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A preliminary study on the spatial distribution of lead, cadmium, aluminium, and copper in different potato (*Solanum tuberosum* L.) varieties – implications for food safety and risk assessment

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Original article

Abstract

Food safety regarding heavy metal contamination is a critical global challenge due to the toxic nature of these elements and their ability to bioaccumulate in the food chain. This pilot study investigates the spatial distribution at different depths of potato tubers (*Solanum tuberosum* L.), of toxic elements such as lead and cadmium (both highly toxic) as well as aluminium (far less toxic compared to the previous two) and copper (micronutrient) to evaluate the efficacy of culinary processing in reducing toxic metal exposure. Three popular cultivars in southern Poland – "Soraya", "Vineta", and "Jelly" available on the Tarnów market were analyzed. Following the wet digestion step, the quantitative determination of selected metals was performed using Graphite–Furnace Atomic Absorption Spectrometry (Agilent 240Z AA). The accuracy of the analyses was validated using certified reference materials. The most interesting findings indicate that while mechanical peeling of tubers effectively minimizes exposure to Pb, it does not significantly reduce Cd levels. Analysis of behavior of aluminium revealed a distribution pattern similar to that observed for lead. Mechanical peeling led to a substantial reduction in the content of lead (69.0–82.0%) and aluminium (96.8–98.6%), as both elements strongly accumulated within the outermost periderm. Conversely, cadmium exhibited high mobility throughout the internal tissues, resulting in a minimal post-peeling concentration decrease ranging from 5.6% to 36.1%.

Keywords

- heavy metals
- potato
- food safety
- bioaccumulation

Authors' contributions

A – Preparation of the research project
B – Assembly of data for the research undertaken
C – Conducting of statistical analysis
D – Interpretation of results
E – Manuscript preparation
F – Literature review
G – Revising the manuscript

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None declared.

Introduction

Food quality and safety constitute fundamental pillars of societal well-being and the sustainable development of global agriculture. According to the World Health Organization (WHO), on average 1 in 10 people fall ill after consuming contaminated food, with approximately 420,000 deaths occurring annually worldwide due to this cause [1]. These figures underscore large scale of the problem and illustrate the immense responsibility borne by food producents. Diseases resulting from the consumption of contaminated food remain one of the significant social challenges in both developing and developed countries. The presence of heavy metals in consumed vegetables poses a significant risk to human health due to their toxic effects, even at trace concentrations [2]. The term "heavy metal" refers to a metal or a metalloid with a relatively high density, typically ranging from 4 to 6 g cm^{-3} [3]. Furthermore, these metals possess atomic mass of no less than 63.5 u and no more than 200.6 u. Heavy metals can be classified into three group according to their toxicity: highly toxic, e.g. Cd, Pb, As; moderately toxic, e.g. Ni, Co, Cu; low-toxicity metals, e.g. Fe, Mn, Mo [3,4].

Heavy metals are characterized by their capacity for bioaccumulation within the tissues of living organisms. Unlike many toxic organic compounds, they do not undergo degradation. In the case of edible plants, bioaccumulation occurs primarily through uptake via the root system. Consequently, soil quality, type and acid-base characteristic (pH) exert a direct influence on the overall of contamination scale. While heavy metals in soil can originate from natural sources, such as the weathering of parent rocks or the soil's natural geochemical background, anthropogenic activity is the primary driver of their prevalence in ecosystems. The range of human activities resulting in the release of heavy metals is very extensive, however the most significant contributors include industrial emissions, the combustion of fossil fuels, the applications of pesticides and synthetic fertilizers, transportation and waste disposal [4–7].

Heavy metals are absorbed by plants from the soil in the form of ions or complex compounds, e.g. chelates. The transport mechanism is directly associated with bioavailability of a given chemical form of the metal. Within the plant's root system, two primary transport pathways are distinguished: the passive (apoplastic) and the active (symplastic). The latter involves membrane ion transporters responsible for the uptake of essential nutrients [8–10]. The transport of heavy metals from the soil into plants organisms often relies on the same systems used for the absorption of essential minerals. For example, the uptake of cadmium is largely based on the same transmembrane carriers involved in the transport of magnesium, calcium or zinc [11].

