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Factors Affecting Cadmium Accumulation and Mitigation: A Literature Review to Inform Spinach and Carrot Producers

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Abstract. **Cadmium (Cd), a nonessential element with potential adverse health consequences, enters the human food system predominantly through plant uptake from soils. In the United States, some regions that are known to have elevated levels of Cd are otherwise ideal for the production of fresh produce, including spinach (*Spinacia oleracea* L.) and carrots (*Daucus carota* L.). Given the considerable nutritional benefits of these commodities, they are often incorporated into the diets of infants and young children, either as processed ingredients or as those eaten whole. To reduce levels of dietary Cd and support the US Food and Drug Administration's Closer to Zero initiative, it is important to understand factors that affect the Cd uptake by crops (i.e., phytoavailability) and the ability of Cd to be absorbed by the human body (i.e., bioavailability) from crops such as carrots and spinach. The state of knowledge of factors that affect the phytoavailability of Cd in these two crops and potential mitigation strategies to benefit growers as they consider their individual soils, crops, and circumstances are summarized. These include amending soil (with organic amendments, such as manures, composts, or biosolids, chloride, or elements such as zinc), the potential use of cultivars with lower rates of uptake, and the use of novel methods such as phytoextraction. The impact of some of these mitigations on microbial food safety efforts is also noted.**

Questions and concerns regarding the potential adverse health effects associated with dietary exposure to heavy metals and metalloids [e.g., arsenic, cadmium (Cd), lead (Pb), and mercury] are longstanding. These toxic elements can be present in foods because they are in the soil, water, or air (e.g., dust) where food crops are grown, harvested, or processed; as a result, they may be associated with a wide range of foods. Soils that contain elevated levels of these toxic elements, whether from natural sources, soil amendments, or industrial sources, can lead to accumulation in crops grown on that land. In other cases, they may be introduced during food processing and manufacturing (e.g., from food contact surfaces) (US Food and Drug Administration 2004). The relationship between bioavailability of Cd in crops and the impact on human health is an active area of research.

Considerable interest has been generated regarding the dietary exposure of infants and young children to these toxic elements (Hoffman-Pennesi et al. 2024; Subcommittee on Economic and Consumer Policy, US House of Representatives 2021) because data indicate that infants and young children are generally more vulnerable to their effects (Gray 2023; Meharg et al. 2008). Food intake per kilogram of body weight is higher for infants and young children than for adults, causing higher exposures (e.g., μg Cd/kg body weight/day) at a given toxic element concentration in food. In response, the US Food and Drug Administration (FDA) created the Closer to Zero initiative to reduce dietary exposures to these toxic elements in infants and young children and limit unintended consequences such as restricting foods from the marketplace that have significant nutritional benefits (US Food and Drug Administration 2021). This initiative recognizes that reducing levels of toxic elements in foods is complicated and multifaceted and involves components such as the following: 1) developing improved testing methods capable of measuring lower levels of toxic elements in foods; 2) identifying toxicological reference values for these contaminants to determine levels of concern; 3) conducting surveys of foods commonly eaten by infants and young children to assess variability in levels of the toxic elements in these foods; 4) evaluating consumption patterns; 5) understanding how nutrients in foods can help protect against adverse health effects of toxic elements in foods; 6) establishing action levels; and 7) encouraging the adoption of agricultural and food processing practices by industry to lower levels of toxic elements in agricultural commodities and food products.

In Oct 2023, the Western Growers Association in collaboration with the FDA and US Department of Agriculture held a pilot workshop to facilitate collaboration between industry, government, and academia to benefit food safety and public health. The workshop focused on Cd in spinach and carrots grown in California and Arizona. The workshop included discussions of the health effects of Cd, nutritional benefits of carrots and spinach, crop production practices, research on plant uptake, and Cd mitigation methods and practices (Leaman et al. 2025). Information exchanged during this workshop, which was attended by the majority of the authors, and additional literature searches helped to inform this publication. At the workshop, attendees suggested that such a review would be helpful for growers of these crops in the major US growing regions.

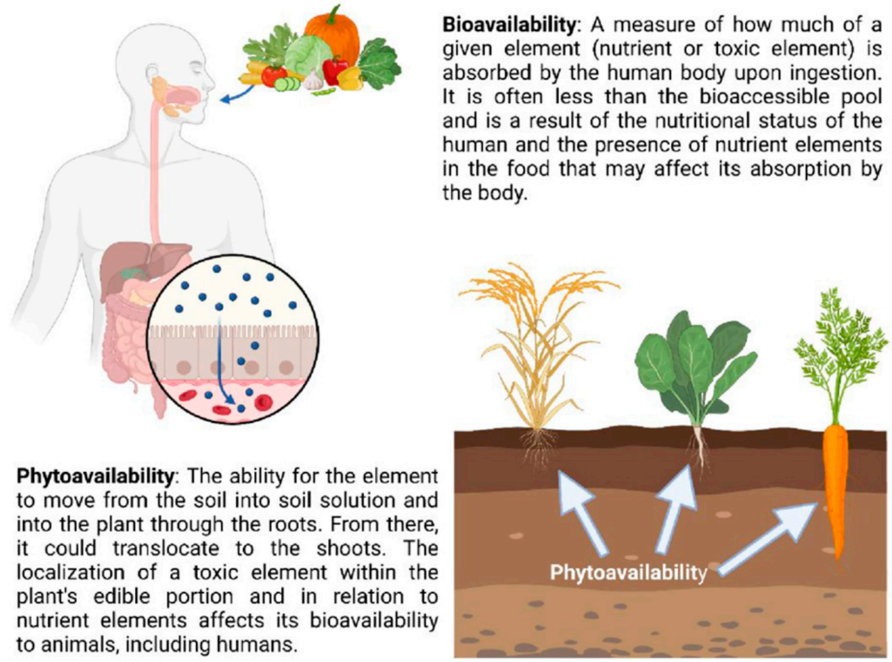

Fig. 1. Bioavailability vs. phytoavailability.

As a nonessential element with no biological function in plants or humans, Cd can adversely impact human health, even at low concentrations, and is often readily taken-up by plants (Schaefer et al. 2022, 2023; Wagner 1993). The levels of Cd detected in some food products occasionally have triggered regulatory action by the FDA (US Food and Drug Administration 2024). This has ignited discussions among crop producers, food processors, crop marketers, researchers, regulators, and other stakeholders about the factors that influence Cd accumulation by crops, the bioavailability of Cd in foods, the contribution of individual foods to overall exposure (Scrafford et al. 2025), and approaches to mitigation.

