

## UTILIZATION OF AGRICULTURAL LAND POLLUTED WITH HEAVY METALS: A CASE IN THE MARAMUREȘ REGION, ROMANIA

Valeria M. Brezoczki<sup>1,2\*</sup>, Teodora Ungureanu<sup>3</sup>

<sup>1</sup>*Technical University of Cluj-Napoca/ North University Centre at Baia Mare, Engineering Faculty/ Mineral Resource, Material, Environment Engineering Department, 430083, Baia Mare, Maramureș, Romania*

<sup>2</sup>*European University of Technology, European Union*

<sup>3</sup>*The National Institute for Research and Development in Constructions/ Urbanism and Sustainable Spatial Development URBAN-INCERC/ 021652, Bucharest, Romania*

\*Corresponding author: [valeria.brezoczki@irmmm.utcluj.ro](mailto:valeria.brezoczki@irmmm.utcluj.ro)

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**Abstract:** This study investigates agricultural land in Maramureș County, Romania, located near an extensive mining site with a history of heavy metal contamination. The polluted area lies adjacent to the Cavnic River, downstream from the Plopiș-Răchițele tailings pond. Local farmers use various fertilization practices, including the application of sediments extracted from the Cavnic River bed and, occasionally, nutrient-rich sludge from municipal wastewater treatment plants. While these materials are valued for their essential nutrient content (NPK), their use may worsen existing soil pollution.

The research assesses contamination levels, considering both the legacy of mining activities and current agricultural practices. The findings indicate that, although sewage sludge is rich in nutrients, it does not currently represent a viable solution for improving soil quality in this area due to the persistent heavy metal contamination from past mining operations.

The study recommends the implementation of local phytoremediation strategies and more accessible government policies focused on the remediation of former mining sites and environmental safety. These should be pursued in parallel with a revised local land-use strategy aimed at reducing the risks associated with pollutant exposure.

**Keywords:** *corn plants, environmental risks, farming practices, food safety, local urban planning, mining area, sewage sludge*

## INTRODUCTION

Land resource management policies in rural agricultural areas should be oriented towards promoting sustainable and resilient local development [1]. In Romania, as in other European countries with a significant rural population, agricultural land is predominantly under private ownership. This often results in inconsistent farming practices and a lack of long-term strategic approaches to preserving soil quality. Landowners may frequently overlook the full spectrum of risks associated with soil degradation, particularly contamination with heavy metals, which can adversely affect both human and animal health through the consumption of cultivated crops [2 – 4].

One of the primary sources of such contamination is the legacy of industrial activity. Soil pollution frequently arises from improperly decommissioned mining sites or from the mismanagement of sewage sludge applications-both of which can introduce significant concentrations of persistent pollutants into agricultural systems [5 – 8]. These forms of diffuse contamination are particularly challenging to monitor and mitigate, especially in areas lacking coordinated land-use governance.

In Maramureş County, significant environmental degradation is strongly linked to historical mining activities, particularly in areas such as Cavnic, where extensive extraction and processing of polymetallic and gold-silver ores have led to the long-term contamination of environmental matrices. These operations released substantial quantities of pollutants, including heavy metals, which have accumulated in soil and watercourses-especially along the Cavnic River. Although mining operations officially ceased in 2006, residual pollution continues to affect soil productivity and ecosystem stability. Recent studies highlight elevated concentrations of heavy metals such as lead (Pb), cadmium (Cd) and zinc (Zn) in soils within the mining basin, emphasizing the urgent need for remediation measures to restore ecological balance and support safe agricultural practices in affected areas [9, 10].

Sewage sludge management is also essential for minimizing environmental contamination. In European countries, there are legal regulations and procedures for sewage sludge management; consequently, the practice of fertilizing agricultural soils with sewage sludge is an important step in the transition toward a circular economy [11 – 15], with direct benefits through the presence of important nutrients for crop productivity nitrogen (N), phosphorus (P), and potassium (K) [16]. However, this practice is only beneficial if preceded by thorough analyses of the types of harmful chemical elements present in the sludge and the available methods for mitigating their potential impact [17 – 20].

Soil can act as a reservoir for environmental contaminants due to its capacity to bind chemical substances. The toxicity of these compounds poses risks to ecosystems, and factors such as soil variability and climate can trigger the leaching of toxic trace elements like heavy metals [21]. These heavy metals adversely affect soil microbial communities, reducing their abundance, diversity, and biological activity [22, 23]. Moreover, they may also harm plants and humans, prompting the establishment of regulatory limits for their concentrations in soils. These limits often vary according to land use or specific soil properties, although some countries enforce uniform standards [24].