Cadmium is a major public health threat, ranked 7th on the ATSDR (Agency for Toxic Substances and Disease Registry) *Substance Priority List* [12]. Beyond its presence in tobacco smoke, it is widely used in battery production [6]. Cadmium bioaccumulates in the kidneys and liver, causing neurotoxicity, renal dysfunction, hypertension, diabetes, and carcinogenicity. In plants, it is absorbed via the apoplastic pathway, transported through the xylem [7,13,14], and induces oxidative stress, organelle degradation, and photosynthetic disruption [15].

Arsenic is a toxic metalloid derived from geological and industrial sources. Inorganic forms such as arsenates (As(V)) and arsenites (As(III)) pose the greatest food safety risks [6,16]. Its toxicity stems from binding to protein thiol groups (–SH) and replacing phosphorus in metabolic pathways [7]. Chronic exposure to soluble in water arsenic compounds causes renal, hepatic, and vascular damage, as well as skin, bladder, and lung cancers [16–18]. Elevated blood arsenic levels have also been linked to an increased risk of breast cancer in Polish women [19].

Lead is an environmental pollutant originating mainly from metallurgy, fossil fuel combustion, ammunition, and transport [6,20]. Absorbed via respiratory, dermal, and gastrointestinal routes, it accumulates in bones and teeth, where it poses a long-term risk during periods of increased bone resorption. Children are particularly vulnerable due to an immature blood–brain barrier [7,21,22]. Lead toxicity (saturnism) causes anemia, peripheral neuropathy, cognitive impairment, and renal failure, which can be fatal in acute cases [7,23].

The distribution of non-essential metals for plants, such as aluminium, and essential ones like copper, can be a great comparison for uptake patterns for heavy metals. Copper is considered as a micronutrient. It plays a vital role in cell wall metabolism, oxidative stress protection, and the biogenesis of the molybdenum cofactor. To manage its distribution, plants utilize a complex network of trafficking pathways that ensure copper homeostasis and appropriate delivery to target metalloproteins [24]. In contrast, aluminium, while not an essential nutrient, is a common soil component whose presence in different tuber layers can indicate the effectiveness of the periderm as a mechanical barrier [25]. Investigating these elements alongside lead, arsenic and cadmium allows for a more comprehensive understanding of how structural barriers and physiological processes influence the final mineral composition of the potato tuber.

The potato (*Solanum tuberosum* L.) ranks as the third most significant food crop worldwide, surpassed only by wheat and rice [26]. In Poland, according to data from the Statistics Poland (GUS), sales of table potatoes reached 1.6 million tonnes in the 2024/2025 season. During this period, total domestic production amounted to 6.35 million tonnes, with a cultivation area of 205,000 hectares [27]. The primary nutrients in potatoes are carbohydrates, which, in many varieties, constitute over 75% of the tuber's dry matter, most commonly in the form of starch. Despite their low protein content, potatoes can provide certain essential amino acids, such as lysine. Furthermore, they serve as a source of B complex vitamins, including riboflavin, thiamine, niacin, and folic acid, as well as vitamin C [3,13,26]. The global scale of potato cultivation for food purposes underscores the critical importance of ensuring their safety in the context of public health. This vegetable is particularly susceptible to the uptake of heavy metals due to the direct contact between the developing tuber and the soil [28]. A significant aspect of this issue is the variation in heavy metal bioaccumulation across different layers of potato tuber. Consequently, this pilot study aims to evaluate whether analyzing the distribution of metals within the tuber's structure is justified from the perspective of food safety and consumer risk assessment, while providing novel data regarding the chemical safety of potatoes commercially offered on the Tarnów local market

Regional data further underline the relevance of this issue for the Tarnów area. Elevated cadmium, nickel and zinc levels, as well as cadmium exceeding admissible limits in plants, were previously reported in soils and vegetation near Tarnów region, linked to local industrial pressure [29]. On a national scale, Lesser Poland, the province where Tarnów is located, was identified among the regions with the highest non-carcinogenic and carcinogenic consumer risk from potentially harmful elements in edible plants, including Cd, Cu, Pb and As [30].

