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MOBILITY AND TOXICOLOGICAL RELEVANCE IN THE EVALUATION OF HEAVY METAL TRANSFER FROM SOIL TO PLANTS

Claudiu-Denis FILIP[1], Mirela Ana COMAN[1, 2]

[1]University of Agricultural Sciences and Veterinary Medicine of Cluj-Napoca,
3-5 Calea Mănăștur, Cluj-Napoca, Romania
[2]Technical University of Cluj-Napoca, 62A V. Babeș Street, Baia Mare, Romania

Corresponding author email: claudiu.filip98@gmail.com

Abstract

The classic transfer factor formula, widely used in studies dedicated to heavy metal mobility in the soil-plant system, represents a direct ratio between the metal concentration in the plant and that in the soil. Although valuable for general comparisons and for describing their behaviour in the environment, this formula does not allow for an adequate separation between the actual forms of mobility, the toxicological characteristics of each metal, and strict reporting to the limits regulated by the Codex Alimentarius. In this context, the paper proposes the Assimilated Mobility Transfer Factor (AMTF), an extended, integrative formula that includes the toxicity coefficient, the mobile fraction in the soil, the actual level of accumulation in fruit, and the food regulations in force. Applying the AMTF to data sets from historically polluted areas, such as the Baia Mare Mining Basin, highlights consistent differences between the mobility of heavy metals and their actual accumulation in fruit, discrepancies that the classic ratio cannot capture. The new formula proposed for the AMTF provides an adequate, modern tool for current food safety and ecotoxicological risk studies.

Key words*: food safety, heavy metals, mobile fraction, soil-plant transfer, toxicity coefficient.*

INTRODUCTION

Heavy metals represent a group of elements exhibiting relatively high density and marked toxicity even at low concentrations, including lead (Pb), cadmium (Cd), mercury (Hg), chromium (Cr), and other substances widely recognized as major environmental pollutants. Their presence in natural ecosystems is closely linked to anthropogenic activities, particularly mining and metallurgical operations, industrial discharges, urban waste disposal, and certain agricultural practices such as the application of fertilizers, pesticides, or sewage sludge (Singh et al., 2011; Boros et al., 2015; Roba et al., 2016; Sur et al., 2017; Rusu et al., 2023).

A defining feature of heavy metals is their persistence in the environment, as they are not subject to biological or chemical degradation processes. This stability promotes their accumulation in soils and sediments and facilitates transfer to living organisms, enabling their movement along trophic chains. Their non-biodegradable character, combined with their potential for bioaccumulation and mobility governed by physicochemical conditions, confers major relevance from the perspective of ecosystem protection and human health, underscoring the need for integrated assessments that simultaneously capture their behavior in soil-plant systems and their toxicological implications (Bizo et al., 2014; Minkina et al., 2017; Moț et al., 2019; Moț et al., 2021; Sabir et al., 2022; Filip & Coman, 2025).

The toxicity of heavy metals to human health is extensively documented in scientific literature and is associated with complex molecular mechanisms involving direct interactions with proteins and nucleic acids, induction of oxidative stress, and disruption of cellular homeostasis. Through these processes, they can impair the normal functioning of biological systems, while the severity of toxic effects depends on the nature of the element, the level and duration of exposure, and individual susceptibility (Jaishankar et al., 2014; Mitra et al., 2022; Kotnala et al., 2025; Jomova et al., 2025). Among these elements, lead (Pb) is recognized for its neurotoxic potential, with chronic exposure being linked to cognitive deficits and developmental disorders in children, as well as elevated blood pressure and impaired renal function in adults. Moreover, long-term accumulation of Pb may result in

anemia, reproductive dysfunctions, and other severe systemic manifestations (Oros et al., 2011; Balali-Mood et al., 2021; Ortega et al., 2021). Cadmium (Cd), characterized by high toxicity even at low concentrations, is predominantly associated with renal impairment and bone demineralization processes that may progress to severe conditions such as Itai-itai disease. In addition, Cd is classified as a human carcinogen and has been implicated in the development of lung and prostate cancers, further emphasizing the importance of assessing its mobility in soil-plant systems (Waalkes, 2003; Davidova et al., 2024; Sasaki et al., 2024.)
The aim of this study was to establish the current level of Pb and Cd contamination in soil and fruit within soil-plant system, as well as to evaluate the potential of the AMTF ecotoxicological indicator for the mathematical modeling of the transfer factor.