In response to concerns regarding soil contamination, international organizations such as the World Health Organization (WHO) and the Food and Agriculture Organization (FAO) have issued guidelines for the safe use of sewage sludge in land reclamation

practices [25]. At the legislative level, the use of sewage sludge in agriculture within the European Union is governed by Directive 86/278/EEC (transposed into Romanian law through Government Decision No. 344/2004), which aims to prevent risks to soil, vegetation, animals, and human health [26, 27]. Although sewage sludge contains organic matter and macronutrients such as nitrogen (N), phosphorus (P), and potassium (K), its use is often complicated by the presence of pollutants-including heavy metals, organic contaminants, and pathogens-depending on the initial composition of the wastewater and the treatment processes applied [28 – 30].

However, higher plants are highly sensitive to metal-induced stress. Lead (Pb) inhibits key enzymatic activities, reduces water absorption, and suppresses plant growth. Zinc (Zn) alters microbial activity, affects the physicochemical properties of soils, and slows down organic matter transformation. Cadmium (Cd), commonly found in phosphate fertilizers, disrupts microbial processes and, even at low concentrations, negatively impacts the germination and growth of triticale [31, 32]; it is also more readily absorbed by plants from soil than from water. Copper (Cu), while essential for living organisms, functions both structurally and catalytically in various metabolic processes [33, 34].

This study is grounded in specialized literature, legal frameworks, and applicable standards, and it investigates the agricultural use of land located near the former Cavnic mining perimeter in Maramureș County, Romania. The agricultural plots are located on both banks of the Cavnic River, near the tailing ponds of the former ore processing plant. At the Plopiș-Răchițele tailings pond more than 3.5 million tons of flotation tailings have been deposited because of extensive mining operations in the region. These tailings have led to the formation of considerable volumes of acid mine drainage, which were accidentally released into the Cavnic River and subsequently transported downstream over long distances, significantly contributing to the dissemination of heavy metal contamination. Decades of mining activity in the Cavnic area have left a profound environmental footprint, particularly affecting the water quality of the Cavnic River and the productivity of adjacent soils. Despite the decline in mining operations, the environmental impacts persist, highlighting the long-term consequences of historical mining activities in the region. Most agricultural terrains in the area were subjected to various sources of pollution with heavy metals over the years, either through direct spills from pond, exfiltration, dislodging and carrying away pollutants by air over long distances.

During Romania's post-socialist transition, substantial changes in land ownership took place, with large areas of agricultural land being restituted to former owners or their heirs. These changes have had ecological implications that are often overlooked by landowners [35]. Local farmers continue to cultivate various crops and use sedimentary material from the Cavnic River's bed for soil fertilization-often without full awareness of the potential environmental and health risks involved.

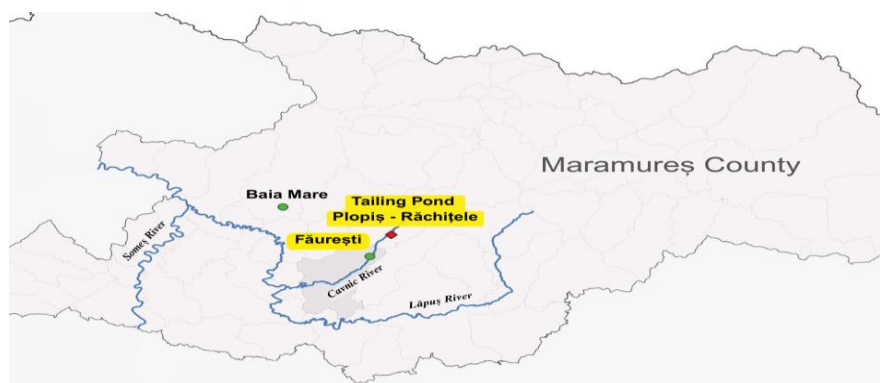
This research specifically monitors the biometric parameters of corn plants cultivated on agricultural land deemed potentially affected by legacy contamination with heavy metals resulting from historical mining activities, and, in parallel, the study evaluates the influence of sewage sludge-sourced from the local municipal wastewater treatment plant-on soil quality and crop development, within the context of its use as an agricultural fertilizer.