Materials and methods

The research material consisted of tubers from three edible potato cultivars: "Soraya", "Vineta", and "Jelly". To reflect both certified agricultural practice and realistic retail scenarios, samples were obtained from three distinct supply channels: "Jelly" tubers were sourced directly from a local agricultural producer with confirmed cultivar seed provenance, while "Soraya" and "Vineta" were acquired from a major supermarket chain and a local greengrocer, respectively, representing produce as typically purchased by consumers. Several potato tubers of each variety were purchased for the study, from which one tuber of a given variety was randomly selected and used for the laboratory testing.

The research material was collected in Tarnów (Poland) during the fourth quarter of 2024.

To remove mineral impurities in the form of soil, the tubers were thoroughly dry cleaned mechanically using clean paper towels. Subsequently, using a stainless steel kitchen peeler (previously rinsed with deionized water and dried), the sampling areas for the peel and pulp were separated for further analysis. Three distinct zones were isolated from each potato: the peel and two layers of pulp. The resulting samples were weighed using an analytical balance (Radwag), and the thickness of the layers was measured with a caliper to an accuracy of 0.01 mm. Additionally, research material was collected from the central part of the tuber. Detailed samples labelling and their measured depths are presented in Table 1.

Table 1. Labeling of tested samples of potatoes tubers

Cultivar	Sample code	Depth [mm]
Soraya	P1L1	1.36
	P2L2	2.48
	P1L3	3.61
	P1M	11.34
Vineta	P2L1	1.62
	P2L2	2.80
	P2L3	3.79
	P2M	7.69
Jelly	P3L1	1.28
	P3L2	2.60
	P3L3	3.85
	P3M	7.66

To ensure systematic data management, the following coding system was used: P – denotes the potato cultivar, L – represents the sampled layer, and M – refers to the tuber core (flesh).

Approximately 1 g of each sample (measured to an accuracy of 0.0001 g) was weighed and placed in PTFE digestion vessels. Subsequently, 6 mL of concentrated ultra pure nitric(V) acid (Supelco, Sigma Aldrich) was added to each vessel. Next, a wet digestion of the samples was performed using a closed-vessel microwave-assisted digestion system (MAGNUM II, Ertec, Poland) with the temperature of up to 250°C and the pressure of up to 25 bar.

In order to provide a proper quality assurance, a reagent blank was prepared to account for potential background contamination from the reagents used. Following the completion of the digestion process and the cooling of the samples, the resulting solutions were quantitatively transferred into 50 mL volumetric flasks and diluted to the mark with deionized water. The final solutions were then stored in polypropylene vials.

Spectrometric analysis

To determine the concentrations of selected elements in the digested samples, Agilent 240Z AA atomic absorption spectrometer with graphite–furnace atomizer and Zeeman background correction was used. Each sample was analyzed in four replicates.

Results and discussion

Quality control

Concentrations of selected heavy metals in procedural blanks were very low, except for aluminium (which is a common contaminant of many materials), and therefore considered negligible relative to concentration of heavy metals in tuber samples. Based on the blank results, limits of quantifications (LOQ) were calculated. In order to confirm the accuracy of the calibration, a certified reference material (ESH3 – contaminated water, prod. by SPC Science, Canada) was measured in parallel to the samples. The calculated recoveries are close to 100% which confirms accuracy of the method calibration. Each calibration curve was based on 4 points. Quality control results, including LOQ and certified reference material, are summarized in Table 2.

Selected metals concentrations

The concentrations of selected metals in analyzed tubers together with expanded uncertainties are summarized in Table 3. and their distribution and overall reduction are illustrated in Figure 1. The overall reduction is calculated as a percentage drop in concentration of a given metal between the top layer and the core. Due to the concentrations of arsenic remaining consistently below or near the method's limit of quantification (140.6 µg kg^{-1}), this element was excluded from the graphical distribution analysis. The trace levels observed in all layers did not allow for a meaningful comparison of its spatial distribution across the tuber.