The human food system is predominantly affected by Cd through plant uptake from soils (Chaney 2015; Kubier et al. 2019; McLaughlin et al. 2021). Sources and levels of Cd present in soil across the United States vary (Holmgren et al. 1993; Smith et al. 2013). Some regions that are known to have elevated levels of Cd are otherwise ideal for the production of fresh produce, including spinach and carrots. Given the considerable nutritional benefits of these commodities, they are often incorporated in the diets of infants and young children, either as processed ingredients or as those eaten whole; therefore, they were selected for this review.

To help support the Closer to Zero initiative, because there are no regulatory limits for the amount of Cd in agricultural soils, it is important to understand factors that affect Cd uptake by crops (i.e., phytoavailability) and the ability of Cd to be absorbed by the human body (i.e., bioavailability) from crops such as carrots and spinach (Fig. 1). These insights can help determine mitigation measures and identify where data gaps remain.

Recent work has highlighted the differences between metals (Cd and Pb) in their phytoavailability to spinach, approaches to mitigate the phytoavailability of Cd and Pb to spinach, and, consequently, the exposure of humans to Cd and Pb in leafy greens (Seyfferth et al. 2024). The focus of this work is on two contrasting crops—spinach and carrots—and their association with Cd, although many other foods have been associated with Cd or other potentially toxic elements. The state of knowledge of factors that affect the phytoavailability of Cd to spinach and carrots and potential mitigation strategies to benefit growers as they consider their individual soils, crops, and circumstances are summarized. Although this work focused on factors that influence levels of Cd in spinach and carrots, the concentration of Cd in edible crop tissues is not the only factor to consider when understanding human health impacts. Another factor, bioavailability of Cd in the diet, is a similarly complex nutritional and biochemical process. For example, certain nutrients [e.g., iron (Fe), zinc (Zn), calcium (Ca)] present in spinach and carrots can inhibit Cd absorption by humans (Reeves and Chaney 2008). While bioavailability will be addressed in a forthcoming review, the relationship between varying soil compositions, their impact on crop Cd levels, and subsequent dietary effects are briefly described. Because research specific to Cd in spinach and carrots is limited and continues to be explored, this review also draws from the experiences and knowledge gained from other crops and mitigation techniques to the extent that they may reveal insights applicable to reducing levels of Cd in spinach and carrots.

Sources of cadmium in soils in US regions where spinach and carrot are grown. In general, plants grown in soils with higher levels of Cd have higher plant Cd levels. There are multiple sources of Cd in soils (McLaughlin et al. 2021; Pan et al. 2016) that are both geogenic (naturally occurring) and anthropogenic (human influenced). Managing geogenic Cd is more challenging than anthropogenic Cd because the high Cd concentration is not limited to surface layers (Burau 1983); these geogenic subsurface soil horizons also contribute a significant amount of Cd to crops, depending on the rooting depth of plants (deVries and Tiller 1978; McLaughlin et al. 2021).

Geogenic sources of Cd include the weathering of Cd-rich rocks, minerals, and other organic and inorganic earthly substances (Chaney et al. 2006; Cheng et al. 2005; Jacob et al. 2013; Jyoti et al. 2015), Cd-adsorbing carbonate rocks (Quezada-Hinojosa et al. 2009), shale parent materials, and weathering of black shales (Liu et al. 2022; Park et al. 2010), all of which may contribute to increased phytoavailability of Cd in soils. Overall, metamorphic rocks have lower concentrations of Cd than sedimentary deposits, which are found closer to the earth's surface (Kabata-Pendias 2010). Additionally, Cd is released from mineral lattice layers into more soluble forms and then adsorbed by surfaces of soil organic matter, clays, and Fe and manganese (Mn) hydrous oxides (Robson et al. 2014). Often, Cd is accumulated in higher concentrations in phosphatic sedimentary rocks (McLaughlin et al. 2021). In the case of black shales, exposed sulfides, mostly pyrite and sphalerite, are oxidized to release Cd (Liu et al. 2013; Perkins and Mason 2015). In some locations, the natural Cd is from phosphate ore, while in other locations higher natural Cd is attributed to parent rock other than phosphate, such as shale-derived soils in the European Union (Birke et al. 2017). Maps of soil Cd, soil Zn, and soil Cd:Zn reveal areas with high Cd:Zn soils in many nations (Birke et al. 2017). Some of these soils are known for production of crops with an affinity for Cd uptake and require special management to produce marketable plant products. Growing spinach and carrots in areas low in Cd may not always be practical, and mitigation and management strategies discussed in this work can be used to reduce plant uptake and potential for human health impacts.

The US Geological Survey has developed "heat maps" showing levels of Cd at varying

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depths in US soils (Smith et al. 2014). Figure 2A and 2B show the amounts of Cd in horizon A (topsoil) and horizon C (weathered rock), illustrating that Cd is present at appreciable soil depths in many areas.

Agricultural soils used for the production of 12 different crops in the United States had levels of soil Cd ranging from 0.01 to 2 mg/kg (Burau et al. 1981; Holmgren et al. 1993). Some soils may have even higher levels, such as those derived from shale parent material in specific regions or where Cd-bearing inputs such as limestone and phosphate rock or industrial emissions have accumulated (Chaney 2012; Mulla et al. 1980; Page et al. 1986). Agricultural soils have levels approaching 9 mg/kg in some places (Burau 1983; Burau et al. 1981; Page et al. 1986).