## MATERIALS AND METHODS

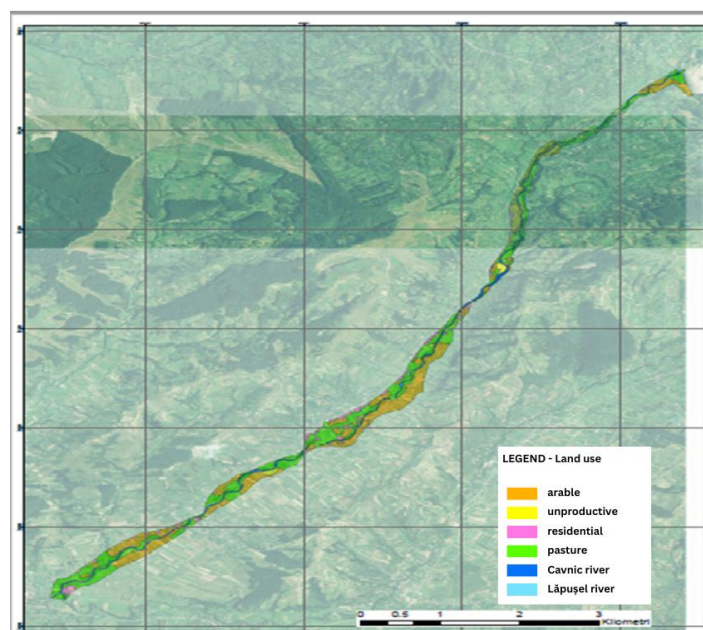
### Description of the study area

The studied agricultural land, measuring about 1 hectare, is in Făurești village, Maramureș County presented in Figure 1. It is part of a much larger area, which geographically is located on the right bank of the Cavnic River, from the area of the Plopiș-Răchițele settling pond to the overflow of the Cavnic River into the Lăpuș River, Figure 2.

The soil in this area is characterized by alluvial soils, developed under well-drained conditions and characterized by low accumulation of unsaturated humus and low-moderate fertility potential. The fine-textured surface horizon is formed under arid conditions on periodically flooded soils [36].



**Figure 1.** The geographical location of village in Maramureș County, Romania [37]



**Figure 2.** The geographical location of land area near of Cavnic River [38]

The area, categorized by land use, includes approximately 124.75 hectares of arable land for agricultural crops, 128.75 hectares of grassland, 4.70 hectares of non-productive land, and 20.25 hectares of building land [38]. According to the data, an area of about 260 hectares may be subject to varying levels of historical heavy metal pollution.

The studied agricultural land is a few meters away from the River Cavnic (Figure 3a), only 4817 m from the perimetral dam of the tailing pond Plopiș-Răchițele (Figure 3b), and the body of the pond is parallel to the bed of the River Cavnic. The location of the site investigated was obtained using GIS technology [37].

Over the years, most agricultural land in the surrounding area has been exposed to multiple sources of heavy metal pollution, including direct discharges from the tailings pond, infiltration into soil and groundwater, as well as the atmospheric dispersion and deposition of airborne contaminants across extended areas.

In the area studied, a great part of the agricultural land is cultivated with cereals (corn and wheat), and vegetables (tomatoes, cucumbers, potatoes, salad, onion etc.), used for human and animal consumption.



(a) The distance between the agricultural land and the River Cavnic [37]



(b) The distance between the agricultural land and tailing pond Plopiș-Răchițele [37]

**Figure 3.** Location of the investigated site

### Research Procedures

The study was conducted within the Environmental Factors Analysis Laboratory of the North University Centre in Baia Mare and aimed to evaluate the bioaccumulation of heavy metals in corn crops cultivated on substrates composed of fertile soil mixed in varying proportions with sewage sludge originating from the municipal wastewater treatment plant. The experimental design included the application of terrestrial plant assays, specifically the Seedling Emergence and Seedling Growth Test, in accordance

with the OECD Guideline 208 (updated in 2006). This method is intended to assess the potential phytotoxic effects of substances on plant germination and growth [39].

Bioaccumulation levels of heavy metals were evaluated by performing chemical analyses on both soil and plant samples, focusing on the mobile (bioavailable) fractions of copper (Cu), zinc (Zn), and cadmium (Cd).

The research methodology followed the steps below:

- Collection of soil samples using soil sampling probes.
- Homogenization of soil samples through the ring method, followed by the creation of a representative composite sample using the quartering technique.
- Moisture determination of both soil and sludge using the gravimetric method, followed by the preparation of experimental pots.
- Establishing the mixing ratios between fertile soil and sewage sludge for each experimental variant.
- Measurement of pH, electrical conductivity and salinity for each soil-sludge mixture, as well as for control samples, using the ExStik II EC500 multi-parameter device.
- Monitoring of biometric parameters of corn plants throughout the experimental period and observation of water and temperature conditions.
- The analytical results regarding the content of Cu, Zn, and Cd in the soil samples, the bioaccumulation of these metals in corn plants as well as transfer of metals soil into plant.

