



Research Article



Heavy Metal Bioaccumulation in Leek (*Allium porrum* L.) Cultivars

Natália Čeryová^{*1}, Jana Jakubčinová¹, Judita Lidiková¹, Olga Grygorieva², Ľuboš Harangozo¹

¹Slovak University of Agriculture in Nitra, Faculty of Biotechnology and Food Sciences, Institute of Food Sciences, Nitra, Slovak Republic

²M. M. Gryshko National Botanical Garden of the National Academy of Sciences of Ukraine, Department of Fruit Plants Acclimatisation, Kyiv, Ukraine

Natália Čeryová: <https://orcid.org/0000-0002-1865-5131>

Jana Jakubčinová: <https://orcid.org/0000-0002-3759-1372>

Judita Lidiková: <https://orcid.org/0000-0001-9922-4300>

Olga Grygorieva: <https://orcid.org/0000-0003-1161-0018>

Ľuboš Harangozo: <https://orcid.org/0000-0001-7243-9803>



Article Details:

Received: 2025-07-10

Accepted: 2025-08-02

Available online: 2025-11-30

DOI: <https://doi.org/10.15414/ainhlq.2025.0021>

This study investigated the elemental composition and cultivar-dependent variability in the accumulation of heavy metals in leek (*Allium porrum* L.) grown under field conditions. The aim of the research was to assess how different leek cultivars accumulate essential and potentially toxic elements and to identify genotypic traits influencing heavy-metal uptake under similar environmental conditions. Four cultivars (Albos, De Carentan, Elefant, Lungo Della Riviera) were analyzed for Fe, Mn, Zn, Cu, Co, Ni, Cr, Pb, and Cd contents using atomic absorption spectrometry. Among cultivars, Elefant exhibited the highest Fe, Cu, and Cd contents, while De Carentan accumulated more Zn and Pb. When recalculated to fresh mass, Cd concentrations in leek tissues remained below the permissible limit (0.04 mg·kg⁻¹ fresh matter), whereas Pb levels exceeded the threshold (0.10 mg·kg⁻¹ fresh matter). Principal component analysis (PCA) explained 76.1% of the total variance and revealed distinct clustering of cultivars according to their elemental profiles. Zn, Cu, Pb, and Co were the major contributors to PC1, while Mn and Cr influenced PC2. The findings demonstrate that both soil properties and genetic factors significantly affect heavy-metal uptake and accumulation in leek. Although the analyzed soil was moderately fertile and suitable for vegetable production, elevated Cd and Pb levels underline the need for continuous environmental monitoring, the implementation of soil remediation measures, and careful selection of cultivars with lower accumulation potential to ensure the safety and quality of vegetable produce.

Keywords: *Allium porrum*, heavy metals, bioaccumulation

***Corresponding Author:** Natália Čeryová, Institute of Food Sciences, Faculty of Biotechnology and Food Sciences, Slovak University of Agriculture in Nitra, Tr. A. Hlinku 2, 949 76 Nitra, Slovak Republic
[✉ natalia.ceryova@uniag.sk](mailto:natalia.ceryova@uniag.sk)

Introduction

The genus *Allium* L. belongs to the family Amaryllidaceae J.St.-Hil. (formerly classified under the family Liliaceae Juss.) and includes more than 800 species, including *Allium porrum* L., commonly known as leek (Sengupta et al., 2004). It is a hardy biennial crop known for both its culinary and medicinal values. The cultivation of leek has a long history, dating back to ancient Egypt. Leek originates from temperate climate zones and is currently grown on various continents including Africa, Australia, Europe, and South America (Sakthi and Monika, 2018). Unlike onion (*Allium cepa*) and garlic (*Allium sativum*), leek does not form typical bulbs or cloves. It has cylindrical or ovoid underground parts with one to two developed bulbs (Swamy and Gowda, 2006). The outer sheath is typically yellowish and membranous, while the inner layers are white to light brown. The leaves are linear to lanceolate, and the flower umbel is perennial, upright, and compact, often bearing more than 500 flowers (Sakthi and Monika, 2018). All parts of the plant have a distinctive, pungent aroma and taste, caused by the essential oils presence, with the most important component being allyl sulphide (Upadhyay, 2017).

Vegetables, including leek, play an important role in human nutrition, as they contain numerous health-beneficial compounds with preventive effects against various diseases (Cao et al., 1996). The nutritional composition of leek can vary significantly depending on the cultivar, climatic conditions (temperature, rainfall, solar radiation), soil type, as well as cultivation practices and interactions with other organisms in the agroecosystem (Shelke et al., 2020). *Allium* species are known as rich sources of secondary metabolites, including phenolic acids, their derivatives, and various groups of flavonoids (e.g., flavanones, flavones, flavonols, flavan-3-ols, and proanthocyanidins), which are associated with various biological effects (Strati et al., 2018).

In recent years, *Allium porrum* has also been considered a promising plant for the study of new phytochemicals with potential in the treatment of allergies (Benedé et al., 2019). Leek is a low-calorie food (100 g contains approximately 25 kcal) and a rich source of minerals such as zinc, iron, calcium, phosphorus, copper, potassium, sodium, manganese, and magnesium (Aljuhaumi et al., 2025). In addition, it also contains important vitamins – vitamin A (carotene), B-group vitamins (B1, B2, B3, B5), and vitamins C, E, and K – as well as folic acid. Other significant components include antioxidants such as lutein, zeaxanthin, and nicotinic acid, as well as plant proteins, fiber, sugars, and

sulphur compounds with proven bactericidal effects (Biernacka et al., 2021). Recent studies highlight the positive effects of leek consumption, including lowering cholesterol levels and reducing the risk of several types of cancer such as prostate, colon, stomach, and breast cancer as well as the prevention of neural tube defects and other developmental disorders (Sakthi and Monika, 2018).

