix (sugar, rice, wheat, corn, apple, cabbage, powdered milk, pork, or egg) and mouse basal feed (B). Under fasted state, a single dose of Pb acetate was gavaged to fasted animals daily for 10-d, while under fed states, Pb acetate was administered to mice via food-amended feeds for 10-d. Each bar represents the mean and standard deviation of 3 separate mice.

\[
Pb-RBA(%) = \left( \frac{\text{Pb in liver for Pb acetate-fasted}}{\text{Pb in liver for Pb acetate-fasted}} \times \frac{\text{Pb dose for Pb acetate-fasted}}{\text{Pb dose for Pb acetate-fasted}} \right) \times 100%
\]

where, liver Pb_{food} is Pb concentration in liver following 10-d exposure to soil via diet amended with food; and Pb dose_{soil-food} is the soil Pb dose level via diet amended with food. The same reference dose (i.e.,

<table>
<thead>
<tr>
<th>Table 3 Composition of diets prepared by mixing different amounts of food and mouse feed with soil or Pb acetate solution (100 mg L⁻¹ Pb) and resulted Pb concentration in diets to determine Pb relative bioavailability in ZS, WR, and MM soils under fed status.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>soil / Pb acetate</strong></td>
</tr>
<tr>
<td><strong>food</strong></td>
</tr>
<tr>
<td>ZS</td>
</tr>
<tr>
<td>WR</td>
</tr>
<tr>
<td>MM</td>
</tr>
<tr>
<td>Pb acetate</td>
</tr>
</tbody>
</table>

* representing 9 foods including sugar, rice, wheat, corn, apple, cabbage, milk, pork, and egg.
difference might be attributed to different contamination sources. More soluble Pb species in gastrointestinal (GI) fluids were probably dominated in ZS and WR soils contaminated by artisanal Zn smelting and molten Pb activities [32]. This was confirmed by X-ray diffraction analysis, showing the presence of calcium lead oxide in ZS soil (Fig. S2). For MM soil contaminated by mining activities, Pb may be present as less soluble Pb species such as galena and Pb sulfate, which have been identified in mining-impacted soils [9,31]. In addition, Pb-RBA in MM soil may also be influenced by its much greater Fe and Mn concentrations (128 and 11.9 g kg\(^{-1}\) vs. 26–49 and 0.5–0.8 g kg\(^{-1}\), Table 1). Lead sorption onto Fe/Mn oxides in MM soil may decrease Pb dissolution in the GI tract [33].

3.2. Pb-RBA under fed state with foods

Using a steady state mouse model via soil-amended diets over a 10-d period, Pb-RBA in 3 soils was determined under fed state with 9 foods (Eq. 2). The diets prepared from 50% food and 50% mouse feed (i.e., food matrices) showed similar mineral concentrations except for cabbage-amended diet (Table S1). However, the pork and egg diets contained significantly higher protein and fat contents (28–36 and 17–30%) than other diets (10–19 and 1.8–9.0%). Daily diet consumption by mice was 3–4 g per mouse, being similar between different diets except for relatively lower rate for pork diet (Fig. S3).

Overall, compared with fasted state, soil Pb-RBA under fed state with foods was significantly lower (Fig. 2A–C). In ZS soil, Pb-RBA was reduced from 84.4 ± 10.3% under fasted state to 23.9–58.8% under fed state with foods. A similar decrease in Pb-RBA from 82.6 ± 4.7 to 25.6–49.9% was observed for WR soil excluding the egg diet showing enhanced soil Pb-RBA at 97.3 ± 4.5%. For MM soil, Pb-RBA was reduced from 32.2 ± 1.1 to 14.8–24.2% excluding the cabbage and egg diet at 40.0 ± 8.6 and 44.4 ± 1.0%. High fat and protein contents in egg diet and high organic acid content in cabbage diet were probably responsible for the enhanced Pb-RBA in WR and MM soils which was discussed in details later. Our study was the first report of the influences of real foods on soil Pb-RBA. Studies have assessed the influences of dietary factors on Pb absorption from soluble Pb such as Pb(AC)\(_2\) or PbCl\(_2\) [23,24]. Our results were similar to reports that soluble Pb is absorbed in a much lower extent under fed state (4.0–8.2%) than fasted state (35–80%) [21,22].