#### ***Collecting, homogenizing and preparing the samples***

The fertile soil samples were collected from an agricultural land using a sampling probe, over a rectangular surface area of 1 hectare, subdivided into equal units forming a 20 x 20 m grid. The samples were taken from a predetermined depth of 0 – 20 cm. The collected soil samples were cleaned of vegetal and inert residues and subsequently homogenized to obtain representative composite samples for the analyzed surface.

#### ***Determining the proportions of fertile soil-sludge mixture and measuring the parameters***

During laboratory tests, two control samples were used: the fertile soil control sample (PM-1000 g) and the sludge control sample (PN-1000 g) obtained from the city wastewater treatment plant. For the other five samples, considering the composition of the sludge, various proportions of fertile soil-sludge mixture were selected: P1 - 990 g fertile soil + 10 g sludge; P2 - 970 g fertile soil + 30 g sludge; P3 - 950 g fertile soil + 50 g sludge; P4 - 925 g fertile soil + 75 g sludge; and P5 - 900 g fertile soil + 100 g sludge. For all samples, the following parameters were determined: pH (pH units), salinity (ppm), electrical conductivity ( $\mu\text{S}\cdot\text{cm}^{-1}$ ), and environmental temperature ( $^{\circ}\text{C}$ ).

#### ***Sowing corn and monitoring the plants biometrical data***

The corn kernels (cultivar PR38A24) were treated with the fungicide Maxim XL 035 FS, which is effective against vascular wilt (Fusariosis) caused by *Fusarium* spp. and damping-off due to *Pythium* spp. Fifteen kernels were sown in each flowerpot assigned to the control samples (PM and PN), and the same number of kernels was maintained for treatments P1–P5. The experimental study was conducted over a 42-day calendar period, during which we recorded biometric parameters (meaning plant height and number of germinated kernels), monitored the irrigation regime and ambient temperature, and

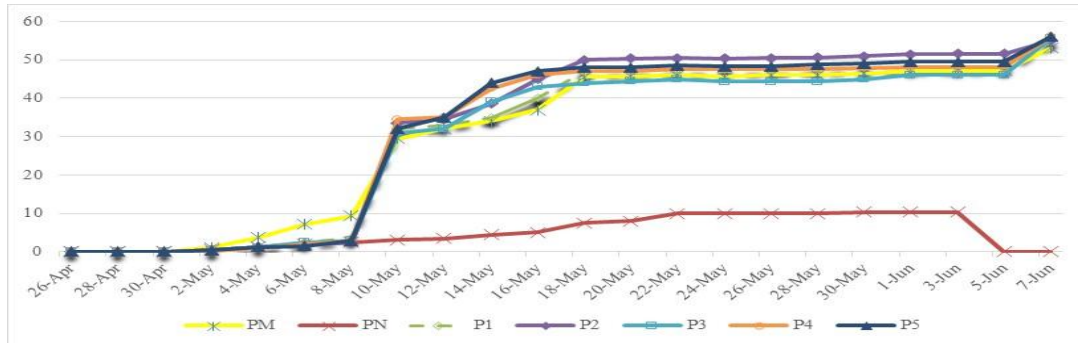
inspected plant surfaces for physiological symptoms such as spotting or chlorosis (Figure 4).



*Figure 4. The corn plants after 42 test days*

***Water regime, environmental temperature, and maize growth***

An initial irrigation volume of 100 mL per sample was delivered every other day for the first eight days of the trial; thereafter, the application rate was reduced to 50 mL per sample until the end of the experiment. During this period, ambient temperatures fluctuated between a minimum of 19 °C (recorded on day 1) and a maximum of 26 °C, with most measurements falling within the 20 – 22 °C range. High temperatures can enhance the mobility of heavy metals in the soil, increasing their solubility and availability for plant uptake [40]. The mean growth trajectory of the corn plants from 26 April to 07 June is shown in Figure 5.



*Figure 5. The average growth variation of the growth of the corn plants*

***Assessment of Heavy Metal Content in Soil and Plants and Evaluation of Metal Transfer Factors***

After 42 days of growth, the corn plants were harvested along with their roots, weighed, packaged in appropriate bags, and sent for analysis to determine their heavy metal content (Cu, Zn, and Cd) through atomic absorption spectroscopy. Total metals (copper, zinc, and cadmium) that were mobile in both the soil samples and the plants were extracted using an ammonium acetate-EDTA solution and measured through atomic absorption spectroscopy, in accordance with SR ISO 11047:1998, PLT 32.