This work aims to analyse the composition and cultivar-dependent variability in the accumulation of heavy metals in *Allium porrum* cultivated under field conditions. The results of this analysis may contribute to a better understanding of the mechanisms governing heavy metal uptake and accumulation in *Allium porrum*, as well as to the identification of cultivars with lower accumulation potential that are more suitable for cultivation in areas with increased soil metal content. Furthermore, the findings can support the development of targeted soil management and crop selection strategies aimed at minimizing the transfer of toxic elements into the food chain, thereby improving the safety and quality of vegetable production.

Material and Methodology

Plant Material Four leek (*Allium porrum* L.) cultivars (Albos (A), De Carentan (DC), Elefant (E), and Lungo Della Riviera (LDR)) were cultivated conventionally under identical agronomic and environmental conditions at the same locality (Veľká Mača, Slovak Republic). Fully mature plants were harvested manually and mechanically cleaned of organic and inorganic impurities immediately after collection.

Sample Preparation

For chemical analysis, the edible portion of the leek was used. Approximately 1 kg of each cultivar was washed with distilled water, sliced, and dried to constant weight at 45 °C. The resulting dry matter (100–150 g per cultivar) was homogenized for 30 s at 25,000 rpm using an IKA A10 basic grinder (IKA-Werke GmbH & Co. KG, Staufen, Germany) and stored in polyethylene bags until analysis. The dry matter content was determined by drying samples at 105 °C to constant weight using a Kern DLB 160-3A moisture analyzer (KERN & SOHN GmbH, Frommern, Germany).

Soil Sampling and Preparation

Soil samples were collected from a depth of 0–0.1 m using a GeoSampler pedological probe (Thermo Fisher Scientific, Hampton, NH, USA). Organic residues and debris were removed, and the samples were air-

dried at room temperature. After drying, the soil was ground using a VEB Thurm ZG 1 grinding machine (Stahlbau Magdeburg GmbH, Magdeburg, Germany) to obtain fine soil with an average particle size of 0.125 mm. The homogenized soil samples were stored in polyethylene bags before analysis.

Soil Analysis

The exchange soil reaction (pHKCl) was determined potentiometrically. A total of 20 g of soil was mixed with 50 mL of potassium chloride solution ($c = 0.01 \text{ mol} \cdot \text{dm}^{-3}$; Sigma-Aldrich Inc., St. Louis, MO, USA) in a 100 mL plastic bottle and shaken on a Unimax 2010 horizontal shaker (Heidolph Instrument GmbH, Schwabach, Germany) for 20 min. The suspension was subsequently filtered through Filtrak 390 quantitative filter paper (Munktell GmbH, Bärenstein, Germany). The pH of the filtrate was measured using a Metrohm 691 pH meter (Metrohm AG, Herisau, Switzerland).

The humus content and organic carbon (C_{ox}) in soil were determined by the modified Tjurin method (Nelson and Sommers, 1996). In brief, 1 g of soil was mixed with 0.1 g of Ag_2SO_4 and 10 mL of a pre-prepared chromium-sulfuric acid oxidation mixture. The mixture was heated to 150 °C for 20 min until the colour changed from brown to orange-yellow. After cooling, the samples were titrated with Mohr's salt solution ($c = 0.1 \text{ mol} \cdot \text{dm}^{-3}$) using diphenylamine as an indicator. The humus content was then calculated from the oxidized carbon concentration.

The inorganic nitrogen content ($\text{N-NO}_3^- + \text{N-NH}_4^+$) in soil was determined spectrophotometrically. Finely ground soil samples were extracted with a 1% K_2SO_4 solution at a ratio of 1 : 5 (w/v). The resulting suspension was shaken for 1 h on a Promax 1020 reciprocating shaker (Heidolph Instruments GmbH, Schwabach, Germany) at a frequency of 180 oscillations per minute. After extraction, the suspension was filtered through Filtrak 390 quantitative filter paper (Munktell & Filtrak GmbH, Bärenstein, Germany). The obtained filtrate was evaporated to dryness in a porcelain dish on a water bath. The residue was dissolved in 10–15 mL of distilled water with the addition of 3 mL of 4-hydroxybenzene-1,3-disulfonic acid reagent. The pH was adjusted using NH_4OH ($c = 6 \text{ mol L}^{-1}$) until a stable yellow coloration developed. The absorbance of the resulting solution was measured at $\lambda = 420 \text{ nm}$ using a Shimadzu UV-1800 UV/VIS spectrophotometer (Shimadzu Corp., Kyoto, Japan). The inorganic nitrogen content was calculated as the sum of nitrate (N-NO_3^-) and ammonium (N-NH_4^+) nitrogen, expressed in $\text{mg} \cdot \text{kg}^{-1}$, based on calibration

curves prepared from standard KNO_3 and $(\text{NH}_4)_2\text{SO}_4$ solutions.

Determination of Available Contents of Ca, K, Mg, and P in Soil

The available contents of macronutrients (Ca, K, Mg, and P) in soil were determined using the Mehlich II extraction method. The Mehlich II solution was prepared by dissolving 10.7 g of NH_4Cl , 0.56 g of NH_4F , and adding 11.5 mL of glacial acetic acid and 1 mL of concentrated HCl in a 1000 mL volumetric flask, then filling to volume with deionized water. For extraction, 5 g of air-dried, fine soil were weighed into a 100 mL plastic bottle, and 50 mL of Mehlich II solution was added. The suspension was shaken for 10 min on a Unimax 2010 horizontal shaker (Heidolph Instrument GmbH, Schwabach, Germany). The mixture was subsequently filtered through Filtrak 390 quantitative filter paper (Munktell GmbH, Bärenstein, Germany). Blank samples were prepared following the same procedure to ensure analytical accuracy.