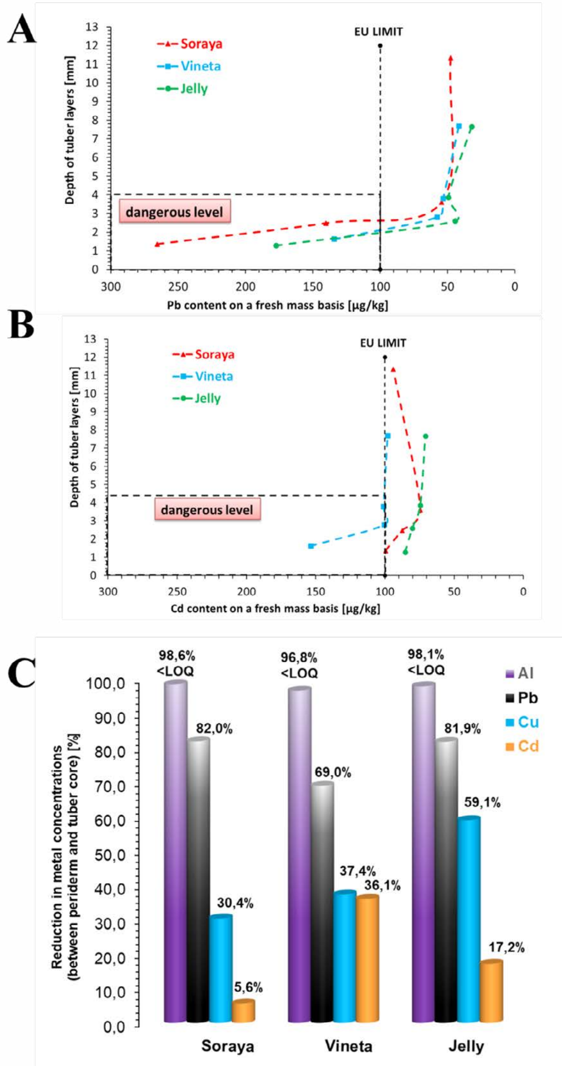

Figure 1. (A) Lead and (B) cadmium concentration profiles in the analyzed tubers; (C) Overall reduction in metal concentrations between the skin and the tuber core; and for Al between the skin and the LOQ

Lead displayed a pronounced decline in concentration with increasing depth in all three tubers. The observed changes correspond to the reductions of 82.0%, 69.0% and 81.9%, respectively, between the outermost layer (skin) and the flesh. The strongest decrease in lead concentration was observed within the 2–3 mm layer below the skin, after which the lead profile became noticeably flatter. Considering the 100 µg kg^{-1} threshold established by The European Commission as the maximum level of lead in peeled potatoes [31], Pb reached this level at 3 mm in tuber 1 and 2 mm in

Table 2. Calibration details, certified reference material recoveries, blank results and LOQ for lead, cadmium, copper, aluminium and arsenic

Sample	Parameter	Pb	Cd	Cu	Al	As
Calibration	calibration range [μg kg^{-1}]	0–20	0–1,2	0–50	0–30	0–100
	calibration curve *r*-value	0.9989	0.9983	0.9986	0.9998	0.9966
ESH3 (CRM)	Certified value [mg kg^{-1}]	5.6	11.2	42.2	11.65	21.9
	Tolerance interval [mg kg^{-1}]	5.05–6.15	10.15–12.20	37.85–46.55	9.95–13.4	19.5–24.3
	Determined value [mg kg^{-1}]	5.9 ± 0.3	11.5 ± 1.2	44.1 ± 0.9	12.99 ± 0.9	24.1 ± 0.16
	Recovery [%]	105.9	102.6	104.5	111.5	110.0
Blank	Experimental value [μg kg^{-1}]	0.26	0.06	0.83	31	2.6
	RSD [%]	13	23	9	1,7	0,8
–	Limit of quantification [μg kg^{-1}]*	29.4	13	79.7	1795	140.6

*LOQ = blank + 10 SD, where 'blank' is an average blank result for a given element; the result is further multiplied by the mean dilution factor (approx. 50 times) in order to represent the dry samples rather than their digested solutions.