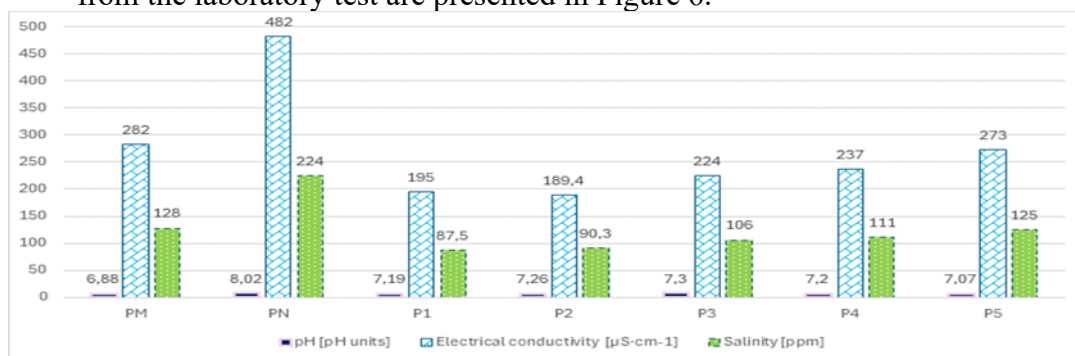
Soil transfer of metals to plant is one of the main ways of human exposure to soil contamination. The formula for TF's calculation, equation (1), is the ratio between concentration of heavy metals in soils ( $\text{mg}\cdot\text{kg}^{-1}$ ) and concentration of heavy metals in plants ( $\text{mg}\cdot\text{kg}^{-1}$ ) [41].

$$TF = \frac{\text{Concentration of heavy metals in plants (mg} \cdot \text{kg}^{-1})}{\text{Concentration of heavy metals in soils (mg} \cdot \text{kg}^{-1})} \quad (1)$$

In general, the values of the transfer factor differ according to the type of plant, the bioavailability of the plant, the part of the plant analyzed, the type of soil used, but especially the type of metal transferred and its mobility in the soil.

## RESULTS AND DISCUSSION

- **Quality parameters measured in the studied samples** - The results obtained from the laboratory test are presented in Figure 6.



**Figure 6.** Variation of the parameters determined in the analyzed samples

The highest salinity and conductivity values were recorded in the sludge sample obtained from the municipal wastewater treatment plant. The lower salinity and electrical conductivity (EC) values observed in the soil–sludge mixtures compared with the control soil may be related to the high organic matter content of the sewage sludge. This can increase the soil's cation exchange capacity and promote the adsorption of soluble ions by soil colloids, reducing the concentration of dissolved salts in the soil solution and consequently lowering both salinity and EC. Moisture content in both the fertile soil and sludge was determined by gravimetric analysis using a Binder drying oven, yielding 24 % moisture for the fertile soil control sample and 80 % moisture for the sludge control sample.

- **The characteristics of the sludge used** in tests are presented in Table 1.

**Table 1.** The characteristics of the end sludge from wastewater treatment plant

Characteristics of the sludge used	Units	Measured values	Analysis method
pH	units pH	7.77	SR EN 12176:2000
Humidity	%	79.8	SR EN 14346:2007
Dry matter	%	20.2	SR EN 14346:2007
Cadmium	$\text{mg}\cdot\text{kg}^{-1}$	12.6	SR EN ISO 11885:2009
Copper	$\text{mg}\cdot\text{kg}^{-1}$	391.0	SR EN ISO 11885:2009
Zinc	$\text{mg}\cdot\text{kg}^{-1}$	2080.0	SR EN ISO 11885:2009
Phosphorus	$\text{mg}\cdot\text{kg}^{-1}$	1820.0	SR EN ISO 11885:2009
Azote	$\text{mg}\cdot\text{kg}^{-1}$	55.1	SR EN ISO 11885:2009
Potassium	$\text{mg}\cdot\text{kg}^{-1}$	1030.0	SR EN ISO 11885:2009

The sewage sludge is rich in essential plant nutrients: phosphorus (1820 mg·kg<sup>-1</sup>), nitrogen (55.1 mg·kg<sup>-1</sup>), and potassium (1030 mg·kg<sup>-1</sup>), highlighting its fertilizing potential.