Decreased Pb absorption across the GI barrier probably contributed largely to the lower soil Pb-RBA under fed state. To test this hypothesis, accumulation of soluble Pb as Pb(AC)\(_2\) in mouse liver was also determined under fed state in the presence of 9 foods. Similar to soils, reduced Pb(AC)\(_2\) accumulation in mouse liver from 0.26 to 0.06–0.20 μg g\(^{-1}\) was observed under fed state with sugar, rice, wheat, corn, apple, and cabbaged compared to fasted state accumulation (Fig. 1B), suggesting the contribution of decreased Pb absorption to lower soil Pb-RBA under fed state. The decreased Pb absorption with food was possibly attributed to competition of divalent metal ions in the diets including Fe, Ca, Mg, Zn with Pb for absorption transporters. Lead shares several absorption transporters with divalent metal ions [34]. Absorption of ingested Pb tracers averaged 63% in eight male volunteers when ingested without Ca and P, but its absorption decreased to 11% with Ca and P [35]. In addition, in vivo formation of insoluble Pb phosphate such as pyromorphite might also contribute to decreased Pb-RBA under fed state [31]. However, it should be noted there was difference in influence of milk, egg, and Pb on Pb bioavailability between the soils and Pb(AC)\(_2\). Pb(AC)\(_2\) accumulation in mouse liver (0.23–0.28 μg g\(^{-1}\)) under fed state with milk, pork, and egg was comparable to fasted state (Fig. 1B), while milk and pork significantly decreased Pb-RBA in all the 3 soils and egg leaded to increased soil Pb-RBA in WR and MM soils (Fig. 2). The difference suggested that in addition to Pb absorption across the GI barrier, Pb dissolution from soils might also be affected by the presence of foods, which depended strongly on soil properties.
Until now, there was no report of soil Pb-RBA determination in the presence of different diets. Studies employed in vitro bioaccessibility assays to assess dietary influence on soil Pb bioavailability, showing increased soil Pb solubility in simulated human GI fluids when powdered milk was added [36,37]. However, our study showed that Pb-RBA determined under fed state with milk-amended diets was significantly lower compared to fasted state for all the 3 soils. The inconsistency suggested the importance of using bioassays to accurately assess dietary influences on soil Pb bioavailability.

3.3. Higher soil Pb-RBA under fed state with egg and pork

Under fed state with different foods, we observed that Pb-RBA in the 3 soils was the highest with egg or pork which showed significantly higher contents of protein and fat (Fig. 2), suggesting the potential of increased soil Pb-RBA with diets higher in protein and fat. One explanation is that high-protein and high-fat diets caused a decrease in food motility in GI track, increasing transit time in proximal small intestine and allowing a longer time for Pb to enter epithelial mucosal cells in the duodenum where main Pb absorption occurs [38]. This was reflected by lower daily diet consumption rate by mice when pork was amended to the diet compared to other foods (Fig. S3). In addition, high-fat and high-protein diets can enhance bile secretion in the GI tract [39], increasing Pb absorption [40]. Also, excessive fat intake could increase the intestinal permeability via activation of mast cells in the intestinal mucosa [41], which might in turn favor Pb absorption. In addition, a reduction in the enzyme activity of alkaline phosphatase has been observed in rats receiving high-fat diet [42], reducing the production of phosphate anion and free hydroxyl in the duodenum. This probably enhances Pb solubility when the acid gastric lumen is mixed with neutral bile salt and pancreatin. Further studies are needed to identify the dominant mechanisms of increased soil Pb-RBA with dietary fat and protein.

To verify the increased soil Pb-RBA with high fat or protein diets, influence of sequential gavage of Pb(AC)2 and ZS soils with pure food constituents (starch, fiber, protein, and oil) on Pb absorption in mice was investigated (Fig. 3). The data showed that after sequential gavage of corn oil, dose-normalized Pb accumulation in mouse liver from Pb (AC)2 and soil Pb dose significantly increased from 0.14 ± 0.01 and 0.11 ± 0.02 to 0.55 ± 0.22 and 0.60 ± 0.08 μg g⁻¹, while sequential gavage with starch, fiber, or protein showed little influence on Pb accumulation in the liver. The data ascertained that fat might be the most important dietary factor that increased soil Pb-RBA.