In addition to geogenic sources of Cd, human activities can also impact levels of Cd in soil. For example, upstream mining of Zn or Pb ores and failure to control release of those

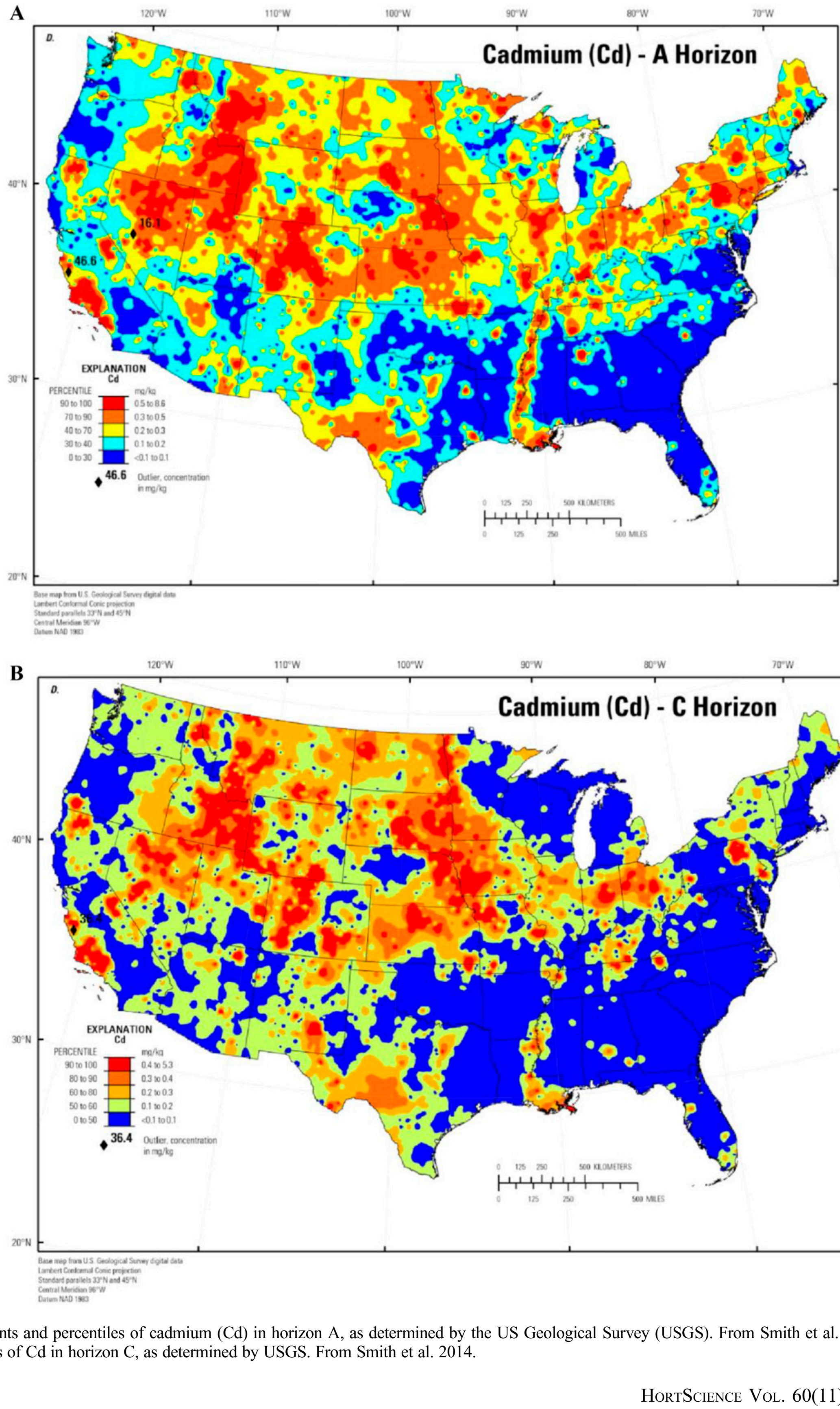

Fig. 2. (**A**) Amounts and percentiles of cadmium (Cd) in horizon A, as determined by the US Geological Survey (USGS). From Smith et al. 2014. (**B**) Amounts and percentiles of Cd in horizon C, as determined by USGS. From Smith et al. 2014.

wastes to rivers used to irrigate rice (*Oryza sativa* L.) paddies allowed high accumulations of Cd and Zn in rice paddy soils in Japan, China, and Thailand (Chaney 2015; Kobayashi 1978). The mine waste-contaminated soils caused high Cd levels in rice, and humans suffered osteomalacia resulting from high Cd exposure (*itai-itai*, or ouch-ouch disease). This was the first example of food-related disease in humans caused by Cd exposure.

In general, Cd levels in agricultural soils have increased somewhat over time, in part because of the application of phosphate fertilizers (Suciu et al. 2022). Australia and New Zealand have set maximum levels and conducted research on Cd mitigation given the accumulation in their soils that was caused by phosphate fertilizers sourced from ores (island guano deposits) that were rich in Cd (McLaughlin et al. 2021). The production of low-Cd phosphate fertilizers, partly in response to national regulations, has slowed Cd accumulation substantially (Smolders 2017). If feed ingredients containing elevated Cd levels are fed to livestock, then the resulting manures, when used as soil amendments, may increase soil Cd levels faster over time than current phosphate fertilizers. Some soil amendments historically contained relatively high levels of Cd and higher Cd:Zn ratios, adding to Cd uptake by crops (Chaney 2012). Given the microbiological food safety risk associated with manure and other biological soil amendments of animal origin, the US FDA and Environmental Protection Agency have set microbial food safety standards for their use in fresh produce growing operations, including spinach and carrot production (US Food and Drug Administration 2015). Specifically, 21 CFR Part 112.53 notes that growers may not use human waste for growing covered produce, except sewage sludge biosolids used in accordance with the requirements of 40 CFR part 503, subpart D, or equivalent regulatory requirements. This prohibition also appears in many food safety audits (California Leafy Greens Marketing Agreement 2023). Growers should consider not only the microbiological food safety risk of fertilizers and amendments used in their operations but also whether the sources of those amendments are associated with elevated Cd levels that may necessitate additional verification steps before supplier approval or use.

Influence of zinc and other elements on cadmium in crops. The uptake of Cd by many crops is strongly affected by co-occurring Zn, making this element important in the potential mitigation of Cd. In these crops, Cd is accumulated on the Zn-uptake transporter (ZIP). Rice is an exception because Cd is absorbed on the reduced natural resistance-associated macrophage protein (NRAMP) 5 (NRAMP5) transporter, while Zn is absorbed on a ZIP transporter (Ishikawa et al. 2012). Animal feeding studies suggest that higher levels of Zn in the edible portion of the crop could confer benefits related to lower Cd bioavailability to consumers (Reeves and Chaney 2008). When the ratio of Cd:Zn is higher than normal background levels (1:100), crops can naturally accumulate higher levels of Cd. Conversely, higher soil Zn concentrations, and thus lower Cd:Zn ratios, can limit Cd accumulation (Chaney 2012; Wang et al. 2023). For example, Monterey shale soils in California are unique because they contain low Zn but are higher in Cd than most California and other US soils, which can lead to elevated Cd in plants grown on these soils (Burau et al. 1981; Paul and Chaney 2017; Smith et al. 2013).