➤ **The analysis of the data on average growth variation of the growth of the corn plants** leads to the following observations:

- The germination period for the corn kernels, as well as the sprouting phase, consistently lasted 3 to 4 days across all samples.
- Corn kernels germination rates varied among the samples studied. The soil control sample (PM) exhibited a germination rate of 71.4 %, while the sludge sample had a lower germination rate of 57.14 %.
- The germination percentages for the corn kernels in the mixed soil-sludge samples were as follows: P1 – 80.00 %, P2 – 80.00 %, P3 – 93.33 %, P4 – 86.66 %, and P5 – 100 %. Notably, P5 was the only sample where all kernels successfully germinated.
- Growth and development patterns differed significantly between the two control samples. Plant height in the sludge sample was reduced by 78.26% when compared to the soil control sample. Additionally, plants in the sludge control sample exhibited necrosis and leaf discoloration.

In contrast, the corn plants in the soil-sludge mixtures demonstrated an overall growth rate that slightly exceeded the average height growth observed in the fertile soil control sample.

➤ **The presence and distribution of heavy metals - copper (Cu), zinc (Zn), and cadmium (Cd) in soil samples**, as well as the transfer efficiency of these metals in corn plants, are presented in Table 2.

**Table 2.** The results of Zn, Cu, and Cd concentrations in soil samples and corn plants, along with the transfer factor values for these metals

Samples	Heavy metal content in soils samples [mg·kg <sup>-1</sup> d.m.]			Heavy metal content in plants [mg·kg <sup>-1</sup> ]			Transfer factor (TF) [mg·kg <sup>-1</sup> ]		
	Zn	Cu	Cd	Zn	Cu	Cd	Zn	Cu	Cd
PM	528,3	79.7	10.75	372.8	24.6	1.85	0.71	0.31	0.17
P1	552.7	81.5	12.37	461.4	34.0	2.56	0.83	0.42	0.21
P2	525.9	81.6	11.18	500.2	42.7	0.69	0.95	0.52	0.06
P3	546.4	82.2	12.53	526.3	45.9	0.76	0.96	0.56	0.06
P4	585.1	82.9	12.39	665.8	36.6	0.73	1.14	0.44	0.06
P5	580.1	83.2	12.5	592.8	20.6	0.44	1.02	0.25	0.04
Arithmetic mean	553.2	81.9	11.95	519.9	34.1	1.17	0.94	0.42	0.10
Standard deviation (SD)	±25.1	±1.25	±0.78	±102.1	±9.92	±0.84	±0.15	±0.12	±0.07

✓ **The cooper concentrations** in all samples approached or exceeded regulatory thresholds. According to Decree No. 756/1997 (updated in 2011), the alert threshold for sensitive soils is 100 mg·kg<sup>-1</sup> dry matter. The control soil sample, representing fertile untreated soil, showed a Cu concentration of 79.7 mg·kg<sup>-1</sup> - well above the normal background value of 20 mg·kg<sup>-1</sup> specified in Decree No. 184/1997. The highest Cu level

was detected in the sewage sludge sample ( $391 \text{ mg}\cdot\text{kg}^{-1}$ ), suggesting a significant anthropogenic source. The copper content in samples P1-P5 shows an increase of 1.8 - 3.5 points compared to the copper content in the control sample, PM. These elevated concentrations raise concerns regarding the long-term accumulation of Cu in soil systems, especially under repeated sludge applications.

✓ **Zinc concentrations** also revealed contamination trends. The Zn level in the sludge sample reached  $2080 \text{ mg}\cdot\text{kg}^{-1}$ , slightly exceeding the maximum allowable concentration ( $2000 \text{ mg}\cdot\text{kg}^{-1}$ ) stipulated in Decree No. 344/2004, which governs the agricultural use of sewage sludge. Interestingly, the Zn content in the soil-sludge mixtures did not correlate proportionally with the proportion of sludge, indicating possible soil buffering effects or non-uniform metal distribution.

Of particular concern is the fertile soil control sample, which displayed a Zn concentration of  $528.3 \text{ mg}\cdot\text{kg}^{-1}$ . This value exceeds both the maximum permitted concentration for sludge-treated soils ( $300 \text{ mg}\cdot\text{kg}^{-1}$ ) and the normal background level for Zn in soils ( $100 \text{ mg}\cdot\text{kg}^{-1}$ ). All composite samples (P1–P5) confirmed Zn levels above these thresholds, underscoring widespread contamination even before sludge amendment.

✓ **Cadmium** showed less consistent trends across the sample set. The highest average Cd concentration was recorded in the sludge sample, followed by sample P3, which had a high sludge content. However, Cd levels did not increase linearly with sludge proportion in the mixtures, suggesting that other factors (*e.g.*, pH, organic matter content) may influence its mobility and retention in soil. The control sample exhibited a Cd concentration of  $10.75 \text{ mg}\cdot\text{kg}^{-1}$ , significantly exceeding the threshold value of  $3 \text{ mg}\cdot\text{kg}^{-1}$  for sensitive agricultural soils [42]. This indicates potential prior exposure to contamination, possibly from historical agricultural or industrial activity.