The concentrations of K, Ca, and Mg in the filtrates were determined by flame atomic absorption spectrometry (FAAS) using a SpectrAA 240FS instrument (Varian Inc., Mulgrave, VIC, Australia). The phosphorus content was determined spectrophotometrically using the molybdenum blue method. For this purpose, 1 mL of the filtrate was pipetted into a volumetric flask, followed by the addition of 8 mL of reagent B, and the volume was made up to 50 mL with deionized water. After 2 h of color development, the phosphorus concentration was measured spectrophotometrically at $\lambda = 666 \text{ nm}$ using a Shimadzu UV-VIS 1800 spectrophotometer (Shimadzu Corp., Kyoto, Japan).

Determination of Pseudo-total Heavy Metal Content in Soil

The pseudo-total contents of heavy metals, including all forms except those bound within silicate and aluminosilicate soil lattice structures, were determined spectrometrically. Soil samples were digested using a MarsX-press 5 microwave digestion system (CEM Corp., Matthews, NC, USA) with aqua regia consisting of 2.5 mL of 65% HNO_3 Suprapur® (Merck, Darmstadt, Germany) and 7.5 mL of 37% HCl Suprapur® (Merck, Darmstadt, Germany). Following digestion, the samples were filtered through Filtrak 390 quantitative filter paper (Munktell GmbH, Bärenstein, Germany) and diluted with deionized water ($0.054 \mu\text{S cm}^{-1}$).

The concentrations of Fe, Mn, Zn, Cu, Co, Ni, and Cr were determined by flame atomic absorption

spectrometry (FAAS) using a VARIAN AASpectra DUO 240FS spectrophotometer (Varian Ltd., Mulgrave, VIC, Australia). Cadmium (Cd) and lead (Pb) were quantified by graphite furnace atomic absorption spectrometry (GFAAS) using a VARIAN AASpectra DUO 240Z spectrophotometer (Varian Ltd., Mulgrave, VIC, Australia). Calibration of both instruments was performed using CertiPUR® multi-element standards (Merck, Darmstadt, Germany).

Determination of Bioavailable Forms of Heavy Metals in Soil

The bioavailable (mobile) forms of heavy metals were determined by extraction with ammonium nitrate. Dried soil samples (20 g) were shaken with 50 mL of NH_4NO_3 solution ($c = 1 \text{ mol}\cdot\text{L}^{-1}$; Merck, Germany) for 2 h using a Unimax 2010 horizontal shaker (Heidolph Instrument GmbH, Schwabach, Germany). The suspension was then filtered through Filtrak 390 quantitative filter paper (Munktell GmbH, Bärenstein, Germany).

The concentrations of Fe, Mn, Zn, Cu, Co, Ni, and Cr in the filtrates were determined by FAAS (VARIAN AASpectra DUO 240FS), while Cd and Pb were determined by GFAAS (VARIAN AASpectra DUO 240Z). Calibration was again performed using CertiPUR® standard solutions (Merck, Darmstadt, Germany).

The measured concentrations of selected heavy metals in the soil samples were evaluated in comparison with the maximum permissible and critical values defined by Act No. 220/2004 Coll. on the Protection and Use of Agricultural Land (Slovak Republic).

Determination of Heavy Metal Content in Plant Material

Homogenized dried plant samples were digested using a Mars Xpress 5 closed microwave digestion system (CEM Corp., Matthews, NC, USA). Each sample (approximately 0.5 g) was mineralized in a mixture of 5 mL of HNO_3 Suprapur® (Merck, Darmstadt, Germany) and 5 mL of deionized water ($0.054 \mu\text{S}\cdot\text{cm}^{-1}$) at 160°C for 15 min, followed by a 10 min holding period at constant temperature. After digestion, the samples were filtered through Filtrak 390 quantitative filter paper (Munktell GmbH, Bärenstein, Germany) and diluted to a final volume of 50 mL with deionized water. The concentrations of Fe, Mn, Zn, Cu, Co, Ni, and Cr were determined by flame atomic absorption spectrometry (FAAS) using a VARIAN AASpectra DUO 240FS spectrophotometer (Varian Ltd., Mulgrave, VIC, Australia). Cadmium (Cd) and lead (Pb) were

determined by graphite furnace atomic absorption spectrometry (GFAAS) using a VARIAN AASpectra DUO 240Z spectrophotometer (Varian Ltd., Mulgrave, VIC, Australia).

The concentrations of heavy metals determined in leek samples were compared with the maximum permissible levels for vegetables established by Commission Regulation (EU) 2023/915, to evaluate food safety compliance.

Statistical analysis

Statistical analyses were conducted using XLSTAT (Lumivero, 2025). Results are presented as mean $\pm$ standard deviation (SD) of four replicates. Data normality and variance homogeneity were tested using Shapiro-Wilk and Levene's tests. Differences among cultivars were assessed by one-way ANOVA followed by Tukey's post hoc test ($p < 0.05$). When ANOVA assumptions were not met, the Kruskal–Wallis test with Dunn's multiple comparison ($p < 0.05$) was applied. Principal Component Analysis (PCA) was used to explore relationships among elements and visualize cultivar grouping based on elemental composition.

Results and Discussion

The chemical composition of the soil plays a crucial role in the uptake and accumulation of essential and potentially toxic elements by plants (Intawongse and Dean, 2006; Tangahu et al., 2011; Uchimiya et al., 2020; Chen et al., 2024). In this study, the analyzed soil sample exhibited a neutral to slightly alkaline reaction ($\text{pH}_{\text{KCl}} = 7.57$), which is generally favorable for nutrient availability and microbial activity (Table 1).