MATERIALS AND METHODS

This study employed an experimental design structured to provide an integrated evaluation of Pb and Cd behavior within the soil–plant–fruit system by investigating contamination levels, bioaccumulation processes, and transfer dynamics in an area known for historical pollution associated with mining and metallurgical activities. The experimental framework consisted of three major analytical components:

a) Regarding heavy metal content in soil;
b) Regarding heavy metal content in fruits;
c) Regarding the transfer factor.

The mathematical modeling of heavy metal pollutant transfer was performed using the AMTF ecotoxicological indicator, which integrates the total and mobile forms of metals in soil, the concentration identified in fruit, and the relation to the maximum permissible limit, allowing classification into transfer classes and the integrated characterization of Pb and Cd heavy metal pollutant behavior within the soil–plant system.
The area of interest covers approximately 588.8 km^2 within the Baia Mare Depression and was evaluated in comparison with a less impacted reference area of about 111 km^2 located in the Maramureș Depression, namely the Sighetu Marmației. Within these perimeters, soil samples were collected at several sampling depths in accordance with Order No. 184/1997, while plum samples were obtained following the provisions of Order No. 1048/2003.
The Baia Mare Depression (Figure 1) represents a geomorphological contact zone between the Someșan Plateau and the Eastern Carpathians, developed along the southern flank of the Gutâi-Țibleș Neogene mountain units.

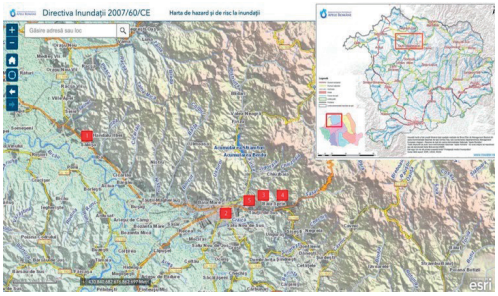


Figure 1. Sampling points

From an altimetric perspective, the base level of the depression ranges between 150-350 m, whereas morphologically it exhibits a basin-shaped configuration. The relief is heterogeneous, and the present study focuses on the Seini-Baia Mare-Baia Sprie piedmont glacis and contact piedmont sectors, extending toward the southern foothills of the Igniș-Gutâi Mountains, which constitute the main investigated zone, while the Sighetu Marmației sector served as the reference area (Coman, 2006; Coman et al., 2010; Ștefan et al., 2012; Marian et al., 2016; Manoiu & Spiridon, 2017).

Working Method

a) Regarding heavy metal content in soil
Soil sampling was conducted in accordance with the existing methodological regulations and standards stipulated in Order No. 184/1997. Samples were collected from the Baia Mare Depression, specifically from the piedmont glacis and contact piedmont sectors, as well as from the Sighetu Marmației sector located in the Maramureș Depression, which served as the reference area. For each sampling point, the soil profile was opened, and samples were obtained from four different depths, namely 5, 30, 50, and

100 cm, to capture the vertical distribution of the investigated elements.
Following field collection, physicochemical analyses were carried out in an accredited laboratory, namely INCDO ICIA Cluj-Napoca, in accordance with the following international standards: SR ISO 11464:1994, SR ISO 11047:1999-PIS-03, and SR EN ISO 1185:2009. The analytical results were subsequently evaluated in relation to the regulatory thresholds in force at the national level (Order No. 756/1997), at the European level (European Council Directive 86/278/EEC 1986), and at international level (US EPA, 2002 after He et al., 2015).