➤ **The bioaccumulation of heavy metals - copper (Cu), zinc (Zn), and cadmium (Cd) in corn plants** (green mass and corn roots).

The study evaluated the bioaccumulation of heavy metals (Cu, Zn, and Cd) in corn plants (*Zea mays*) grown in soil amended with various quantities of sewage sludge. The results (based on the data in Table 2) reveal complex interactions between sludge dosage, metal mobility, and plant uptake.

✓ **Copper (Cu) bioaccumulation** - In sample P5, where the highest amount of sludge (100 g) was applied and corn germination reached 100 %, the lowest level of Cu bioaccumulation was recorded ( $20.6 \text{ mg}\cdot\text{kg}^{-1}$ ). In contrast, sample P3 - amended with 50 g of sludge - showed a slightly lower germination rate (93.33 %) but the highest concentration of mobile Cu absorbed by the plants ( $45.9 \text{ mg}\cdot\text{kg}^{-1}$ ). This inverse relationship between sludge dosage and Cu uptake suggests a potential dilution or immobilization effect at higher sludge concentrations, possibly due to organic matter binding or pH changes that reduce Cu mobility.

✓ **Zinc (Zn) bioaccumulation** - Zinc was consistently absorbed in significant quantities by all plant samples, often surpassing the acceptable limits for soils intended for sludge treatment. The highest Zn bioaccumulation was observed in sample P4 ( $665.8 \text{ mg}\cdot\text{kg}^{-1}$ ), indicating strong mobility and plant availability of this element in the tested substrate. A clear trend was observed in samples P1 to P3, where Zn uptake increased with the amount of applied sludge. These findings support the high phytoavailability of Zn in sludge-amended soils. It is important to note that Zn becomes phytotoxic at concentrations above  $400 \text{ mg}\cdot\text{kg}^{-1}$  in plant tissue, as it interferes with the

uptake of other essential nutrients and disrupts soil biological activity. Excess Zn can inhibit microbial function and reduce earthworm populations, ultimately slowing down the decomposition of organic matter - an essential process in maintaining soil fertility.

Biochar, phytoremediation, soil washing and amendment with gypsum and lime can play a great role in reducing the bioavailability of Pb and Zn in soils, protecting land and the environment [43, 44].

✓ **Cadmium (Cd) bioaccumulation** - Cadmium uptake showed a less predictable pattern. Sample P1, with the smallest sludge dose (10 g), exhibited the highest level of Cd bio absorption among all treatments, while sample P5, which received the highest sludge amount (100 g) and had the largest number of corn plants (15), displayed the lowest Cd accumulation. These results suggest that Cd mobility and plant assimilation are influenced not only by sludge quantity but also by other factors such as competition between plants, metal interactions, and soil physicochemical properties.

➤ **The transfer factor (TF)**, the data are presented in summary form in Table 2.

✓ The transfer factor for Zn is subunit for PM, P1, P2 and P3, but reaches above 1.00 for samples P4 (1.14) and P5 (1.02), where bioaccumulation of zinc occurs in corn plants.

✓ The transfer factor for Cu shows only subunit values ranging from a minimum of 0.25 in sample P5 to a maximum of 0.56 for sample P3.

✓ The transfer factor for Cd has only subunit values between 0.04 in sample P5 and 0.21 in sample P1.

✓ Copper exhibits a moderate Transfer Factor (TF) of 0.42, indicating controlled absorption. Zinc shows a relatively high TF (~0.94), suggesting increased mobility and a potential for bioaccumulation. Sample P4 displays a TF greater than 1, which is indicative of hyperaccumulation. Cadmium has the lowest TF (0.10), possibly reflecting physiological mechanisms that limit or block its uptake.

According to the results obtained, a trend of decreasing heavy metal transfer factor values from soil samples to corn plants is outlined in the following order: Zn > Cu > Cd.

The findings suggest a notable degree of pre-existing contamination in the fertile control soil, with heavy metals such as Cu, Zn, and Cd exceeding normal or threshold values. The application of sewage sludge further elevates the concentrations of these metals in most cases, posing risks to soil health, plant uptake, and ultimately, food safety. These results highlight the need for continuous monitoring and stricter regulation of sludge application, particularly on sensitive or already impacted soils.