The humus (2.54%) and organic carbon (1.47%) contents indicate a moderate organic matter level, suggesting balanced fertility and moderate biological activity. The macro-element concentrations were typical for agricultural soils, with calcium ($3,443.4 \text{ mg}\cdot\text{kg}^{-1}$) and magnesium ($690.7 \text{ mg}\cdot\text{kg}^{-1}$) dominating, followed by potassium ($425.6 \text{ mg}\cdot\text{kg}^{-1}$) and phosphorus ($298.7 \text{ mg}\cdot\text{kg}^{-1}$). The total nitrogen ($\text{N}_{\text{an}} = 6.5 \text{ mg}\cdot\text{kg}^{-1}$) suggests a relatively low nitrogen reserve, consistent with soils of moderate humus content. The total heavy metal contents were within or slightly above background levels for uncontaminated soils. Iron ($16,969 \text{ mg}\cdot\text{kg}^{-1}$) and manganese ($549 \text{ mg}\cdot\text{kg}^{-1}$) reflected a natural lithogenic origin. Zinc ($85.8 \text{ mg}\cdot\text{kg}^{-1}$), copper ($29.6 \text{ mg}\cdot\text{kg}^{-1}$), and nickel ($35.2 \text{ mg}\cdot\text{kg}^{-1}$) concentrations were below the respective limit values ($150 \text{ mg}\cdot\text{kg}^{-1}$, $60 \text{ mg}\cdot\text{kg}^{-1}$, and $50 \text{ mg}\cdot\text{kg}^{-1}$). Lead ($26.3 \text{ mg}\cdot\text{kg}^{-1}$) was below its limit ($70 \text{ mg}\cdot\text{kg}^{-1}$), but cadmium ($2.06 \text{ mg}\cdot\text{kg}^{-1}$)

Table 1 Agrochemical characterisation of soil

Mineral content	K	Ca	Mg	P	pH _{KCl}	humus	C _{ox}	N _{An}	
Total content	425.60	3,443.40	690.73	298.73	7.57	2.54	1.47	6.50	
Heavy metal content	Fe	Mn	Zn	Cu	Co	Ni	Cr	Pb	Cd
Total content	16,969	549	85.8	29.6	8.88	35.2	18.5	26.3	2.06
Limit value*	NE	NE	150	60.0	NE	50.0	NE	70.0	0.70
Mobile forms	0.15	0.09	0.17	0.12	0.15	0.24	0.03	0.57	0.13
Critical value*	NE	NE	2.00	1.00	NE	1.50	NE	0.10	0.10

Notes: NE – not established

exceeded the critical value of 0.7 mg·kg⁻¹, indicating a potential contamination risk. The mobile forms of metals, which represent the bioavailable fraction, were significantly below the critical values for all elements except lead (0.57 mg·kg⁻¹) and cadmium (0.13 mg·kg⁻¹). Although these levels are still moderate, the relatively higher mobility of Pb and Cd suggests a potential environmental concern, particularly under acidic or changing redox conditions. Overall, the soil shows satisfactory fertility parameters and low to moderate contamination levels, with cadmium being the main element of concern. Continuous monitoring is recommended to assess possible accumulation trends, especially if the site is used for cultivating edible plants.

The concentrations of essential and potentially toxic elements in different leek cultivars revealed noticeable variability among the tested varieties (Table 2). Iron (Fe) content ranged from 31.5 mg·kg⁻¹ DW in cv. Lungo Della Riviera to 69.7 mg·kg⁻¹ DW in cv. Elefant, indicating significant cultivar-dependent differences ($p < 0.05$). Mužek et al. (2017) reported substantially higher iron concentrations in leek tissues, with 721.10 mg·kg⁻¹ DM in the underground part and 116.80 mg·kg⁻¹ DM in the above-ground part. Manganese (Mn) content showed a narrower variation (8.80–12.1 mg·kg⁻¹ DW), with cv. Lungo Della Riviera recorded the highest value. Mužek et al. (2017) reported a manganese concentration of 30.16 mg·kg⁻¹ DM in the underground part of garden leek, indicating substantially higher Mn accumulation in below-ground tissues compared to the present study. Zinc (Zn) levels varied between 9.90

and 13.1 mg·kg⁻¹ DW, with cv. De Carentan is the richest source of this micronutrient. Nazemi (2012) reported a markedly high zinc concentration in a selected garden leek cultivar, reaching 263.50 mg·kg⁻¹ DM, indicating substantial genotypic variability in trace element accumulation within *A. porrum*. In comparison, Mužek et al. (2017) observed an average value of 36.42 mg·kg⁻¹ DM in the primary edible portion of leek, further confirming that mineral composition in leek is strongly influenced by cultivar and growing conditions. Copper (Cu) content ranged widely from 2.40 to 6.50 mg·kg⁻¹ DW, reaching a maximum in cv. Elefant, which also exhibited elevated Fe and Zn levels, indicating a possible co-accumulation trend of transition metals in this cultivar. Mužek et al. (2017) evaluated copper content in two morphological parts of leek and recorded a higher concentration in the main edible portion (6.59 mg·kg⁻¹ DM) compared with the leaves, highlighting tissue-specific Cu accumulation patterns in *A. porrum*. Among trace and risk elements, cobalt (Co) and chromium (Cr) concentrations were uniform across cultivars (0.10–0.20 mg·kg⁻¹ DW), suggesting low variability and levels within the typical background range for leeks. Nickel (Ni) concentrations ranged from 0.70 to 1.20 mg·kg⁻¹ DW, while lead (Pb) and cadmium (Cd) contents were generally low, not exceeding 2.33 mg·kg⁻¹ DW and 0.28 mg·kg⁻¹ DW, respectively. When recalculated to fresh mass, cadmium concentrations in all leek cultivars remained below the maximum allowable limit of 0.04 mg·kg⁻¹ FM established by Commission Regulation (EU)