3.4. Decreased soil Pb-RBA with increasing dietary minerals

In addition to soil Pb-RBA determination under fed state with food and mouse feed matrix (50% each), soil Pb-RBA was also determined using 100% mouse feed matrix. Since mouse feed was significantly (p < 0.05) richer in mineral concentrations (e.g., Fe, Mn, Ca, and Mg) than the 9 foods except for cabbage (Table 2), the mouse feed diet was significantly (p < 0.05) higher in mineral contents than the diets prepared at 50% food and 50% mouse feed (Table S1).

Under mouse feed matrix, Pb-RBA was 13.5 ± 2.35, 12.3 ± 0.88, and 9.41 ± 1.39% for ZS, WR, and MM soils, respectively, being significantly (p < 0.05) lower than those determined under fed state with the 9 foods (Fig. 2), suggesting high dietary mineral content had a potential to decrease soil Pb-RBA. This could be explained by the competition between Pb and mineral nutrient (e.g., Fe, Ca, Mg, Zn) for shared absorption transporters [34]. The results suggested that consumption of high mineral diets or dietary mineral amendments might be effective in reducing Pb bioavailability in contaminated soils, thereby alleviating the associated health risk for children living nearby contaminated sites.

However, it should be noted that although cabbage contained significantly higher minerals than mouse feed (Table 2), Pb-RBA in the 3 soils determined with cabbage was significantly higher than that with mouse feed (Fig. 2). An increase in Pb-RBA in MM soil with cabbage compared to fasted state was even observed (Fig. 2C). One possible explanation is that compared to other foods, cabbage contained the highest concentrations (158 mg g⁻¹) of organic acids (Fig. S4). The dominant organic acid in cabbage was oxalic acid (53.2 mg g⁻¹), followed by phytic, acetic, succinic, malic, and citric acids (7.95–26.4 mg g⁻¹). In vitro Pb bioaccessibility assays have shown that organic acids especially citric acid inhibit Pb co-precipitation with Fe under neutral intestinal conditions, thereby increasing Pb solubility in the GI tract and leading to high Pb absorption [33]. Increased Pb absorption with dietary citrate has been observed in rats [27], supporting higher soil Pb-RBA with cabbage-amended diet.

For cabbage, the increased soil Pb solubility in the gut with high contents of organic acids might counteract the decreased Pb absorption across the GI barrier with high mineral contents, thereby leading to higher Pb-RBA in soils under fed state with cabbage compared to with mouse feed. However, increased Pb-RBA with cabbage compared to fasted state was only observed for MM soil (Fig. 2C), possibly due to significantly higher Fe concentration in MM soil than other two soils (Table 1). In MM soil, Pb solubility in the GI tract might be controlled by Fe dissolution and precipitation at a greater extent. Via inhibiting Fe precipitation, the influence of organic acids on soil Pb solubility would be greater in MM soil than other two soils. Therefore, for high Fe soil, the presence of foods with high organic acid content in the gut might intensify Pb toxicity. Further quantitative studies are needed to compare the contrary influences of dietary minerals and organic acids on Pb absorption.

3.5. Health implication

In this study, an overall significant decrease in soil Pb-RBA with food consumption were observed compared to fasted state (Fig. 2), which were influenced by dietary fat, protein, and mineral contents. One important health implication is that assessment of Pb-RBA in soils under fasted state might overestimate the risk of soil Pb to humans. In addition, the impact may vary considerably depending on foods consumed. For example, under fasted state, significant lower Pb-RBA was observed in MM soil (32%) than ZS and WR soils (82–84%). However, under fed state with cabbage-amended diet, Pb-RBA in MM soil increased to 40%, being similar to that in ZS (40%) but higher than that.


21 H.M. James, M.E. Hilburn, J.A. Blair, Effects of meals and meal times on uptake of lead from the gastrointestinal tract in humans, Hum. Toxicol. 4 (1985) 401–407.


29 S.W. Li, H.J. Sun, H.B. Li, J. Luo, L-Q. Ma, Assessment of cadmium bioaccessibility to predict its bioavailability in contaminated soils, Environ. Int. 94 (2016) 600–606.


38 T. Suzuki, H. Hara, Dietary fat and bile juice, but not obesity, are responsible for the increase in small intestine permeability induced through the suppression of tight junction protein expression in LETO and OLETF rats, Nutr. Metab. 12 (2010) 7–19.