Table 3. The results for all potato tuber samples. Concentrations are mean values (n = 4); expanded uncertainties are given with the coverage factor of k = 2

Sample code	Pb [μg kg^{-1}]	SD	U_{exp}	Cd [μg kg^{-1}]	SD	U_{exp}	Cu [μg kg^{-1}]	SD	U_{exp}	Al [μg kg^{-1}]	SD	U_{exp}
P1L1	266	21.5	97	99.5	1.9	6.3	1077	8	25	128.4	3.1	5.10
P1L2	140	3.8	13	87.5	0.4	1.5	776	6	21	4.44	0.10	0.16
P1L3	54	3.6	12	74.4	0.2	0.7	606	4	14	<1.8		
P1M	48	1.6	7	93.9	0.8	2.5	749	3	10	<1.8		
P2L1	134	3.1	10	154	3.4	11	871	3	9	55.7	1.6	2.7
P2L2	58	1.3	6	100.4	0.5	1.7	586	8	25	<1.8		
P2L3	53	2.1	10	101.0	1.3	4.3	519	5	15	<1.8		
P2M	42	1.5	5	98.2	0.8	2.6	545	10	32	<1.8		
P3L1	177	1.4	5	85.5	0.8	2.6	1110	4	15	93.4	0.4	0.6
P3L2	44	2.0	9	80.1	0.7	2.4	690	3	9	4.26	0.2	0.37
P3L3	49	2.5	8	74.5	0.7	2.5	1063	4	14	<1.8		
P3M	32	2.5	8	70.7	0.4	1.4	454	6	20	<1.8		

tubers 2 and 3 [31]. The differences in lead concentrations between the skin and flesh are consistent with past studies on determining Pb levels in produces grown in the UK. As reported previously, lead concentrations in potato tubers were high in the first 1 mm layer of the tuber and significantly reduced in the deeper layers [32]. The results also indicate, that the transport of lead in the tuber is limited due to its immobility in the phloem. Furthermore, it was demonstrated that the areas of potato tubers enriched with the highest dry matter content are located in the periphery, and the most mobile elements in potatoes included magnesium, sulphur, phosphorus, chlorine and potassium [33]. Additionally, lead in plants is accumulated in their cell wall after exposure to this element, since plant cell wall is rich in lead–binding compounds. When plants are exposed to stress induced by the presence of Pb, the cell wall thickens and acts as a physical barrier against lead ions, demonstrating their defensive mechanism [34].

Unlike lead, cadmium did not show a uniform decrease in concentration relative to the depth. In tuber 1 the concentration through studied layers ranged from 99.51, to 93.91 μg kg-1, reporting an overall reduction of 5.6%. In tuber 2, the reduction in Cd concentration was 36.1%, fluctuating from 98.21 to 153.67 μg kg^{-1} from the outermost layer to the core. Tuber 3 ("Jelly" variety) also exhibited a low reduction in cadmium concentration of 17.2%, with concentrations changing from 70.74 to 85.48 μg kg^{-1}. The lowest cadmium reduction values indicate high mobility of the element within the potato tuber. It was reported that Cd in potatoes is transported in both xylem and phloem throughout the tuber [35]. Therefore, due to its high mobility, cadmium may be less concentrated in the skin but evenly distributed across all layers of the tuber.

Similarly to lead, copper tended to accumulate in the outer layers of the tubers, but it did not display a uniform decrease across all potato tubers as lead did. Tuber 1 ("Soraya") exhibited an overall reduction of copper of 30.4% and its concentrations ranged from 1076.55to 749.09 μg kg^{-1} from the outermost layer to the core. Concentration changes in tuber 2 ("Vineta") ranged from 870.71to 545.35 μg kg-1 with a Cu reduction of 37.4%. The greatest reduction of copper at 59.1% was observed in tuber 3 ("Jelly"), where concentrations ranged from 1109.58to 454.27 μg kg^{-1}. In addition, tuber 3 exhibited the most non-monotonic profile of all samples in which copper was determined. The Cu concentration results indicate a similar pattern to that of lead, namely a higher concentration of the heavy metal is found in the outermost layer than in the flesh, especially the tuber core. Previous research demonstrated in their research that the distribution of copper is similar to that of phosphorus and calcium, indicating that despite its moderate mobility in phloem, it can move and accumulate in tissues similarly to one of these two elements [33].