b) Regarding heavy metal content in fruit
The sampling plan overlaps perfectly with that of the soils, including for the control sample.
Fruit samples (plums) were collected annually from privately owned orchards in August 2023, 2024, and 2025. The Pb and Cd content in the fruit was determined. The results were interpreted in accordance with the legislation in force, namely Order 975/1998 at national level, EU Directive 2023/915 at European Union level, and Codex Alimentarius, 1995 at international level.

c) Regarding the transfer factor
The transfer factor (TF), also known in the literature as the bioaccumulation factor (BAF), biological accumulation factor (BCF), or bioconcentration factor (BCFT), represents the ratio between the content in plants and the content in soil. This factor has been studied nationally and internationally (Olănescu, 2007; Ivasuc & Rusu, 2011; Big et al., 2012; Jolly et al., 2013; Aladesanmi et al., 2019; Jakubus et al., 2019; Nițu et al., 2019; Pehoiu et al., 2020; Noman et al., 2022; Pruteanu et al., 2022; Tong et al., 2022).
The calculation assumes that the transfer of heavy metal pollutants into the soil-plant system is not determined exclusively by the total form, but by the interaction between the mobile fraction, the level of accumulation in the fruit, and the maximum permissible limit.

$$AMTF = (C_{mobile}/C_{mobile}+1) \times \log(C_{total} + 1) \times (C_{fruit}/Standard) \times \delta$$

where:
δ = metal-specific toxicity coefficient ($\delta_{Cd} = 1$, $\delta_{Pb} = 2$);
C_{mobile} = mobile concentration of the metal in the soil (mg/kg);
C_{total} = total concentration of the metal in the soil (mg/kg);
C_{fruit} = concentration of the metal in the fruit (mg/kg);
Standard = maximum permitted limit in fruit (mg/kg wet substance).

In this calculation formula, the coefficient δ was introduced as a toxicological weighting factor to reflect the differences in hazard associated with the metals analyzed. δ was established based on the IARC classification of carcinogenicity:

- ⇒ Cd and its compounds are classified in Group 1,
- ⇒ Pb compounds in Group 2A (EFSA, 2010).

Thus, discrete weights corresponding to these groups were used ($\delta Cd = 1$, $\delta Pb = 2$).

To interpret the AMTF indicator values (Table 1), a transfer class classification system was used, established based on the distribution of the values obtained, the reporting of the accepted normative limits, and a non-linear progression inspired by the Fibonacci sequence (Φ=1.6818).

The application of the logarithmic function attenuates the influence of very high total concentrations and improves the stability of the indicator. Thus, very large differences in the total fraction do not monopolize the result.

Table 1. AMTF ranges

No. crt.	AMTF values range	Interpretation	Chromatic scale of transfer
1	<0.1	Very low transfer	
2	0.10-0.21	Low transfer	
3	0.21-0.55	Medium transfer	
4	0.55-0.89	High transfer	
5	0.89-1.44	Very high transfer	
6	≥1.44	Extreme transfer	

RESULTS AND DISCUSSIONS

a) Soil sampling

The results for total and mobile Pb content are presented in Table 2.

Table 2. Pb content in soil

No. crt.	Sampling point	Depth (cm)	Pb content (mg/kg)	
			Total	Mobile
1.	Săbișa	5	35.0	0.10
		30	42.7	<0.02
		50	22.9	<0.02
		100	21.0	0.09
2.	Baia Mare	5	27.0	<0.02
		30	**385.0**	<0.02
		50	**238.0**	<0.02
		100	**480.0**	<0.02
3.	Baia Sprie I	5	**211.0**	0.68
		30	**88.3**	0.34
		50	35.0	0.28
		100	32.8	<0.10
4.	Baia Sprie II	5	**261.0**	0.60
		30	41.7	<0.10
		50	33.3	<0.10
		100	29.1	<0.10
5.	Tăuții de Sus	5	**890.0**	0.087
		30	**141.0**	1.20
		50	35.3	0.16
		100	37.7	0.17
6.	Sighetu Marmației (the control)	5	40.7	<0.02
		30	28.8	<0.02
		50	31.6	<0.02
		100	27.7	<0.02
7.	MAL RO[a]	-	50	-
8.	MAL EU[b]	-	50-300	-
9	MAL INT[c]	-	200	-

MAL-maximum allowed limit, RO-Romania, EU-Europe INT-International, a - Order No. 756/1997, b - Council Directive 86/278/CEE 1986; c - US EPA, 2002 after He et al., 2015.

