INFLUENCE OF SOIL AMENDMENTS AND VARIETAL DIFFERENCES ON HEAVY METAL UPTAKE IN MICHIGAN WINTER WHEAT (*Triticum aestivum* L.)

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ABSTRACT

Crop heavy metal(loid) uptake is governed by complex interactions among soil properties, climatic conditions, and plant traits creating challenges for mitigating plant absorption. Field-level prevention is often less costly than remediation during processing thus pre-harvest management is critical for regulatory compliance and long-term profitability. Soil amendments and varietal selection offer practical mitigation strategies for potential grower adoption.

The objectives of this study were to (1) evaluate soil amendment strategies for reducing heavy metal(loid) concentrations in winter wheat and (2) investigate varietal differences in heavy metal accumulation in grain and straw at harvest. The soil amendment trial evaluated ten treatments: check or control, dolomitic lime, dairy compost, biochar, gypsum, granular and foliar $ZnSO_4$, varying N rates (low, mid, and high), and the chelating agent ethylenediaminedisuccinic acid (EDDS) for determining effectiveness in reducing heavy metal(loid) uptake.

In the 2024 amendment trial, plant height was identified as a yield-related trait associated with reduced heavy metal(loid) uptake. We hypothesized that greater stem elongation distributed heavy metal(loid)s across a larger tissue area resulting in a dilution effect. Building on these findings, 12 soft red winter wheat varieties representing both short and tall-statured types were sampled pre-harvest in 2025 and 2026 to quantify grain and straw heavy metal(loid) concentrations. Results will provide insight into agronomic factors influencing heavy metal(loid) uptake to support food safety and strengthen industry resilience amongst evolving regulatory pressures.

INTRODUCTION

The United States Food and Drug Administration (FDA) released its *Closer to Zero (C2Z) Action Plan* which aims to reduce exposure to heavy metals in foods consumed by infants and young children to the lowest levels reasonably achievable (US FDA, 2025). This initiative was prompted by the 2021 Congressional Staff Report, which identified elevated concentrations of arsenic (As), cadmium (Cd), and lead (Pb) in commercially available infant foods (U.S. House of Representatives, 2021). Infants and young children are vulnerable due to their immature physiological development and relatively high food intake-to-body-weight ratio which can result in neurodevelopmental effects (Bair, 2022; Grandjean & Landrigan, 2014). In January 2025, the FDA issued guidance for Pb in foods intended for babies and young children while proposed limits for As and Cd will be forthcoming (US FDA, 2025). Once action levels are established,

targeted compliance will be implemented affecting stakeholders from producers to manufacturers.

Several approaches have been investigated to reduce heavy metal (and metalloid) uptake in crops including the application of soil amendments, phytoremediation (phytoextraction), and crop cultivar selection (Elango et al., 2022; Khan et al., 2023; Wang et al., 2020; Xu et al., 2021). Among these approaches, soil amendment application received significant attention due to relatively rapid implementation and cost-effectiveness. Previous literature reported different mechanisms by which soil amendments decrease heavy metal(loid) bioavailability and uptake such as adsorption, immobilization, ion competition, complexation, detoxification, and precipitation. Overall, the main purpose of these mechanisms is to “stabilize” the heavy metal(loid) in soils and to decrease crop uptake and translocation.

Reducing human exposure to dietary heavy metal(loids) requires the development of crop cultivars that accumulate lower concentrations of these contaminants (Grant et al., 2008). Among the heavy metal(loid), cadmium (Cd) is a well-studied contaminant, and the impact of genetic variation on its uptake has been examined. Previous studies have demonstrated that varieties within the same plant species can differ in Cd uptake due to variations in their biochemical and physiological characteristics (Clemens et al., 2013; Mench, 1998; Rizwan et al., 2016). In winter wheat, Strawn et al. (2022) highlighted the importance of developing “ultra-low-Cd grain” varieties for infant food production further emphasizing the potential of genetic variation to reduce heavy metal(loid) concentrations in edible plant tissues. Although differences in grain Cd accumulation among wheat varieties have been reported, the underlying mechanisms responsible for this variation remain unclear.

MATERIALS AND METHODS

Study 1: Soil amendment trial

Field studies were established in Lansing, MI (42.689176, -84.485032) from 2023 to 2026. Sites were established on a Conover loam soil (Fine-loamy, mixed, active, mesic *Aquic Hapludalfs*) with a surface layer of 41.6% sand, 39.2% silt and 19.2% clay (USDA-NRCS, 2026).