Table 2 Content of heavy metals in plant samples

Cultivar	Fe	Mn	Zn	Cu	Co	Ni	Cr	Pb	Cd
A	57.6±3.2 ^{ab}	8.80±0.5 ^a	10.8±0.9 ^{ab}	3.50±0.2 ^b	0.10±0.01 ^a	1.10±0.08 ^{bc}	0.20±0.01 ^a	2.12±0.01 ^{bc}	0.25±0.01 ^{ab}
DC	33.2±2.1 ^a	11.0±0.9 ^b	13.1±1 ^c	4.60±0.2 ^c	0.20±0.01 ^a	0.70±0.05 ^a	0.10±0.01 ^a	2.33±0.01 ^c	0.23±0.01 ^a
E	69.7±5.5 ^b	11.1±1.1 ^b	12.3±0.9 ^{bc}	6.50±0.4 ^d	0.10±0.01 ^a	1.00±0.05 ^b	0.10±0.01 ^a	1.92±0.01 ^b	0.28±0.02 ^b
LDR	31.5±1.3 ^a	12.1±0.9 ^b	9.90±0.5 ^a	2.40±0.2 ^a	0.10±0.01 ^a	1.20±0.07 ^c	0.10±0.01 ^a	1.29±0.01 ^a	0.27±0.01 ^b

Notes: A – cv. Albos; DC – cv. De Carentan; E – cv. Elefant; LRD – cv. Lungo Della Riviera

2023/915, confirming their compliance with food safety requirements. In contrast, lead levels exceeded the regulatory threshold of $0.10 \text{ mg}\cdot\text{kg}^{-1} \text{ FM}$ in all cultivars, with the highest Pb content observed in cv. De Carentan ($0.30 \text{ mg}\cdot\text{kg}^{-1} \text{ FM}$). This finding indicates potential environmental contamination of the cultivation area or cultivar-specific uptake efficiency for lead. Elevated Pb concentrations in vegetables are of particular concern due to their ability to accumulate this element in edible tissues through foliar deposition and root absorption. Other authors have also reported pronounced cultivar variability in the accumulation and content of heavy metals in leek, confirming that genetic factors strongly influence the uptake, translocation, and storage of these elements within plant tissues. Lidiková et al. (2021) observed significant differences among leek cultivars in heavy metal contents. Aljuhaimi et al. (2025) reported that among various metals analyzed in different parts of the leek, arsenic (As) and barium (Ba) were found in the highest concentrations, while other heavy metals, including Cd, Pb, Cr, Ni, and Cu, were detected only in trace amounts across the root, leaf, and bulbous layers. The authors concluded that the low levels of toxic metals, combined with a favorable content of essential elements such as Fe, Zn, and Mn, make leek a safe and nutritionally beneficial vegetable for human consumption.

According to Kučová et al. (2018), the content of heavy metals in leek can also be influenced by biological and environmental factors. Their study demonstrated that inoculation with arbuscular mycorrhizal fungi (AMF) slightly affected the accumulation of certain metals in *A. porrum*; however, the course of the weather had a more pronounced effect. In particular, higher temperatures during the growing season led to increased concentrations of zinc, lead, copper, and cadmium, regardless of AMF inoculation. This suggests that environmental conditions, such as temperature and moisture regime, can significantly modulate the bioavailability and uptake of heavy metals, even when soil conditions and microbial associations remain similar. The present findings, showing cultivar-dependent variability in metal accumulation, are therefore consistent with the view that both genetic factors and environmental influences jointly determine the elemental composition of leek.

Principal component analysis (PCA) was performed to explore relationships among the analysed elements (Fe, Mn, Zn, Cu, Co, Ni, Cr, Pb, Cd) and to identify similarities and differences among leek cultivars (Figure 1). The first two principal components (PC1 and PC2) together explained 76.1% of the total variance in the dataset (PC1 = 47.0%, PC2 = 29.1%), indicating that they capture most of the variability

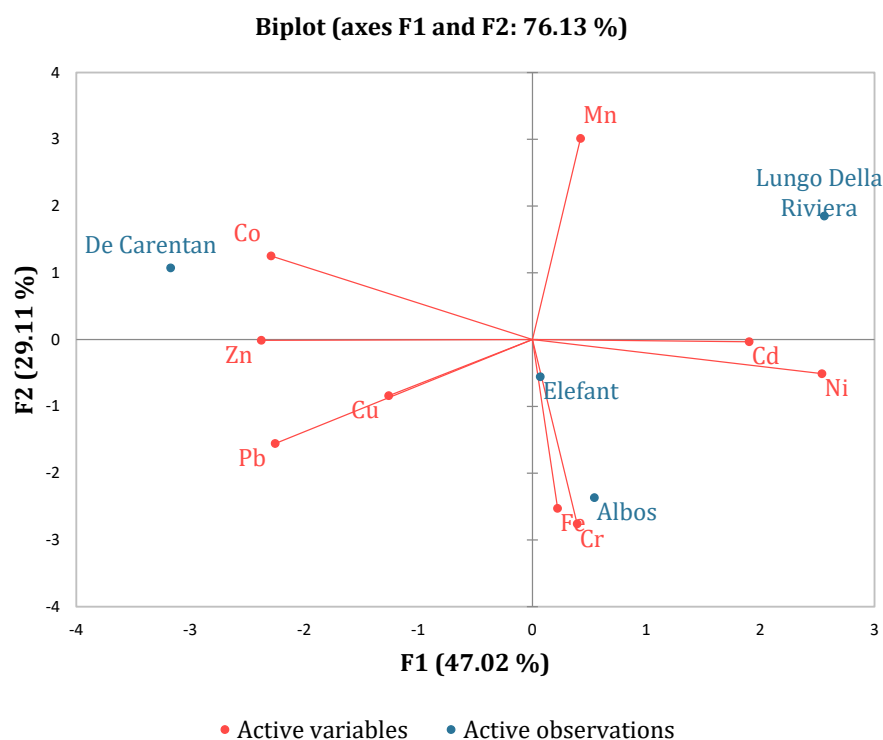


Figure 1 PCA biplot of *Allium porrum* L. cultivars based on elemental composition