Sampling points - Pb

In Săbișa, the Pb content in total form is below the maximum permissible limit at all depths analyzed. The maximum value determined, 42.7 mg/kg at a depth of 30 cm, is 15% lower than the maximum permissible limit, with no exceedances of the legal threshold recorded. The Pb content in mobile form is below 0.10 mg/kg, with no legislative reference framework.

In Baia Mare, Pb content in total form is below the maximum permissible limit in the surface horizon, but in the intermediate and deep horizons there are significant exceedances of this limit. At 30 cm, the concentration of 385 mg/kg exceeds the maximum permissible limit by 7.7 times, at 50 cm by 4.76 times, and at 100 cm it reaches a maximum of 9.6 times, highlighting a marked accumulation and historical migration of Pb in the soil profile, specific to areas affected by mining and metallurgical activities. The content of Pb in mobile form remains below 0.02 mg/kg throughout the analyzed profile, with no legislative reference framework.

At Baia Sprie I, the total Pb content exceeds the maximum permissible limit in the surface horizon, where the value of 211 mg/kg represents an exceedance of 4.22 times, as well as in the intermediate horizon, with an exceedance of 1.77 times, while in the deep horizon the concentrations determined are below the maximum permissible limit. The Pb content in mobile decreases with depth.

At Baia Sprie II, the total Pb content exceeds the maximum permissible limit in the surface horizon, where the value of 261 mg/kg represents an exceedance of 5.22 times, while in the intermediate horizon and in the depth horizon the concentrations determined are below the maximum permissible limit. The Pb content in mobile form recording maximum values in the surface horizon and a progressive decrease towards the deep horizon.

In Tăuții de Sus, the total Pb content records the highest values in the analyzed reference area, with a concentration of 890 mg/kg in the surface horizon, corresponding to a 17.8-fold exceedance of the maximum permissible limit, with exceedances also occurring in the intermediate horizon, where the value of 141 mg/kg represents a 2.82-fold exceedance. In the deep horizon, the concentrations determined are below the maximum permissible limit. The Pb content in mobile form varies between 0.087 and 1.20 mg/kg on the analyzed profile, with maximum values in the intermediate horizon and a decrease towards the deep horizon. These values cannot be evaluated comparatively from a regulatory point of view, as there is no legislative framework in force for the mobile form.

In Sighetu Marmației (the control), the total Pb content is below the maximum permissible limit in all horizons analyzed. The Pb content in the mobile form is below 0.02 mg/kg across the entire soil profile.

Therefore, the control site can be considered uncontaminated, confirming the absence of Pb contamination and validating the use of this point as a reference area for the comparative interpretation of the results obtained in areas affected by anthropogenic activities.

Sampling points -Cd

The results for total and mobile Cd content are presented in Table 3.

Table 3. Cd content in soil

No. crt.	Sampling point	Depth (cm)	Cd content (mg/kg)	
			Total	Mobile
1.	Săbișa	5	<0.33	<0.02
		30	<0.33	<0.02
		50	<0.33	<0.02
		100	<0.33	<0.02
2.	Baia Mare	5	1.73	<0.02
		30	**3.47**	0.03
		50	0.83	<0.02
		100	**4.0**	<0.02
3.	Baia Sprie I	5	2.50	<0.05
		30	1.60	<0.05
		50	1.20	<0.05
		100	1.17	<0.05
4.	Baia Sprie II	5	2.57	<0.05
		30	1.27	<0.05
		50	1.40	<0.05
		100	1.23	<0.05
5.	Tăuții de Sus	5	**8.80**	<0.05
		30	1.67	<0.05
		50	1.43	<0.05
		100	1.33	<0.05
6.	Sighetu Marmației (the control)	5	<0.33	<0.02
		30	<0.33	<0.02
		50	<0.33	<0.02
		100	<0.33	<0.02
7.	MAL RO[a]	-	3	-
8.	MAL EU[b]	-	1-3	-
9.	MAL INT[c]	-	0.48	-

MAL-maximum allowed limit, RO-Romania, EU-Europe INT-International, a - Order No. 756/1997, b - Council Directive 86/278/CEE 1986; c- US EPA, 2002 after He et al., 2015.