Laboratory animal feeding studies support that the levels of Zn in the edible portion of the crop can also potentially confer benefits related to lower Cd bioavailability (Reeves and Chaney 2008). Therefore, increasing Zn levels in spinach and carrots may offer a protective effect. Most biosolids have 100-fold higher Zn compared with Cd, and Zn can inhibit Cd absorption both in the crop and in the intestine of laboratory animals (Chaney et al. 1978b). For example, Chaney et al. (1978b) grew Swiss chard (*Beta vulgaris* L., var. *cicla*) on field soils amended with three biosolids of varied composition plus a control. The biosolids-amended soils had higher ratios of Zn to Cd (ranging from 138- to 390-times as much Zn than Cd) compared with the control soil, which had a Zn:Cd ratio of approximately 10:1. Even when the amended soils contained higher levels of Cd than those of the control soil (up to four-times as much total Cd), and the resulting chard also contained more than five-times as much Cd compared with chard grown in control soil [0.5 ppm Cd dry weight (DW) vs. up to 2.7 ppm Cd DW], the levels of Cd in the kidney and liver of guinea pigs (*Cavi porcellus* L.) fed this chard as 20% or 28% of their diet for 80 d were not increased compared with those of the control (Chaney et al. 1978b). In the following year, Chaney et al. (1978a) grew Romaine lettuce (*Lactuca sativa* L. var. *longifolia*) on the same plots used for conducting laboratory animal feeding tests. When Milorganite (a high Cd-containing and high Cd:Zn ratio heat-dried activated biosolids product usually used as a slow-release "organic" nitrogen fertilizer) was applied, Cd in Romaine lettuce was greatly increased (26.4 ppm DW Cd) compared with the three biosolids products in the previous year's study (range, 1.7–11.6 ppm DW Cd) (Chaney et al. 1978a). Mice (*Mus musculus* L.) were fed this lettuce as 45% of the diet. The Cd levels in the kidneys of mice fed lettuce with the highest Cd level increased compared with those of mice fed control lettuce without a direct or predictable relationship between the intermediate Cd levels in the lettuce and in the kidneys. McKenna et al. (1992a, 1992b) grew lettuce and spinach to achieve similar concentrations of leaf Cd (9.6–10.7 mg/kg DW) with either high (400–449 ppm Zn DW) or low (58–96 ppm Zn DW) Zn concentrations. Although not statistically significant when assessed within plant species, when crops were pooled, Japanese quail (*Coturnix japonica*) fed the higher-Zn leafy greens had lower levels of Cd accumulated in the liver and kidney than those of quail fed the lower-Zn leafy greens. Specifically for leafy greens, increased Zn could potentially decrease the bioavailability of Cd to humans, but additional research of the effects of Zn on Cd bioavailability and its effects in humans is needed.

Influence of soil chemistry and soil pH on cadmium phytoavailability. As illustrated in Fig. 3, in addition to Cd and Zn concentrations, soil properties including chloride ion concentration, pH, and organic matter (as well as Fe and Mn hydrous oxides and the microbial community; not shown in figure) influence the phytoavailability of Cd in soils (Seyfferth et al. 2024).

Increasing chloride in the soil–plant system increases the phytoavailability of Cd. In the soil solution, chlorine occurs as the chloride anion (Cl^-). The Cl^- content of soil varies because of several factors, such as underlying parent bedrock, deposition from sea spray and dust, use of high chloride-containing irrigation water, and use of fertilizers (e.g., KCl) and biological soil amendments of animal origin that are inherently rich in chloride (Geilfus 2019).

Chloride increases the uptake of Cd in spinach plants (Brierley and Sanchez 2017; Smith and Hartz 2017) and other crops because it complexes with Cd^{2+} to form $CdCl^+$, which is less strongly adsorbed than Cd^{2+}, and thus more soluble and more mobile in soil than Cd^{2+}. Smith and Hartz (2017) performed a pot study and showed that the spinach tissue Cd concentration increased linearly with the increasing irrigation water Cl^- concentration; in other words, each meq/L increase in irrigation water Cl^- corresponded to an increase 0.25 mg/kg in spinach dry tissue Cd concentration.

Growers should consider minimizing the use of Cl^--containing fertilizers (e.g., K_2SO_4 rather than KCl) and high chloride manures. However, given that coastal irrigation wells typically have Cl^- levels ranging from 1 to 8 meq Cl^-/L, finding wells with lower Cl^- may be difficult for growers depending on their location. For example, fields irrigated with water at the high end of this range (8 meq Cl^-/L) may have spinach Cd concentrations more than 24% higher than those of wells with 2 meq Cl^-/L (Smith and Hartz 2017). However, limiting chlorine in irrigation water may lead to undesirable microbiological consequences because chlorine-containing antimicrobials are important to reducing crop disease and microbial contamination.

Water treatment involving chlorine is increasingly used for certain crops, such as leafy greens. Growers should consider the totality of hazards and mitigation strategies so the mitigation of one group of hazards (i.e., microbiological) does not significantly increase the risk of another group of hazards (e.g., Cd).

Soil chemical properties including pH and organic matter also strongly influence Cd phytoavailability, as described by Seyfferth et al. 2024. Soil pH is a primary variable that affects phytoavailability of metals (e.g., Cd^{2+}) because of its effect on metal adsorption on soil surfaces. In general, Cd phytoavailability decreases as soil pH increases (Yi et al. 2020). Increased soil pH increases Cd adsorption to