A total of 10 treatments were arranged in a randomized complete block design with four replications. Treatments represented industry-standard (IND) plus treatment structures across varying levels of management intensity. Treatments include: 1) IND, autumn starter fertilizer at 12.5 lbs. S/A during planting and 100 lbs. N/A at Feekes 4 (08 April 2024, 08 April 2025, 08 April 2026); 2) IND + Lime, dolomitic lime (20% Ca, 12% Mg) at 2.0 ton/A broadcast before planting; 3) IND + Gyp, gypsum (23.3% Ca, 18.6% S) at 1.0 ton/A broadcast before planting; 4) IND + $ZnSO_4$, zinc sulfate ($ZnSO_4$) (35.5% Zn, 15.5% S) at 10 lbs. Zn/A broadcast before planting and foliar $ZnSO_4$ (10% Zn, 4.5% S) at 0.13 gal./A (TraFix Zn) (Helena Agri-Enterprises, LLC, Dansville, MI, USA) applied during Feekes (FK) 9 (08 May, 2024, 14 May 2025, 19 May 2026); 5) IND + DC, dairy compost (1.42-3.25-1.06, N-P_2O_5-K_2O) at 5.0 ton/A broadcast before planting, 6) FP +

BC, wood-based biochar soil conditioner at 2.0 ton/A of broadcast before planting; 7) IND + EDDS, a biodegradable chelating agent Ethylenediamine-N,N'-disuccinic acid (molecular wt. = 358.19 g mol^{-1}, 35% water) (Sigma Aldrich, Buchs, CH) was applied at 2 mmol/L solution (7.74 mL in 3.785 L. mix) during FK 5, + 1 week, +2 weeks (14, 22, 29 April 2024, 14, 20, 29 April 2025, 13, 21, 26 April 2026). For the remaining treatments, instead of 100 lbs. N/A applied at FK 4, different N rates were used: 8) IND - Low N, 50 lbs. N/A at FK 4; 9) IND + High N, 150 lbs. N/A of 46-0-0 at FK 4; 10) Check, no added fertilizer or soil amendment to determine the responsiveness of the field with regard to IND alone.

Autumn starter fertilizer (12-40-0-10-1, N-P-K-S-Zn) (MicroEssentials SZ [MESZ] [Mosaic CO.] was top-dressed at a rate of 125 lbs./A to supply 12.5 lbs. S/A during 2023 planting except for the check treatment. Ammonium sulfate (21-0-0-24, N-P-K-S) was top-dressed at a rate of 52 lbs./A to supply the same 12.5 lbs. S/A during 2024 and 2025 planting except for the check treatment. All treatments received a base green-up N application rate of 100 lbs. N/A of urea (46-0-0) except for the check and N fertilizer treatments (treatments 8-10).

Study 2: Variety Trial

Field studies were established in Mason, Michigan (MI.), USA (42° 37′ 44.89″ N, 84° 25′ 54.06″ W) from 2024-2026. The experimental site was established on a Conover loam (Fine-loamy, mixed, semiactive, mesic *Aquic Hapludalfs*) with a surface layer of 47% sand, 38% silt and 15% clay (National Cooperative Soil Survey, 2018).

The selected soft red winter wheat lines were from the 2025 Michigan State Wheat Performance Trials. Plant populations were 1.5 million seeds/A planted on 19 September 2024 and 19 September 2025. Since the objective of this study was to determine whether plant stature (tall vs semi-dwarf) is associated with risk of winter wheat grain and straw contamination, lines were selected according to plant height near maturity and classified into two main categories using the 2024 performance trial: tall stature (≥ 81.2 cm) and semi-dwarf (< 81.2 cm).

Elemental Analysis Using ICP-QQQ-MS

Total cadmium (Cd), arsenic (As), and lead (Pb) concentrations were determined using Triple Quadrupole Inductively Coupled Plasma Mass Spectrometry (ICP-QQQ-MS; 8900 Triple Quadrupole ICP-MS, Agilent Technologies, Santa Clara, CA). Isotopes for each element were selected according to the FDA Elemental Analysis Manual, Section 4.7 ICP-MS Method. Certified reference materials (NIST 1517a tomato leaves and NIST 1515 apple leaves; National Institute of Standards and Technology, Gaithersburg, MD) and at least one analytical blank were included in each run for quality control.