Distribution of aluminium in all analyzed tubers exhibited the most pronounced gradient among all investigated elements. The highest accumulation of Al was consistently recorded in the periderm, with concentration levels reaching their peak in all three analyzed samples. In tuber 1 ("Soraya"), Al concentrations decreased gradually from 128,430 μg kg^{-1} in the outermost layer to 428.99 μg kg^{-1} in the core. The last result lie already below method's LOQ but based on this limit (1795 μg kg^{-1}), the resulting reduction of Al content reaches 98.6%. In tuber 2, aluminium concentrations decreased gradually from 55,705 μg kg^{-1} in the peel, through 1782.66 (just below the LOQ) and 1028.29 μg kg-1, to 623.60 μg kg^{-1} in the core. Based on the LOQ, corresponding overall reduction reaches 96.8%. For tuber 3, the recorded aluminium concentrations were 93,374, 4258.39, 995.40 and 476.79 μg kg^{-1} from the outermost layer to the core, which similarly, represented a total reduction of 98.1%. This distribution pattern indicates that Al is primarily adsorbed or sequestered in the outer protective layers, with minimal translocation into the internal storage tissues. A similar pattern was previously reported showing, that the distribution of Al in potato tuber is not uniform [25]. Their study reported that while some elements are distributed more evenly, others, such as iron, aluminium, silicon, and sodium exhibited an opposite distribution pattern, with higher concentrations in the peripheral regions of the tuber and a lower concentration near its core. Our results for Al strongly correlate with this model.

Conclusions

The distribution pattern of lead was consistent across all tested varieties. The pronounced accumulation of lead in the periderm indicates that this tissue acts as an effective barrier, making mechanical peeling an effective food safety measure. In contrast to lead, cadmium exhibited greater variability and a more uniform distribution within the tuber. Its high mobility suggests that cadmium levels are less affected by culinary processing (peeling), indicating that food safety regarding cadmium should be managed at the soil-cultivation stage rather than during food preparation. Furthermore, arsenic levels in all analyzed tuber layers remained consistently very low, which is positive from a consumer health perspective, as it minimizes the risk associated with chronic exposure to this toxic metalloid. It is crucial to emphasize that the EU limit for lead and cadmium (100 μg kg^{-1})

applies specifically to the product after peeling.. Our study demonstrates that peeling effectively removes the majority of heavy metal contaminants localized in the outer periderm, thereby significantly decreasing human health risk to negligible levels under standard consumption practices. Due to the observed variability in cadmium and copper levels, further studies involving a larger sample size and soil parameters are necessary to establish a more robust statistical model of heavy metal partitioning in *Solanum tuberosum* L.

References

[1] WHO Foodborne Disease Burden Epidemiology Reference Group for 2021–2024: first report. Geneva; 2022.

[2] Musilova J, Bystricka J, Vollmannova A, Volnova B, Hegedusova A. Factors affecting heavy metals accumulation in potato tubers. Environmental Protection and Natural Resources. 2015;26(3):54–9. https://doi.org/10.1515/oszn-2015-0018.

[3] Voica C, Roba C, Molnár C. Heavy metal contamination and health risk assessment of potatoes in Romania. Journal of Food Composition and Analysis. 2025;148:108242. https://doi.org/10.1016/j.jfca.2025.108242.

[4] Jadaa W, Mohammed H. Heavy metals – definition, natural and anthropogenic sources of releasing into ecosystems, toxicity, and removal methods – an overview study. Journal of Ecological Engineering. 2023;24(6):249–271. https://doi.org/10.12911/22998993/162955.

[5] Naveed S, Oladoye PO, Alli YA. Toxic heavy metals: A bibliographic review of risk assessment, toxicity, and phytoremediation technology. Sustainable Chemistry for the Environment. 2023;2:100018. https://doi.org/10.1016/j.scenv.2023.100018.