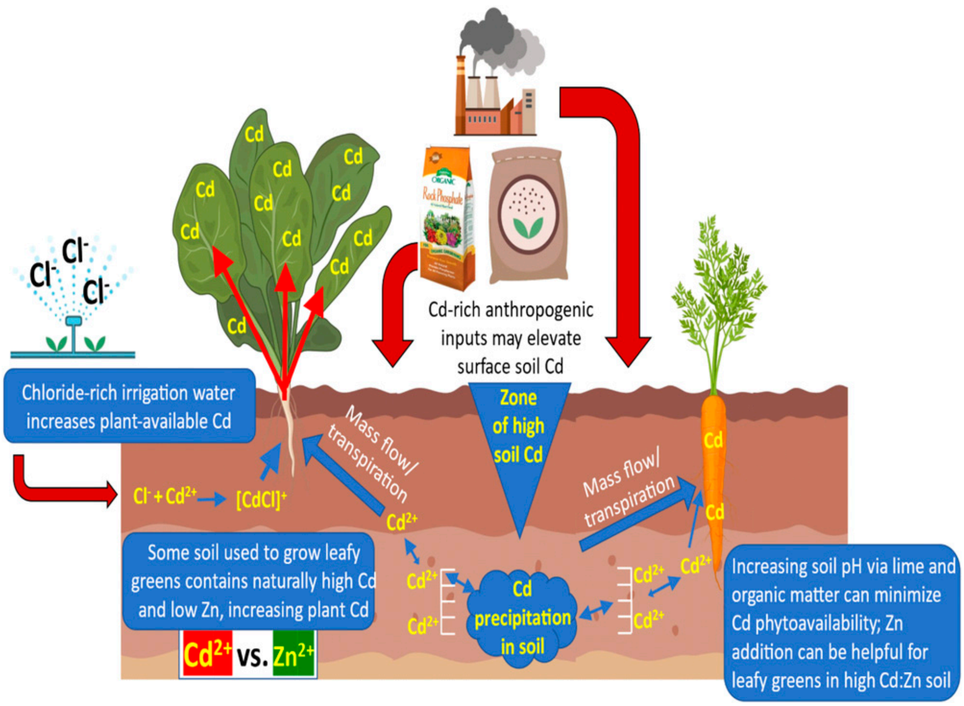

Fig. 3. Summary of processes in soils, crops, and the environment that influence cadmium (Cd) accumulation in cropland soils, which, in turn, can affect concentrations of Cd in crops grown on the soil and the bioavailability of Cd in those crops. Although Cd added to the soil surface remains in the tillage depth for centuries, naturally Cd-mineralized soils can be high in Cd throughout the A, B, and C horizons down to the parent materials below the C horizon.

clay particles, organic matter, and the hydrous oxides of Fe and Mn (Degryse et al. 2009; Kumarpandit et al. 2017; Paul and Chaney 2017; Prokop et al. 2003; Sato et al. 2010). Thus, liming acidic soils has been effective at decreasing Cd phytoavailablity in a variety of crops (Cavanagh et al. 2019; Chaney et al. 2009; Kumarpandit et al. 2017; Pandit et al. 2012). However, for soils with a high Cd:Zn ratio, liming can reduce Zn phytoavailability, thus causing increased Cd accumulation (Paul and Chaney 2017).

Influence of soil organic matter on cadmium phytoavailability. In addition to pH, other factors such as the addition of organic matter (e.g., composts, livestock manures, biosolids, biochars) that promote Cd adsorption/chelation to soil particles tend to decrease Cd phytoavailability by increasing the surface area for adsorption of cations like Cd^{2+} and helping to retain Cd in soil.

Sources of organic matter used in agriculture include manure and composted manure, biosolids and biosolids composts, biochars, and urban plant debris composts. Many sources of organic matter will be composted to protect crops from microbial contamination. This is especially true for organic amendments used in production of leafy vegetables. Before the US Environmental Protection Agency (EPA) and states developed regulations for biosolids use on cropland, some biosolids had more than 1000 mg Cd/kg DW and a high Cd:Zn ratio (Chaney et al. 1978b). Such high Cd-containing biosolids contributed to elevated Cd levels because plant Cd uptake was quite high when plants were grown on these amended soils. Leafy vegetables, particularly spinach and tobacco (*Nicotiana tabacum* L.), accumulate high Cd concentrations when soil Cd is highly phytoavailable. However, the regulation of biosolids use on cropland and limitations on the discharge of industrial wastes to sewer systems has greatly diminished Cd in biosolids. Levels for most US biosolids were less than 5 mg/kg DW (with more than half <2 mg Cd/kg DW in 2023 based on unpublished data from the US EPA). Biosolids constituents (e.g., emerging contaminants like PFAS) and regulation continue to evolve and should be considered when choosing amendments. In addition, if the organic amendment contains high chloride levels, then annual applications may be limited to avoid increased Cd accumulation by crops.

Many forms of organic matter additions can reduce Cd accumulation by crops (Liu et al. 2024). Vegetables grown on soils rich in organic matter (even strongly acidic peat soils) have the lowest levels of Cd compared with acidic or alkaline mineral soils, even when the soil has accumulated significant amounts of Cd from applied phosphate fertilizers used with high-value vegetable crop production. Although the organic matter-rich soils are often acidic, potentially increasing Cd uptake, the high specific adsorption capacity of organic soils reduces Cd phytoavailability in lettuce and spinach (Holmgren, Chaney, and Meyer, unpublished data) as well as in carrots (Ding et al. 2013).

Another soil amendment, biochar, which is a charcoal-like substance, may also be useful in increasing the Cd binding of an amended soil (Nobaharan et al. 2022; Ullah et al. 2024), although the composition of different biochar products varies strongly. Biochar is heated during production, minimizing microbiological food safety risks. We are not aware of any field trials in the United States in which biochar was applied for the production of vegetable crops and in which Cd was measured.

Crop-specific mitigation strategies

Spinach. As noted, Zn can effectively compete with Cd for transport into the plant root systems. Soils with high ratios of Cd to Zn are found in the coastal farming areas from Southern to Central California (Chaney et al. 2009). The Lockwood loam soil is a Cd-mineralized soil derived from marine shale rocks that have elevated Cd levels. Fertilization with Zn on soils with high Cd:Zn is a viable mitigation practice used to reduce Cd uptake in spinach (Smith and Hartz 2016, 2017). In 2024, Zn cost $8.70/kg Zn as Zn-sulfate and $51.88/kg Zn as Zn-chelate, which can be expensive at the application rates needed to markedly reduce Cd in spinach (e.g., 100 kg/ha or higher, or $875). It is recommended that the amounts of Zn needed to reduce Cd uptake in a particular area should be evaluated for potential adverse impacts on crop health and yield. Paul and Chaney (2017) conducted pot studies of soil amendments to reduce Cd accumulation by spinach grown in a high-Cd and high-Cd:Zn soil series (Lockwood soil with 5.2 mg Cd/kg and 54 mg Zn/kg). Additions of 200 mg Zn/kg resulted in a 70% reduction of Cd in spinach leaves. In pot trials conducted with soils with 1.6 to 2.3 mg Cd/kg and 2.0 to 2.2 mg diethylenetriamine-pentaacetate (DTPA) Zn/kg, Smith and Hartz (2016a) observed 53% to 81% reductions in spinach leaf Cd with additions of 25 to 100 kg Zn/ha as $ZnSO_4$ fertilizer. Their studies also showed that both Zn-sulfate and Zn-chelate reduced Cd uptake by spinach more effectively than Zn-oxide (ZnO) (but the Zn chelates are much more expensive per kg Zn). In addition, incorporation of Zn to a 15-cm soil depth and even incorporation to a 30-cm depth further improved reduction of Cd in spinach compared with shallower surface applications in the spinach fields or in greenhouse pot studies. Of course, incorporating Zn fertilizer more deeply in soils increases costs.