Plant uptake factor

The plant uptake factor (PUF) indicates wheat's capacity to absorb a specific element. The PUF was calculated as the plant tissue elemental concentration divided by the soil elemental concentration where w(plant) is the plant tissue elemental concentration (mg/kg) and w(soil) is the soil elemental concentration (mg/kg).

RESULTS AND DISCUSSION

Table 1. Influence of soil amendments[a] on winter wheat grain arsenic (As), cadmium (Cd), and lead (Pb) concentrations at harvest[d], Lansing, MI, 2024-2026.

	Grain As	Grain Cd	Grain Pb
		µg/kg dry weight	
2024 IND[b]	**3.2**	**33**	**20**
+Lime	(0.6)	(4)	(10)
+Gyp	(0.4)	+3	(14)
+$ZnSO_4$	(0.4)	(3)	(10)
+DC	(0.6)	+2	(6)
+BC	(0.3)	(6)	+6
+EDDS	(0.2)	(3)	(4)
+Low N	(0.2)	+4	+7
+High N	+0.3	(5)	(3)
IND vs. Check[c]	+0.0	+8	(11)
2025 IND	**0.93**	**37**	**8.6**
+Lime	+0.49	(1)	(5)
+Gyp	+0.06	+1	(4)
+$ZnSO_4$	(0.22)	(3)	(1)
+DC	(0.06)	(3)	(7)
+BC	+0.09	(1)	(5)
+EDDS	+0.08	+3	(5)
+Low N	(0.03)	(5)	(6)
+High N	+0.02	+2	(2)
IND vs. Check	+0.04	+0	(1)
2026 IND	**0.60**	**33**	**0.76[e]**
+Lime	+0.35	+8	+5
+Gyp	+0.32	(3)	+6
+$ZnSO_4$	+0.42	+1	+3
+DC	+0.28	(3)	+15
+BC	+0.11	(1)	+1
+EDDS	+0.03	+4	+1
+Low N	(0.04)	(5)	+2
+High N	+0.01	+15**	+1
IND vs. Check	+0.31	(8)	+11

[a] IND = Industry Standard; Lime = dolomitic lime; Gyp = gypsum; $ZnSO_4$ = zinc sulfate; DC = dairy compost; BC = biochar; EDDS = ethylenediamine-N,N′-disuccinic acid; Low N = 56 kg N/ha of urea (46-0-0) at Feekes [FK] 4; High N = 168 kg/ha of 46-0-0 at FK 4; Check = no fertilizer or soil amendment added.

[b] Treatments were compared with the Industry Standard (IND) treatment using the Dunnett-Hsu Test.

[c] Orthogonal contrast was conducted between Industry Standard (IND) and Check.

[d] Asterisks indicate thresholds of significance (*, P < 0.05; **, P < 0.01, ***, < 0.0001) relative with Industry standard (IND).

[e] When samples were below the detection limit, ½ of the detection limit was used as the concentration. DL = 0.002 µg/kg Pb

Regarding grain heavy metal(loid) concentrations, according to the FAO Codex Alimentarius, the maximum amount of Cd that can be present in wheat grains for adult food consumption is 200 µg/kg (Alexander et al., 2009) while for infants, the maximum allowable Cd concentration is set at 40 µg/kg (Barroso, 2014). The average grain Cd levels in the IND treatment were 33, 37, and 33 µg/kg in 2024 to 2026, respectively. When compared to the available regulatory threshold, all grain Cd levels met the food safety standard for adult consumption. However, a few had too much Cd to be acceptable for infant food. In 2024, the high N rate at FK 4 had grain Cd of 41 µg/kg while in 2026 the high N rate at FK 4 significantly increased grain Cd level by 45% (48 µg/kg). The low N rate at FK 4 resulted in grain Cd at 40 µg/kg in 2025 while dolomitic lime resulted in grain Cd at 41 µg/kg in 2026.