[6] Jaishankar M, Tseten T, Anbalagan N, Mathew BB, Beeregowda KN. Toxicity, mechanism and health effects of some heavy metals. Interdisciplinary Toxicology. 2014;7(2):60–72. https://doi.org/10.2478/intox-2014-0009.

[7] Scutarașu EC, Trincă LC. Heavy metals in foods and beverages: Global situation, health risks and reduction methods. Foods. 2023;12(18):3340. https://doi.org/10.3390/foods12183340.

[8] Tangahu BV, Sheikh Abdullah SR, Basri H, Idris M, Anuar N, Mukhlisin M. A review on heavy metals (As, Pb, and Hg) uptake by plants through phytoremediation. International Journal of Chemical Engineering. 2011:939161. https://doi.org/10.1155/2011/939161.

[9] Abdullahi A, Lawal MA, Salisu AM. Heavy metals in contaminated soil: Source, accumulation, health risk and remediation process. Bayero Journal of Pure and Applied Sciences. 2021;14(1):1–12. https://doi.org/10.4314/bajopas.v14i1.1.

[10] Mohamed HI, Ullah I, Toor MD, Tanveer NA, Din MMU, Basit A, Sultan Y, Muhammad M, Rehman MU. Heavy metals toxicity in plants: Understanding mechanisms and developing coping strategies for remediation: A review. Bioresources and Bioprocessing. 2025;12:95. https://doi.org/10.1186/s40643-025-00930-4.

[11] Clemens S. Toxic metal accumulation, responses to exposure and mechanisms of tolerance in plants. Biochimie. 2006;88(11):1707–1719. https://doi.org/10.1016/j.biochi.2006.07.003.

[12] Agency for Toxic Substances and Disease Registry (ATSDR) [Internet]. 2024 [cited 2026 Feb 1]. Substance Priority List 2022. Available from: https://www.atsdr.cdc.gov/programs/substance-priority-list.html.

[13] Musilova J, Bystricka J, Lachman J, Harangozo L, Trebichalsky P, Volnova B. Potatoes: A crop resistant against input of heavy metals from the metallicaly contaminated soil. International Journal of Phytoremediation. 2016;18(6):547–552. https://doi.org/10.1080/15226514.2015.1086303.

[14] Musilova J, Hrabovska D, Volnova B, Polakova Z. Does consumption of potatoes cultivated in soils contaminated by heavy metals pose any risk to human health? Environmental Protection and Natural Resources. 2013;24:25–28. https://doi.org/10.2478/oszn-2013-0011.

[15] Mushtaq G, Agrawal S, Kushwah A, Kumar A, Lone R. Cadmium toxicity in plants and its remediation management: A review. Plant Stress. 2025;16:100894. https://doi.org/10.1016/j.stress.2025.100894.

[16] Schrenk D, Bignami M, Bodin L, et al. Update of the risk assessment of inorganic arsenic in food. EFSA Journal. 2024;22(1):e8488. https://doi.org/10.2903/j.efsa.2024.8488.

[17] Singh S, Yadav R, Sharma S, Singh AN. Arsenic contamination in the food chain: A threat to food security and human health. Journal of Applied Biology and Biotechnology. 2023;11(4):24–33. https://doi.org/10.7324/JABB.2023.69922.

[18] Visciano P. Arsenic in water and food: Toxicity and human exposure. Foods. 2025;14(13):4–6. https://doi.org/10.3390/foods14132229.

[19] Muszyńska M, Jaworska-Bieniek K, Durda K, Sukiennicki G, Gromowski T, Jakubowska A, Morawski A, Lubiński J. Arsenic (As) and breast cancer risk. Hereditary Cancer in Clinical Practice. 2012;10(Suppl 4):A8. https://doi.org/10.1186/1897-4287-10-s4-a8.

[20] Kumar A, Kumar A, Cabral-Pinto MMS, Chaturvedi AK, Shabnam AA, Subrahmanyam G, Mondal R, Gupta DK,Malyan SK, Kumar SS, Kjan SA, Yadav KK. Lead toxicity: Health hazards, influence on food chain, and sustainable remediation approaches. International Journal of Environmental Research and Public Health. 2020;17(7):2179. https://doi.org/10.3390/ijerph17072179.