Studies in commercial fields showed that Zn applications of 45 kg Zn/A in the form of Zn-sulfate (127 kg Zn-sulfate/A) reduced the Cd concentration in spinach by 40% (Smith and Hartz 2016), indicating that under field conditions, Zn applications are also effective; however, there may be more dilution of applied Zn during tillage operations. Plots that received 100 lb Zn/A and were cropped with seven vegetables over 3 years still had soil DTPA extractable soil Zn levels three- to four-times higher than the baseline Zn level (control treatment); in addition, there was a 31% reduction in crop Cd in the final rotation of the study, i.e., peppers (*Capsicum annuum* L.) (Smith and Hartz 2017). These studies demonstrate that Zn applications can be effective across years, which can help alleviate the initial cost of application, but additional Zn application would be required intermittently to maintain maximum efficacy in reducing crop Cd.

In the pot study by Paul and Chaney (2017), a number of potentially effective soil amendments to reduce Cd accumulation by spinach were tested. The authors found that soils receiving Zn fertilizers that had their pH raised to ≥7 resulted in lower Cd in spinach. As shown in Fig. 4, added Zn reduced spinach Cd from 56.7 mg/kg DW to 21.2 mg/kg DW (to convert to wet weights, DWs can be multiplied by 0.075). High rates of $ZnSO_4$ caused soil acidification unless limestone was added to counteract the effect of the $ZnSO_4$; therefore, spinach Cd reduction was inadequate with only the high rate of $ZnSO_4$. In addition, added $MnSO_4$ caused soil acidification and increased spinach Cd. Added limestone to make the soil calcareous reduced spinach Cd to 19.2 mg/kg DW. The combination of Zn with limestone reduced spinach Cd to 5.8 mg/kg DW. The most effective treatments for reducing Cd uptake were those that combined biosolids compost, limestone, and $ZnSO_4$ amendments. Application of biosolids compost sourced from Los Angeles, CA, USA, reduced spinach Cd to 15.4 mg Cd/kg DW, while adding both the compost and limestone reduced Cd to 4.9 mg/kg DW. With the addition of Zn and limestone to the biosolids compost, spinach Cd decreased to 3.0 mg/kg DW.

The perception of microbiological risk associated with composted livestock manure and composted biosolids may limit commercial use. Other potentially effective organic matter-rich amendments to reduce spinach accumulation of Cd include biochar and biochar plus limestone and Zn. These have not been tested in the field with spinach or lettuce.

Carrots. Increasing pH of soils reduces Cd accumulation by carrots (Brallier et al. 1996; Gray et al. 1999; Guttormsen et al. 1995; Jansson and Öborn 2000; Singh et al. 1995). Hooda and Alloway (1996) suggested maintaining soils at pH 7.0 effectively reduced Cd accumulation by carrots in a 2-year field study with sewage sludge amendment in a pot test. Increasing soil organic carbon content also reduced Cd uptake by carrots (Ding et al. 2013). Only one study used additions of soluble Cd and Zn salts to an alkaline soil to evaluate the interaction of Zn and Cd uptake, but the Cd:Zn ratio of the highest Zn additions did not test normal ratios in soils, and, contrary to studies in other crops, did not conclude that Zn reduced Cd uptake (Sharma and Agrawal 2006). Additions of synthetic zeolites and Fe and Mn oxides also bound Cd in the soil and reduced its uptake by crop plants (Singh and Oste 2001).

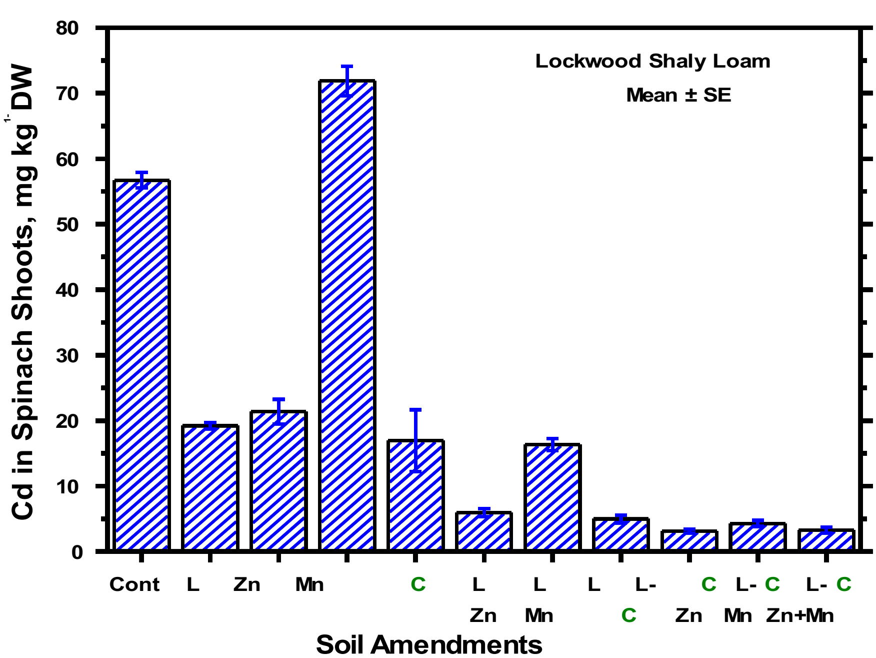

Fig. 4. Effect of soil amendments on cadmium (Cd) accumulation in spinach grown on a Lockwood shaly loam soil from Salinas Valley, CA, USA. C = biosolids compost (10%); Cont = control; L = lime (5%); Mn = manganese (100 mg/kg); Zn = zinc (100 mg/kg). Derived from Paul and Chaney 2017.