In Săbișa, the total Cd content is below the maximum permissible limit in all analyzed horizons, with the determined values being below the maximum permissible limit. These results indicate the absence of Cd contamination. The Cd content in mobile form is below 0.02 mg/kg across the entire soil profile, and these values cannot be evaluated comparatively from a regulatory point of view, as there is no legislative framework in force for mobile form.

In Baia Mare, the Cd content in total form is below the maximum permissible limit in the surface horizon, but in the intermediate and deep horizons, it exceeds this limit. At 30 cm, the value of 3.47 mg/kg exceeds the maximum permissible limit by 1.16 times, and in the deep horizon, the concentration of 4.00 mg/kg corresponds to an exceedance of 1.33 times, highlighting persistent contamination associated with historical pollution, while at 50 cm, the concentration of 0.83 mg/kg remains below the maximum permissible limit. The Cd content in mobile form shows low values across the entire analyzed profile and cannot be evaluated comparatively from a regulatory point of view, as there is no legislative framework in force for mobile form.

At Baia Sprie I, the total Cd content remains below the maximum permissible limit in all analyzed horizons. The maximum value is recorded in the surface horizon, being 17% lower than the maximum permissible limit. Concentrations decrease progressively in the intermediate horizon and in the deep horizon. The Cd content in mobile form shows values below 0.05 mg/kg across the entire soil profile and cannot be evaluated comparatively from a regulatory point of view, as there is no legislative framework of reference for the mobile form.

At Baia Sprie II, the total Cd content is below the maximum permissible limit in all analyzed horizons. The maximum value, recorded in the surface horizon (2.57 mg/kg), is 14% lower than the maximum permissible limit. The concentrations determined in the intermediate horizon and in the depth, horizon show low variations. The Cd content in mobile form is below 0.05 mg/kg across the entire analyzed profile and cannot be evaluated comparatively from a regulatory point of view, as there is no legislative framework in force for mobile form.

In Tăuții de Sus, Cd content in total form shows the highest values in the reference area analyzed. In the surface horizon, the concentration of 8.80 mg/kg exceeds the maximum permissible limit by 2.93 times, while in the intermediate horizon and in the deep horizon, the values determined are below the maximum permissible limit. The Cd content in mobile form remains below 0.05 mg/kg throughout the soil profile, and these values cannot be evaluated comparatively from a regulatory point of view, as there is no legislative framework in force for mobile forms.

In Sighetu Marmației (the control), the total Cd content is below the maximum permissible limit in all horizons analyzed, indicating the absence

of Cd contamination. The Cd content in the mobile form is below 0.02 mg/kg across the entire soil profile, and these values cannot be evaluated comparatively from a regulatory point of view, as there is no legislative framework in force for the mobile form.

b) Fruit samples

The results on the total form of the chemical element Pb in fruits (mg/kg) for 2023, 2024 and 2025 are represented in Table 4.

Table 4. Pb content in fruits

No. crt	Sampling point	Pb content in 2023	Pb content in 2024	Pb content in 2025
1	Săbișa	<0.04	**<0.15**	<0.10
2	Baia Mare	<0.04	**<0.15**	<0.10
3	Baia Sprie I	<0.04	**<0.15**	<0.10
4	Baia Sprie II	<0.04	**<0.15**	<0.10
5	Tăuții de Sus	<0.04	**<0.15**	<0.10
6	Sighetu Marmației (the control)	<0.04	**<0.15**	<0.10
7	MAL RO[a]	0.50		
8	MAL EU[b]	0.10		
9	MAL INT[c]	0.10		

MAL-maximum allowed limit, RO-Romania, EU-Europe INT-International, a - Order no. 975/1998; b - Commission Regulation (EU) 2023/915; c - Codex Alimentarius, 1995.