in the elemental profiles. PC1 was primarily associated with positive loadings for Zn (0.308), Co (0.297), Pb (0.292), and Cu (0.163), suggesting that these elements co-varied and contributed most to the separation of cultivars along the first axis. In contrast, negative loadings for Ni (-0.329) and Cd (-0.246) indicate that these elements had an opposite trend to Zn, Co, and Pb. PC2 was strongly influenced by Mn (-0.307) and Cr (0.281), reflecting their distinct variation patterns among cultivars. The biplot (Figure 1) shows that 'Elefant' and 'De Carentan' are positioned apart from each other along PC1, reflecting their contrasting elemental compositions. Cv. Elefant was characterized by higher levels of Fe, Cu, and Cd, while cv. De Carentan was associated with elevated Zn, Pb, and Co contents. Cv. Lungo Della Riviera occupied the negative PC1–PC2 quadrant, associated with higher Mn and Ni levels but overall lower concentrations of other elements. Cv. Albos was positioned near the positive PC2 region, linked to higher Fe and Cr contributions. The clustering pattern indicates that cultivar-dependent differences in mineral accumulation exist, particularly for trace and potentially toxic elements such as Cd and Pb. These differences likely arise from genotypic variation in metal uptake and translocation mechanisms, as well as interactions among nutrients and soil factors influencing metal bioavailability. Similar cultivar-related patterns in elemental composition have been reported in other *Allium* species (Soudek et al., 2009; Cavanagh et al., 2019; Lidiková et al., 2021; Czarnek et al., 2023; Čeryová et al., 2023).

The calculated bioaccumulation factors (BAF) for heavy metals in leek cultivars indicate clear differences in their capacity to uptake and accumulate metals from the soil (Table 3). Overall, the BAF values were below 1 for all elements, suggesting that leeks act as non-accumulator plants, with limited ability to transfer metals from soil to edible tissues. This finding aligns with the behavior of other *Allium* species, which are known for their restricted mobility of heavy metals and efficient exclusion mechanisms (Sipter et al., 2009; Vuković et al., 2023; Gordanić et al., 2023; Din et al.,

2024). Among the analyzed elements, copper (Cu), zinc (Zn), and cadmium (Cd) exhibited the highest BAF values, ranging from 0.081–0.220, 0.115–0.153, and 0.112–0.136, respectively. This trend reflects the relatively higher mobility and bioavailability of these elements in soil, as well as their essential or semi-mobile nature within plant tissues. In contrast, Fe, Co, Ni, and Cr showed very low BAFs (<0.04), consistent with their strong binding to soil mineral fractions and limited translocation to aboveground parts. Among cultivars, cv. Elefant displayed the highest accumulation capacity for Cu (0.220) and Cd (0.136), aligning with its elevated tissue concentrations observed in the elemental analysis, whereas cv. De Carentan showed the highest Zn accumulation (0.153). The cv. Lungo Della Riviera accumulated the least Pb and Cu, while maintaining moderate Cd uptake. The consistently higher BAFs for Cd and Pb across cultivars highlight the potential risk of these elements entering the food chain, even at relatively low soil concentrations. Cavanagh et al. (2019) demonstrated that soil cadmium content and pH were significant predictors of Cd accumulation in onions, jointly explaining approximately 38% of the variation in bulb Cd concentrations, and when regional factors were included, up to 50% of the variation. This finding underscores the multifactorial nature of metal uptake in *Allium* species, governed not only by the total metal content in soil but also by soil chemistry, mobility, and environmental conditions. Accordingly, the partial mobility of Pb and Cd observed in this study, despite generally low total concentrations, likely reflects both the specific soil characteristics (e.g., slightly alkaline pH and moderate humus content) and the inherent physiological capacity of leeks to absorb and translocate these elements. Similarly, in a controlled hydroponic experiment, Czarnek et al. (2023) reported that the bioaccumulation of heavy metals (Cr, Cu, Zn, Ni, Fe, Mn, Co, Sr, Cd, and Pb) in *Allium cepa* L. was strongly dependent on both metal ion concentration in the nutrient solution and the specific plant organ analysed, confirming that uptake dynamics and tissue partitioning are species- and environment-specific.

Table 3 Bioaccumulation factor of heavy metals in plant samples

Cultivar	Fe	Mn	Zn	Cu	Co	Ni	Cr	Pb	Cd
A	0.003	0.016	0.126	0.118	0.011	0.031	0.011	0.081	0.122
DC	0.002	0.020	0.153	0.156	0.023	0.020	0.005	0.089	0.112
E	0.004	0.020	0.143	0.220	0.011	0.028	0.005	0.073	0.136
LDR	0.002	0.022	0.115	0.081	0.011	0.034	0.005	0.049	0.131

Notes: A – cv. Albos; DC – cv. De Carentan; E – cv. Elefant; LRD – cv. Lungo Della Riviera

Gharehbaghli and Sepehri (2022) reported that garlic (*Allium sativum* L.) cultivated hydroponically with cadmium chloride and sodium hydrosulfide experienced significant growth inhibition and reduced biomass, accompanied by high Cd accumulation in both roots and shoots. Regarding lead, Liu et al. (2009) and Carabulea et al. (2022) reported that Pb exposure negatively affected the growth and development of *A. sativum* plants, with the highest accumulation occurring in the roots and considerably lower amounts detected in bulbs and leaves.