Additional mitigation strategies for spinach and carrots that require further study

Impact of mycorrhizal vs. nonmycorrhizal crop rotations. In recent years, a new factor that affects Cd accumulation by crops has been identified: whether the previous crop had mycorrhizal infection (Cakmak et al. 2023). When crops that support mycorrhiza grow in the field, mycorrhiza can accumulate Cd and limit Cd transport to the shoots and grain of the crop. Spinach is nonmycorrhizal, while lettuce and carrots are mycorrhizal. This new understanding can potentially be used to reduce Cd in lettuce and carrots because soil Cd could accumulate in the mycorrhizae and reduce transfer into the edible plant tissue. Another lesson from this research is that Cd accumulation can be affected by the preceding crop.

Potential cadmium removal from soils using cadmium-hyperaccumulating plants. A possible future method of decreasing excessive Cd in crop plants is to use Cd-accumulating plants to remove Cd from the soil, which is a process called phytoextraction (Chaney et al. 2021). Some strains of *Noccaea caerulescens* [*Noccaea caerulescens* (Presl. & C Presl) Meyer] can accumulate more than 1000 mg Cd/kg dry matter in their shoots that can be harvested to remove Cd from the field. Unfortunately, this species has low biomass yield and grows close to the soil surface such that it is difficult to harvest and, thus, physically remove the plant tissue and the Cd that is accumulated in the biomass. Furthermore, maximum annual removal of Cd requires acidifying the soil and not growing market crops until the soil Cd has been depleted and soil pH returned to normal crop production levels. Research is ongoing to find other species or bioengineer this species to make it more compatible with Cd phytoextraction goals. No practical Cd phytoextraction crop has been identified to date.

Breeding crops to reduce cadmium accumulation. There is wide variation in the accumulation and distribution of Cd among species and cultivars of the same species (Alexander et al. 2006; Bell et al. 1997). Plant breeders can use this variation to reduce the uptake of Cd. Plant breeding programs have been established to reduce Cd accumulation in the edible portion of various crops, including rice, durum wheat (*Triticum durum* L.), sunflower (*Helianthus annuus* L.), soybean [*Glycine max* (L.) Meyer], radish (*Raphanus sativus* L.), brassica vegetables, and spinach (Chen et al. 2021; Greenhut 2018; Miller et al. 2006; Nissan et al. 2022; Sun et al. 2023; Xu et al. 2012;

Zaid et al. 2018; Zhang et al. 2019). Breeding spinach and carrots to accumulate less Cd in edible tissues when grown in high-Cd soil has only recently begun and is discussed later in this section; however, much can be learned from research of other crops. For example, breeders have developed low Cd durum wheat, rice, and sunflower (*Helianthus annuus* L.) cultivars that are in commercial use (Miller et al. 2006; Tittlemier and Richter 2022).

One of the first crops for which plant breeding was evaluated to reduce Cd was durum wheat. This example illustrates a successful multifaceted approach to reducing Cd levels in a crop. Durum wheat is used in pasta manufacturing, and much of the Canadian and US crops have been exported to countries in the European Union. Both the natural soil Cd and chloride contributed to the levels of Cd in durum wheat that were higher than desired. Studies by Norvell et al. (2000) and Wu et al. (2002) showed the strong correlation of grain Cd with soil chloride in a field with a strong gradient in chloride.

Because the European Union sets limits on Cd in durum wheat, the Canadian wheat industry and research community undertook work to ensure lower Cd in the grain. An examination of existing genotypes identified one genotype with much lower Cd than average genotypes when grown on Canadian soils with somewhat elevated native Cd and chloride levels compared with those in average soils. This research identified one gene (HMA3) that involves retention of Cd in the root cell vacuoles. The inactive HMA3 gene in most higher Cd durum germplasm could be rapidly replaced by usual breeding technologies to substantially reduce grain Cd (Archambault et al. 2001). A report by Tittlemier and Richter (2022) summarized the reduction of Cd in durum grain shipped from Canadian ports over time and showed the potential for plant breeding as a mitigation option. When soil Cd level and other factors such as chloride strongly affect crop Cd levels, the only practical alternatives for producing durum grain are to plant elsewhere or develop cultivars with lower grain Cd for farmers to plant.

To develop low-Cd crop cultivars, it is important to identify genes associated with Cd accumulation. Additionally, understanding the function of these genes, although not necessary for breeding, provides insight into Cd–plant interactions and may improve the efficiency of breeding efforts. Studies using the model crop *Arabidopsis* [*Arabidopsis thaliana* (L.) Heynh.] have shown that transport proteins, metal ligands, and chelators play an essential role in heavy metal uptake and homeostasis (Marschner 1995). Multiple Cd mechanisms and the genes that encode them have been identified in wheat, but not in many other crops. The mechanisms most strongly associated with Cd levels in crop species include the following: NRAMPs in rice, durum wheat, barley (*Hordeum vulgare* L.), buckwheat (*Fagopyrum esculentum* Moench,), and tobacco; Zn and Fe regulated transporter proteins (ZIP) in rice, tobacco, and mustards (*Brassica* species); heavy-metal ATPase (HMA) in rice, durum wheat, mustards, and soybean; as well as ATP-binding cassette type transporters in rice and wheat (Tao and Lu 2022). Overexpression of the HMA3 gene very effectively reduced shoot Cd in several crops tested, including rice and *Brassica* vegetables. The significant reduction in Cd transport from roots to shoots, attributed to HMA3 pumping Cd into root cell vacuoles (Ueno et al. 2010), seems to offer a more effective breeding strategy compared with other approaches. This is particularly true for rice, for which reduced NRAMP5 expression can also greatly reduce Cd accumulation in rice grains, but it may induce Mn deficiency (Ishikawa et al. 2012). The insights summarized by Tao and Lu (2022) can inform molecular breeding techniques such as marker-assisted selection and gene editing. However, several important considerations should be kept in mind. Plant species possess distinct transporter families that can vary in expression patterns and substrate specificity. Initial studies that identified transporters involved in Cd uptake and storage should be conducted in the species of interest to confirm their function and ensure that they do not cause unintended nutrient imbalances.