Figure 2 shows, for 2023, the concentrations of Pb in fruit determined at all sampling points were very low and fell entirely within the maximum limits permitted at national, European, and international level. These results indicate an insignificant accumulation of Pb in fruit in the reference area analyzed.

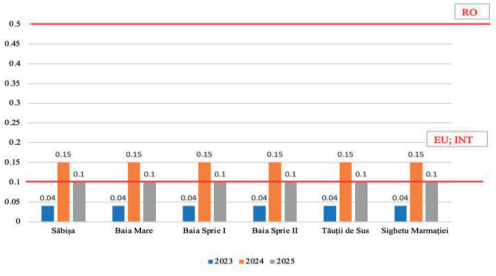


Figure 2. Pb content in fruits

For 2024, Pb concentrations in fruit, determined at all sampling points, showed a sharp increase compared to the previous year, of approximately 275%. The values obtained exceeded the maximum limits allowed at European level but remained below the maximum limits allowed at national level and within the range allowed at international level, as established by the Codex Alimentarius. This development indicates a temporary increase in Pb accumulation in fruit in the reference area analyzed, without generating non-compliance with the national regulatory framework.

For 2025, Pb concentrations in fruit determined at all sampling points decreased by 33.3% compared to the previous year. The values obtained were at the maximum levels allowed at European level and within the maximum levels allowed at national and international level. The trend indicates a partial reduction in Pb accumulation in fruit, following the sharp increase observed for 2024.

In summary, Pb concentrations in fruit were within the maximum limits permitted at national level and within the ranges established by Codex Alimentarius, although a slight exceedance of the European threshold was found for 2024. This behaviour reflects interannual variations in the level of accumulation, without leading to non-compliance with national and international regulatory frameworks.

The results on the total form of the chemical element Cd in fruits (mg/kg) for the year 2023, 2024 and 2025 are represented in Table 5.

Table 5. Cd content in fruits

No. crt	Sampling point	Cd content in 2023	Cd content in 2024	Cd content in 2025
1	Săbișa	<0.04	**<0.15**	<0.10
2	Baia Mare	<0.04	**<0.15**	<0.10
3	Baia Sprie I	<0.04	**<0.15**	<0.10
4	Baia Sprie II	<0.04	**<0.15**	<0.10
5	Tăuții de Sus	<0.04	**<0.15**	<0.10
6	Sighetu Marmației (the control)	<0.04	**<0.15**	<0.10
7	MAL RO[a]	0.05		
8	MAL EU[b]	0.05		
9	MAL INT[c]	0.05		

MAL-maximum allowed limit, RO-Romania, EU-Europe INT-International, a - Order no. 975/1998; b - Commission Regulation (EU) 2023/915; c - Codex Alimentarius, 1995.

Figure 3 shows, for 2023, the values determined for all sampling points (0.04 mg/kg wet weight) indicate levels below the maximum permissible limit set at national, European, and Codex Alimentarius levels, reflecting a low accumulation of Cd in fruit in the reference area analyzed.

For 2024, Cd concentrations in fruit exceed the maximum permissible limit by approximately 60%, suggesting a temporary intensification of Cd transfer from soil to fruit.

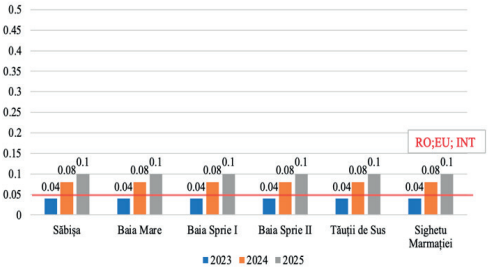


Figure 3. Cd content in fruits

For 2025, the values recorded are significantly higher than the maximum permissible limit set at national, European, and Codex Alimentarius levels, being twice the maximum permissible limit.