Conclusions

This study demonstrated clear cultivar-dependent differences in the accumulation of essential and potentially toxic elements in leek. The cv. Elefant accumulated more Fe, Cu, and Cd, while cv. De Carentan had higher Zn and Pb, indicating that genetic factors strongly influence mineral uptake. Elevated Pb and Cd levels in soil were reflected in plant tissues, with Pb exceeding food safety limits, highlighting a potential contamination risk. PCA revealed distinct cultivar clustering based on elemental composition, confirming differences in metal accumulation patterns. Overall, both environmental conditions and cultivar traits govern metal uptake in leek. The findings emphasize the need for regular soil and crop monitoring, selection of cultivars with lower accumulation potential, and good agricultural practices to ensure the safety and quality of leafy vegetables.

Conflicts of Interest

The authors declare no conflict of interest.

Ethical Statement

This article doesn't contain any studies that would require an ethical statement.

Funding

This research was supported by the Scientific Grant Agency (VEGA) under Grant No. 1/0071/25, by the Cultural and Educational Grant Agency (KEGA) under Grant No. 042SPU-4/2024.

Acknowledgements

The authors are thankful to the International Scientific Network AgroBioNet.

References

- Aljuhaimi, F., Kulluk, D. A., Ahmed, I. A. M., Yilmaz, F. G., Karrar, E., & Özcan, M. M. (2025). The role of edible bulbous layers on macro, micro, and heavy metal contents of leek (*Allium porrum*) plant. *Biological Trace Element Research*, 203, 549–555.
<https://doi.org/10.1007/s12011-024-04181-w>
- Benede, S., Gradillas, A., Villalba, M., & Batanero, E. (2019). *Allium porrum* extract decreases effector cell degranulation and modulates airway epithelial cell function. *Nutrients*, 11(6), 1303.
<https://doi.org/10.3390/nu11061303>
- Biernacka, B., Dżiki, D., Kozłowska, J., Kowalska, I., & Soluch, A. (2021). Dehydrated at different conditions and powdered leek as a concentrate of biologically active substances: Antioxidant activity and phenolic compound profile. *Materials*, 14(20), 6175.
<https://doi.org/10.3390/ma14206127>
- Cao, G., Sofic, E., & Prior, R. L. (1996). Antioxidant activity of tea and common vegetables. *Journal of Agricultural and Food Chemistry*, 44(11), 3426–3431.
<https://doi.org/10.1021/jf9602535>
- Carabulea, V., Motelică, D. M., Vrînceanu, N. O., Ploeanu, G. I., Costea, M., Oprea, B. Ș., & Tănase, V. (2023). Bioaccumulation of heavy metals in garlic bulbs (*Allium sativum* L.) in correlation with soil from private gardens in the Copșa Mică area. *Journal of Applied Life Sciences and Environment*, 55(3), 245–255.
<https://doi.org/10.46909/alse-552061>
- Cavanagh, J. A. E., Yi, Z., Gray, C. W., Munir, K., Lehto, N., & Robinson, B. H. (2019). Cadmium uptake by onions, lettuce and spinach in New Zealand: Implications for management to meet regulatory limits. *Science of the total Environment*, 668, 780–789.
<https://doi.org/10.1016/j.scitotenv.2019.03.010>
- Czarnek, K., Tatarczak-Michalewska, M., Szopa, A., Klimek-Szczykutowicz, M., Jaferník, K., Majerek, D., & Blicharska, E. (2023). Bioaccumulation capacity of onion (*Allium cepa* L.) tested with heavy metals in biofortification. *Molecules*, 29(1), 101.
<https://doi.org/10.3390/molecules29010101>
- Čeryová, N., Lidikova, J., Šnirc, M., Harangozo, L., Pinter, E., Bobko, M., & Vollmannová, A. (2023). Heavy metals in onion (*Allium cepa* L.) and environmental and health risks. *Food Additives & Contaminants: Part B*, 17(1), 66–76. <https://doi.org/10.1080/19393210.2023.2291369>
- Din, I. U., Muhammad, S., Tokatli, C., ur Rehman, I., Ali, W., Shaik, M. R., & Hussain, S. A. (2024). Potentially harmful elements contamination, risk assessment, and their bioaccumulation in food crops. *Physics and Chemistry of the Earth, Parts A/B/C*, 136, 103747.
<https://doi.org/10.1016/j.pce.2024.103747>
- Gharehbaghli, N., & Sepehri, A. (2022). The ameliorative effect of hydrogen sulfide on cadmium toxicity and oxidative stress damage in garlic (*Allium sativum*) seedlings. *South African Journal of Botany*, 150, 161–170.
<https://doi.org/10.1016/j.sajb.2022.07.014>