According to Commission Regulation (EU) 2023/915 of 25 April 2023, which sets maximum levels for certain contaminants in food and repeals Regulation (EC) No 1881/2006, the maximum permissible cadmium content varies by product type: for grains other than wheat and rice, the limit is 0.1 mg·kg<sup>-1</sup>; for wheat, it is 0.2 mg·kg<sup>-1</sup>; for vegetables excluding leafy types, potatoes, and mushrooms, the limit is 0.05 mg·kg<sup>-1</sup>; for peeled potatoes, 0.10 mg·kg<sup>-1</sup>; and for leafy vegetables, fresh herbs, and celery, the maximum allowed concentration is 0.20 mg·kg<sup>-1</sup> [45, 46].

Most plant species extract cadmium and accumulate it in the roots, the content of which is 10 times larger than the strains [46], the transfer factor values of heavy metals from soil to vegetable decrease in the order of Cd > Zn > Cu > Pb > Hg [47, 48]. Under similar soil conditions, heavy metal uptake differs among plant species, generally decreasing from leaf vegetables to fruit vegetables, root vegetables, and grains [49].

Cadmium (Cd) is a widespread environmental contaminant affecting vital organs such as the kidneys, liver, and bones. Some studies suggest a link between Cd exposure and periodontal disease [50, 51]. Overall, the presence of heavy metals in the food chain poses risks to multiple organs, highlighting the need for careful monitoring in agricultural and environmental systems [52].

## CONCLUSIONS

The elevated concentrations of cadmium ( $10.75 \text{ mg}\cdot\text{kg}^{-1}$ ), zinc ( $528.3 \text{ mg}\cdot\text{kg}^{-1}$ ), and copper ( $79.7 \text{ mg}\cdot\text{kg}^{-1}$ ) in the control sample-collected from fertile soil without sludge addition - confirm the existence of residual historical pollution. This contamination is most likely linked to the Cavnice River, which has been significantly impacted by industrial mining activity and effluents from nearby tailings ponds Plopiș-Răchițele.

The data obtained in this study indicate that the bio absorption of heavy metals by corn plants cultivated on historically contaminated agricultural land - amended with varying proportions of sewage sludge - is atypical and does not exhibit a linear increase in relation to the amount of sludge applied. This irregular pattern suggests complex interactions between soil properties, pollutant mobility and plant uptake mechanisms.

A correlation was observed between the concentrations of Cu, Zn, and Cd in the plants and those in the soil, although plant-specific uptake capacities also played a key role.

Corn plants have exhibited a significant ability to absorb and accumulate heavy metals (Zn, Cd, Cu), highlighting the necessity for risk assessment associated with food consumption. This also underscores the need to reconsider regional agricultural management strategies.

Based on these findings, the following recommendations are proposed:

- Due to the high bioavailability of cadmium and zinc in the soil and the substantial accumulation of heavy metals in corn roots and stems, using this land for cultivating crops intended for human or animal consumption is a risk.
- Given the elevated heavy metal concentrations found in the sewage sludge sample, it should not be used as fertilizer unless it undergoes pre-treatment processes to significantly reduce its heavy metal content.

Through localized information and education programs, the local population should be adequately informed about the potential health and environmental risks associated with the use of river sediments from the Cavnice River for soil fertilization, as well as the use of river water for crop irrigation. Enhancing community awareness is essential for promoting safe agricultural practices and mitigating long-term exposure to potentially harmful contaminants.

- To address the historical contamination of the site, we recommend initiating a phytoremediation program using rotational crops known for their metal extraction capacity, such as sunflower (*Helianthus annuus*) for general phytoextraction, white campion (*Thlaspi caerulescens*) - a hyperaccumulator of Cd, Cr, Ni, Pb, Co, and Cu - and highland bentgrass (*Agrostis castellana*) for As, Pb, Mn, Al, and Zn.
- To limit the risk of metal transfer through the food chain, it is advisable to reconsider the land use designation in the area. Local urban planning regulations should be revised to convert this agricultural land into alternative uses such as

residential, industrial, civic, or green spaces, which pose lower exposure risks to environmental contaminants.

#### *Study limitations*

The study could be extended to a broader area within the proposed region, in this area has not previously been investigated in terms of its potential agricultural contamination. Expanding the range of analyzed heavy metals would undoubtedly provide more detailed information on the types and concentrations of metals present, their bioavailability and uptake by plants, as well as the spatial distribution of contamination across the landscape. Based on these site-specific findings, the implementation of a sustainable strategic management approach could enable rural areas to benefit from targeted public and governmental policies. Such policies should aim to restore the balance of agricultural soils and the surrounding environment by accelerating rehabilitation programs for abandoned legacy mining sites.

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