The pronounced rainfall deficit characteristic of 2025 can be correlated with the increase in the mobile fraction of Cd and the intensification of root absorption, mechanisms that support, from a pedological and physiological point of view, the high values determined in fruits.

Interpretation of the results in relation to the legislative framework highlights important differences between lead and cadmium in terms of regulatory requirements. In the case of Pb, the maximum limit allowed by national legislation (0.50 mg/kg) is significantly more permissive than the threshold set by Regulation (EU) 2023/915 and Codex Alimentarius (0.10 mg/kg). This fivefold difference between standards reflects a less restrictive regulatory approach at national level, which may lead to situations where the values determined are compliant internally but may generate non-compliance with European requirements. From this perspective, the interpretation of compliance depends directly on the legislative reference level used.

In contrast, for Cd, the maximum permissible limit is uniformly set at 0.05 mg/kg at all legislative levels analyzed. The harmonization of thresholds indicates international recognition of the high toxic potential of this element and a uniform regulatory approach that is more restrictive than that applicable to Pb. Consequently, any exceedance of the threshold for Cd automatically leads to simultaneous non-compliance at national, European, and international levels.

Thus, from a legislative point of view, Cd presents a higher regulatory risk, as the threshold is lower and does not allow for differences in interpretation between regulatory levels, while for Pb there is a wider margin of tolerance within the national framework. This aspect must be considered in the food risk assessment and in the formulation of conclusions on the safety of the product analyzed.

c) *Transfer factor*

Table 6 shows the results for the assimilated mobility transfer factor (AMTF) for the pollutant -Pb.

Table 6. AMTF-Pb

No. crt.	Sampling point	Depth (*cm*)	AMTF 2023	AMTF 2024	AMTF 2025
1.	Săbișa	5	0.023	0.085	0.057
		30	0.005	0.019	0.013
		50	0.004	0.016	0.011
		100	0.018	0.067	0.044
2.	Baia Mare	5	0.005	0.017	0.011
		30	0.008	0.030	0.020
		50	0.007	0.028	0.019
		100	0.008	0.032	0.021
3.	Baia Sprie I	5	**0.151**	**0.565**	**0.377**
		30	0.079	0.297	**0.198**
		50	0.054	0.204	**0.136**
		100	0.022	0.083	0.056
4.	Baia Sprie II	5	**0.145**	**0.544**	**0.363**
		30	0.024	0.089	0.059
		50	0.022	0.084	0.056
		100	0.022	0.081	0.054
5.	Tăuții de Sus	5	0.038	**0.142**	0.094
		30	**0.188**	**0.704**	**0.470**
		50	0.034	**0.129**	0.086
		100	0.037	**0.138**	0.092
6.	Sighetu Marmației (the control)	5	0.005	0.019	0.013
		30	0.005	0.017	0.012
		50	0.005	0.018	0.012
		100	0.005	0.017	0.011

The analysis of AMTF-Pb values for the period 2023-2025 shows a clear spatial and vertical differentiation of transfer intensity in the soil-plant-fruit system. Overall, the indicator falls predominantly into the very low transfer (AMTF < 0.10) and low transfer (0.10-0.21) classes, with occasional occurrences in the medium transfer (0.21-0.55) and high transfer (0.55-0.89) classes, without reaching the higher

classes of very high transfer (0.89-1.44) or extreme transfer (≥1.44).

At the surface horizon level, AMTF values reflect the direct influence of historical contamination and the mobile surface fraction, but the distribution is relatively heterogeneous, with variations controlled mainly by the local specifics of contamination. In contrast, the analysis becomes more relevant from a procedural point of view at depths of 30 and 50 cm, where the vertical dynamics of transfer are more clearly outlined.