A study of *Brassica rapa* L. vegetables evaluated sequence variation and expression of the HMA3 gene in 60 diverse genotypes and found that HMA3 was a key gene controlling root-to-shoot translocation and Cd accumulation in shoots (Zhang et al. 2019). Additionally, Zhang et al. (2019) conducted a functional genomics study that showed that *BrHMA3* encodes a tonoplast-localized protein and is expressed in the roots—similar to HMA3 orthologs in *A. thaliana* and rice. This study supported earlier findings that natural variation in HMA3 controlling Cd translocation and accumulation in shoots appears to be a conserved mechanism across plant species, including *A. thaliana* (Chao et al. 2012), rice (Sui et al. 2019; Ueno et al. 2010; Yan et al. 2016), and *B. rapa* (Zhang et al. 2019). Overexpression of the HMA3 gene effectively reduced shoot Cd in several crops tested, including rice and *Brassica* vegetables.

An evaluation of germplasms in both spinach and carrot in high Cd soils (>1 mg total Cd/kg) has shown genetic variation that could enable the development of cultivars that accumulate low Cd. Diverse carrot and spinach cultivars, landraces, germplasm, and USDA Agricultural Research Service breeding lines show up to a 30-fold variation in Cd accumulation in carrots (Alexander et al. 2006; Harrison 1986; Zheng et al. 2008) and a 3.3-fold difference in spinach (Alexander et al. 2006; Greenhut 2018). Biparental populations created between high- and low-accumulating genotypes are being developed for greenhouse, hydroponic, and field evaluations to map quantitative trait loci, identify candidate genes, and develop breeding pools for testing in high-Cd soil in California field trials for both spinach and carrot. (Hilborn 2020; Simon P, personal communication). Although variation in Cd uptake within existing germplasm can possibly reduce Cd accumulation, it might not result in cultivars that are low enough in Cd, necessitating the use of gene editing or transgenesis to create very low-accumulating cultivars. Several genes associated with Cd uptake could play a role in decreasing Cd accumulation as well. The gene NRAMP5 controls Cd uptake in rice; however, one study found that DNA polymorphisms in this gene in spinach have weak or no associations with Cd concentrations in spinach leaves (Greenhut 2018). Breeding to increase activity or effectiveness of HMA3 in spinach roots may be an effective approach to limiting Cd in commercial crops for these soils with high Cd:Zn, and research of this question in regard to spinach should be pursued.

Impact of crop mitigation measures on cadmium bioavailability warrants consideration. With the exception of rice, foods that have high levels of Cd generally also have levels of Fe, Ca, and Zn that compete with Cd absorption in animal intestines. The review by Reeves and Chaney (2008) summarized research that showed the relationship between marginal deficiencies of essential nutrients and absorption and organ accumulation of Cd. Polished/milled white rice is inherently low in the essential elements Fe, Ca and Zn, and toxicology research has shown that rats fed rice diets with marginal levels of these elements can markedly increase absorption of Cd (Reeves and Chaney 2002). Long-term health impacts of Cd consumption have been studied because rice grown on contaminated paddy (flooded) soils was consumed for decades by farm families in Japan, China, and Thailand whose rice-based diets were low in Fe, Zn, and Ca, resulting in adverse health effects (Chaney 2015; Kobayashi 1978). Data from toxicology studies suggest that increased Zn in food inhibits Cd intestinal absorption, which is now understood to be on the ferrous uptake transporter of the intestine (Fox 1988; McKenna et al. 1992a). Fox (1988) summarized the early nutritional research of dietary Cd absorption rather than that in toxicology-type studies, emphasizing interactions with food micronutrients (Fe, Zn, Ca) that counteract Cd absorption (Fox 1979, 1988). A recent study by Gu et al. (2025) further illustrated how milling of rice removed Ca, Fe, and Zn and increased rice Cd bioavailability to higher levels than those in the whole grain even though the Cd concentration in milled rice was lower than that in whole grain rice.

Shellfish can accumulate elevated levels of Cd from contaminated waters, but data from toxicology studies suggest that Cd may not be highly bioavailable to consumers because these foods are rich in Fe and Zn (McKenzie-Parnell et al. 1988; Sharma et al. 1983; Sirot et al. 2008; Vahter et al. 1996). However, data from assessments of the relationship between consumption of Cd-containing foods and levels of Cd in blood and urine can be confounded by other factors, such as smoking (Sharma et al. 1983). Additionally, volunteers (33 women and 27 men between 23 and 59 years of age) who consumed varying amounts of sunflower kernels containing 0.52 mg/kg Cd (resulting in increased dietary Cd from 65 to 175 μg Cd per week for 48 weeks) did not have higher blood or urine Cd than those of others who consumed peanuts containing 0.11 mg/kg Cd (Reeves et al. 2001).

While an in-depth discussion of bioavailability is outside the scope of this work, it should be noted that mitigation measures that reduce phytoavailability in soils may similarly reduce bioavailability of the Cd present in the crop. For example, Zn-amended soils may lead not only to lowered Cd uptake but also to increased Zn uptake, which, in turn, may further limit intestinal absorption of Cd after consumption. Further research is warranted to quantify the impact that specific crop mitigation measures have on Cd bioavailability.

Conclusion

Achieving lower concentrations of toxic elements in foods can result in lower dietary exposure. This review used spinach and carrots to illustrate how plant and soil factors as well as agronomic management decisions can affect the concentration of Cd in the crops. Plant factors involve physiological, biochemical, and molecular mechanisms, including the expression of nutrient transporters for uptake, translocation, and sequestration of Cd, and breeding efforts have identified cultivars that accumulate lower concentrations of Cd. More work is needed to bring these lower Cd-accumulating cultivars to market. Soil factors include soil Cd and Zn concentrations, soil pH, organic matter, and chloride. Manipulating these factors through soil amendments can limit Cd concentrations in crops. It is important to ensure that choices of soil amendments do not have unintended consequences, such as the addition of other toxic metals, emerging contaminants, or chloride, the latter of which can increase phytoavailability of Cd. Moreover, addition of chlorine-containing compounds such as sodium hypochlorite to irrigation water may reduce the presence of pathogenic bacteria but enhance Cd uptake in Cd-rich soils. Thus, growers need to consider pathogen mitigation measures that do not exacerbate Cd accumulation in crops, and, likewise, Cd mitigation measures need to prevent exacerbation of microbiological food safety risks. It is important for growers to assess their soil Cd and Zn concentrations, Cl^- inputs, and develop action plans that are suitable for their soil and crop. Industry collaboration with researchers and extension agents at universities and federal agencies can help facilitate access to these resources and minimize the cost to the grower and, ultimately, to the consumer.

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