- Gordanić, S. V., Kostić, A. Ž., Krstić, Đ., Vuković, S., Kilibarda, S., Marković, T., & Moravčević, Đ. (2023). A detailed survey of agroecological status of *Allium ursinum* across the republic of Serbia: Mineral composition and bioaccumulation potential. *Heliyon*, 9(11). <https://doi.org/10.1016/j.heliyon.2023.e22134>
- Chen, X., Zhou, K., Qin, W., Tian, C., Qi, M., & Yan, X. (2024). Study on factors influencing the migration of heavy metals in vegetables and their rhizosphere soils. *Sustainability*, 16(24), 11084. <https://doi.org/10.3390/su162411084>
- Intawongse, M., & Dean, J. R. (2006). Uptake of heavy metals by vegetable plants grown on contaminated soils and their bioavailability in soils. *Environmental Geochemistry and Health*, 28(4), 503–517. <https://doi.org/10.1007/s10653-005-5893-9>
- Kučová, L., Kopta, T., Šekara, A., & Pokluda, R. (2018). Controlling nitrate and heavy metals content in leeks (*Allium porrum* L.) using arbuscular mycorrhizal fungi inoculation. *Polish Journal of Environmental Studies*, 27(1). <https://doi.org/10.15244/pjoes/73799>
- Lidiková, J., Čeryová, N., Šnirc, M., Vollmannová, A., Musilová, J., Brindza, J., ... & Fehér, A. (2021). Comparison of Heavy Metal Intake by Different Species of the Genus *Allium* L. *Biological Trace Element Research*, 199(11), 4360–4369. <https://doi.org/10.1007/s12011-020-02536-7>
- Liu, D., Zou, J., Meng, Q., Zou, J., & Jiang, W. (2009). Uptake and accumulation and oxidative stress in garlic (*Allium sativum* L.) under lead phytotoxicity. *Ecotoxicology*, 18(1), 134–143. <https://doi.org/10.1007/s10646-008-0266-1>
- Lumivero (2025). XLSTAT statistical and data analysis solution. <https://www.xlstat.com/en>
- Mužek, M. N., Đulović, A., Buljac, M., Omanović, D., Kozina, T., Sedlar, A., ... & Blažević, I. (2017). Distribution of volatile sulfur compounds and heavy metals in Kohlrabi and leek. *Radovi Poljoprivrednog fakulteta Univerziteta u Sarajevu*, 62(2), 455–466.
- Nazemi, S. (2012). Concentration of heavy metal in edible vegetables widely consumed in Shahrud, the North East of Iran. *Journal of Applied Environmental and Biological Sciences*, 2(8), 386–391.
- Nelson, D.W., & Sommers, L.E. (1996). Total Carbon, Organic Carbon, and Organic Matter. In *Methods of Soil Analysis. Part 3. Chemical Methods* (pp. 961–1010). Soil Science Society of America, Madison, WI, USA.
- Sakthi, A., & Monika, N. (2018). *Allium porrum*: A review. *World Journal of Pharmaceutical and Life Sciences*, 4(3), 28–40. https://www.researchgate.net/publication/348778474_ALLIUM_PORRUM_A_REVIEW
- Sengupta, A., Ghosh, S., & Bhattacharjee, S. (2004). *Allium* vegetables in cancer prevention: An overview. *Asian Pacific Journal of Cancer Prevention*, 5(3), 237–245.
- Shelke, P. A., Rafiq, S. M., Bhavesh, C. H., Rafiq, S. I., Swapnil, P., & Mushtaq, R. (2020). Leek (*Allium ampeloprasum* L.). In *Antioxidants in Vegetables and Nuts – Properties and Health Benefits* (pp. 309–331). Springer. <https://doi.org/10.1007/978-981-15-7470-2>
- Sipter, E., Auerbach, R., Gruiz, K., & Mathe-Gaspar, G. (2009). Change of bioaccumulation of toxic metals in vegetables. *Communications in Soil Science and Plant Analysis*, 40(1–6), 285–293. <https://doi.org/10.1080/00103620802647165>
- Soudek, P., Kotyza, J., Lenikusová, I., Petrová, Š., Benešová, D., & Vaněk, T. (2009). Accumulation of heavy metals in hydroponically cultivated garlic (*Allium sativum* L.), onion (*Allium cepa* L.), leek (*Allium porrum* L.) and chive (*Allium schoenoprasum* L.). *Journal of Food, Agriculture and Environment*, 7(3), 761–769.
- Strati, I. F., Kostomitsopoulos, G., Lytras, F., Zoumpoulakis, P., Proestos, C., & Sinanoglou, V. J. (2018). Optimization of polyphenol extraction from *Allium ampeloprasum* var. *porrum* through response surface methodology. *Foods*, 7(10), 162. <https://doi.org/10.3390/foods7100162>
- Swamy, K. R. M., & Gowda, R. V. (2006). Leek and shallot. In *Handbook of Herbs and Spices* (vol. 3, pp. 365–389). Woodhead Publishing. <https://doi.org/10.1533/9781845691717.3.365>
- Tangahu, B. V., Sheikh Abdullah, S. R., Basri, H., Idris, M., Anuar, N., & Mukhlisin, M. (2011). A review on heavy metals (As, Pb, and Hg) uptake by plants through phytoremediation. *International Journal of Chemical Engineering*, 2011, Article ID 939161. <https://doi.org/10.1155/2011/939161>
- Uchimiya, M., Mojica, A., & Xie, Q. (2020). Chemical speciation, plant uptake, and toxicity of heavy metals: interactions with soil chemical composition. *Journal of Agricultural and Food Chemistry*, 68(10), 2753–2761. <https://doi.org/10.1021/acs.jafc.0c00183>
- Upadhyay, R. K. (2017). Nutritional and therapeutic potential of *Allium* vegetables. *Journal of Nutritional Therapeutics*, 6(1), 18–37. <https://doi.org/10.6000/1929-5634.2017.06.01.3>
- Vuković, S., Moravčević, D., Gvozdanović-Varga, J., Dojčinović, B., Vujošević, A., Pećinar, I., & Kostić, A. Ž. (2023). Elemental profile, general phytochemical composition and bioaccumulation abilities of selected *Allium* species biofortified with selenium under open field conditions. *Plants*, 12(2), 349. <https://doi.org/10.3390/plants12020349>