Grain Pb concentrations ranged from 3 to 73 (16) µg/kg in 2024, <DL to 20 (5) µg/kg in 2025, and <DL to 64 (4) µg/kg in 2026. The average grain Pb levels in the IND treatment were 20, 8.6, and 1.4 µg/kg in 2024 to 2026, respectively. According to WHO standards, the maximum permissible cereal Pb concentrations for people weighing 60 kg (132 lbs.) are 200 µg/kg fresh weight or 235 µg/kg dry weight at 15% moisture content (European Commission, 2001). Based on the WHO standard, all grain Pb levels met the food safety standard for adult consumption. In the U.S., the action level for Pb in grain mixtures is 10 µg/kg but increases to 20 µg/kg for dry infant cereals (US FDA, 2025). In 2024, biochar (26 µg/kg) and low N rate at FK 4 (27 µg/kg) exceeded both FDA action levels for grain mixtures and dry infant cereals. In 2025, all treatments were below the FDA action level for grain mixtures (10 µg/kg). In 2026, only dairy compost (16 µg/kg) exceeded the FDA action level for grain mixtures (10 µg/kg). It is important to emphasize that during the 2026 harvest year, grain Pb levels in replications 3 and 4 were below the detection limit (0.002684 µg/kg Pb); hence, the ½ of the detection limit was used (0.001342 µg/kg Pb).

There is no available As threshold level proposed by the Codex Alimentarius Commission or the European Union for cereal products (European Commission, 2001; Joint & Commission, 2001). In the U.S., only available regulatory thresholds are commodity-specific such as the FDA action level for infant rice cereal (100 µg/kg inorganic As) (US FDA, 2020). In this study, total As levels were measured in winter wheat grains and did not undergo As speciation. Grain As ranged from 2 to 6 (3) µg/kg in 2024, < detection limit (DL) to 2 (1) µg/kg in 2025, and <DL to 2 (1) µg/kg in 2026. In wheat grain, inorganic arsenic (iAs) accounts for 70% to 100% of the total arsenic (tAs) (Zhao et al., 2010). Therefore, even accounting for the grain As levels as all inorganic, concentrations were still below the FDA action level for infant rice cereal which is one example of a cereal product.

Table 2. Grain and straw plant uptake factor (PUF)[c] at harvest of selected winter wheat varieties[a], Mason, MI, 2025-2026.

	2025 Grain PUF			2026 Grain PUF		
	As	Cd	Pb	As	Cd	Pb
Tall stature	0.001	0.26	0.002	0.0004	0.44	0.001
Semi-dwarf	0.000	0.21	0.002	0.0003	0.44	0.001
TS vs. SD[b]	0.3704	**0.0058**	0.6937	0.1163	0.9572	0.2127
	2025 Straw PUF			**2026 Straw PUF**		
	As	Cd	Pb	As	Cd	Pb
Tall stature	0.01	0.69	0.01	0.01	0.90	0.005
Semi-dwarf	0.01	0.56	0.01	0.01	0.86	0.003
TS vs. SD	0.3785	**0.0193**	0.6723	0.4747	0.4545	0.3740

[a] Classification was based on the plant height of the selected varieties during harvest year 2024 from Michigan Variety Trial canr.msu.edu/varietytrials/uploads/2025MichiganWheatYieldTrialReport.pdf
[b] Orthogonal contrast was conducted between taller stature (TS) versus semi-dwarf (SD) varieties.
[c] Plant uptake factor = plant tissue concentration / soil concentration

In both the 2025 and 2026 cropping seasons, plant uptake factor (PUF) for both As and Pb were comparable regardless of plant stature indicating that crop development has limited impact on As and Pb absorption. Previous studies support the limited movement of As under oxidizing conditions (Tallman & Shaikh, 1980) and potential restricted translocation of Pb from roots to aboveground biomass (Wang et al., 2021).

Cadmium PUF was only significantly different in 2025 in the plant stature treatment where taller varieties had greater grain and straw Cd PUF at harvest than semi-dwarf varieties. Cadmium PUF for both grain and straw were comparable between the two plant stature types during the 2026 harvest season. In 2025 post-harvest, soil samples' pH ranged from moderately acidic (5.7) to neutral (7.1) with an average of 6.3. Meanwhile, in the 2026 post-harvest, soil samples' pH ranged from very strongly acidic (5.0) to slightly acidic (6.3) with an average of 5.5. Soil pH can influence Cd availability as it affects Cd adsorption and solubility. Thus, the more acidic soil conditions in 2026 may have increased Cd bioavailability potentially contributing to the comparable Cd PUF across plant stature types. These findings highlight the importance of integrated Cd management (i.e., soil pH amelioration) in addition to cultivar selection for reducing potential soil Cd uptake.