[21] Ociepa-Kubicka A, Ociepa E. Toksyczne oddziaływanie metali ciężkich na rośliny, zwierzęta i ludzi. Inżynieria i Ochrona Środowiska. 2012;15(2):169–180.

[22] Charkiewicz AE, Backstrand JR. Lead toxicity and pollution in Poland. International Journal of Environmental Research and Public Health. 2020;17(12):1–16. https://doi.org/10.3390/ijerph17124385.

[23] Wani AL, Ara A, Usmani JA. Lead toxicity: A review. Interdisciplinary Toxicology. 2015;8(2):55–64. https://doi.org/10.1515/intox-2015-0009.

[24] Yruela I. Copper in plants: Acquisition, transport and interactions. Functional Plant Biology. 2009;36(5):409–430. https://doi.org/10.1071/FP08288.

[25] LeRiche EL, Wang-Pruski G, Zheljazkov VD. Distribution of elements in potato (*Solanum tuberosum* L.) tubers and their relationship to after-cooking darkening. HortScience. 2009:1866–1873. https://doi.org/10.21273/HORTSCI.44.7.1866.

[26] Górska-Warsewicz H, Rejman K, Kaczorowska J, Laskowski W. Vegetables, potatoes and their products as sources of energy and nutrients to the average diet in poland. International Journal of Environmental Research and Public Health. 2021;18(6):1–23. https://doi.org/10.3390/ijerph18063217.

[27] Dzwonkowski W. Rynek ziemniaka stan i perpektywy. Analizy Rynkowe IERiGŻ PIB. 2024;51.

[28] Sawicka B, Pszczółkowski P, Messaoudi M, Skiba D, Barbaś P, Krochmal-Marczak B, Noaema AH. Genotype, environment, and heavy metals: Variability of the content of elements in 40 potato varieties from Central-Eastern Poland. Chemistry and Biodiversity. 2025;22(6):e202403337. https://doi.org/10.1002/cbdv.202403337.

[29] Gambuś F, Rak M, Wieczorek J. Heavy metals phytoavailability in the soils of the ecologically endangered regions in the province of Tarnów. Acta Agrophysica. 2001;51:221–230.

[30] Wódkowska A, Gruszecka-Kosowska A. Dietary exposure to potentially harmful elements in edible plants in Poland and the health risk dynamics related to their geochemical differentiation. Scientific Reports. 2023;13(1):8521. https://doi.org/10.1038/s41598-023-35647-x.

[31] European Commission. Commission Regulation (EU) 2023/915 of 25 April 2023 on maximum levels for certain contaminants in food and repealing Regulation (EC) No 1881/2006 [Internet]. Official Journal of the European Union; 2023 Apr 25. p. 103–57. Available from: http://data.europa.eu/eli/reg/2023/915/oj

[32] Norton GJ, Deacon CM, Mestrot A, Feldmann J, Jenkins P, Baskaran C, et al. Cadmium and lead in vegetable and fruit produce selected from specific regional areas of the UK. Science of the Total Environment. 2015;533:520–527. https://doi.org/10.1016/j.scitotenv.2015.06.130.

[33] Subramanian NK, White PJ, Broadley MR, Ramsay G. The three-dimensional distribution of minerals in potato tubers. Annals of Botany. 2011;107(4):681–691. https://doi.org/10.1093/aob/mcr009.

[34] Chudzik B, Szczuka E, Leszczuk A, Strubińska J. Modification of pectin distribution in sunflower (*Helianthus annuus* L.) roots in response to lead exposure. Environmental and Experimental Botany. 2018;155:251–259. https://doi.org/10.1016/j.envexpbot.2018.07.005.

[35] Reid RJ, Dunbar KR, McLaughlin MJ. Cadmium loading into potato tubers: The roles of the periderm, xylem and phloem. Plant, Cell and Environment. 2003;26(2):201–206. https://doi.org/10.1046/j.1365-3040.2003.00945.x.