At 30 cm, the most pronounced variability of the indicator is observed. For Săbișa, Baia Mare, and Sighetu Marmației, the values remain constant in the very low or low transfer class, suggesting effective control of mobility and reduced availability for plant uptake, even in the presence of high total concentrations in certain profiles. In contrast, at the Baia Sprie I and Tăuții de Sus sites, 2024 marks a clear intensification of mobilization processes, with values falling within the high transfer class (0.55-0.89). The maximum value of the entire data set, recorded at 30 cm at Tăuții de Sus (AMTF=0.704), confirms that this horizon represents the level at which the interaction between the mobile fraction, total concentration, and accumulation in fruit becomes maximum. The return to the medium transfer class (0.21-0.55) in 2025 indicates a transitional nature of the intensification in 2024.

At 50 cm, AMTF values are systematically lower than those at 30 cm, falling mainly into the very low and low transfer classes, with limited occurrences in the medium transfer class in 2024. This decrease suggests a progressive reduction in effective mobility with depth, associated with the processes of adsorption and stabilization of Pb in the soil matrix. The absence of values in the higher classes at this depth confirms that, although historical contamination is present in the profile, the actual availability to the active root system decreases with depth.

The depth horizon (100 cm), generally shows low AMTF values, falling within the lower transfer classes, which indicates a limited contribution of this level to the accumulation process in the fruit.

From a temporal perspective, the year 2024 is distinguished by systematically higher AMTF values at 30 cm and, to a lesser extent, at 50 cm, suggesting a temporary intensification of Pb mobilization and availability processes in the intermediate zone of the profile. In 2025, a reduction in transfer intensity is observed, without however changing the overall vertical pattern.

Table 7 shows the results for the assimilated mobility transfer factor (AMTF) for the pollutant -Cd.

Table 7. AMTF-Cd

No. crt.	Sampling point	Depth (cm)	AMTF 2023	AMTF 2024	AMTF 2025
1.	Săbișa	5	0.002	0.004	0.005
		30	0.002	0.004	0.005
		50	0.002	0.004	0.005
		100	0.002	0.004	0.005
2.	Baia Mare	5	0.007	0.014	0.017
		30	0.015	0.030	0.038
		50	0.004	0.008	0.01
		100	0.011	0.022	0.027
3.	Baia Sprie I	5	0.021	0.041	0.052
		30	0.016	0.032	0.04
		50	0.013	0.026	0.033
		100	0.013	0.026	0.032
4.	Baia Sprie II	5	0.021	0.042	0.053
		30	0.014	0.027	0.034
		50	0.014	0.029	0.036
		100	0.013	0.027	0.033
5.	Tăuții de Sus	5	0.038	0.076	**0.094**
		30	0.016	0.032	0.041
		50	0.015	0.029	0.037
		100	0.014	0.028	0.035
6.	Sighetu Marmației (the control)	5	0.002	0.004	0.005
		30	0.002	0.004	0.005
		50	0.002	0.004	0.005
		100	0.002	0.004	0.005

The analysis of AMTF-Cd values for the period 2023-2025 shows a distribution that is clearly different from that of Pb, characterized by low values and moderate vertical variability. Across the entire dataset, the indicator falls exclusively into the very low transfer class (AMTF < 0.10), without reaching the higher classes (low, medium, high, very high, or extreme). The range of variation, between 0.002 and 0.094, confirms a limited overall transfer of Cd in the soil–plant–fruit system, from the integrative perspective of the AMTF indicator.

At the surface horizon, the values are higher than those at depth, especially at the Tăuții de Sus site, where the maximum value of the set

(AMTF=0.094) is reached in 2025, but still within the very low transfer class. This distribution reflects the direct influence of the mobile surface fraction and accumulation in the fruit, but without exceeding the threshold of 0.10 that would mark the transition to the low transfer class.

At 30 cm, the AMTF-Cd values show relative uniformity between points, ranging between 0.002 and 0.041. In Baia Mare, Baia Sprie I, Baia Sprie II, and Tăuții de Sus, the year 2025 shows slightly higher values compared to 2023 and 2024, but all remain in the very low transfer class. This stability indicates that, although Cd exceeded the legislative threshold in fruit in 2024 and 2025, the integration of the mobile fraction and total concentration through AMTF mitigates the numerical impact, suggesting that the actual intensity of transfer on the intermediate profile remains low.

At 50 cm, the values are comparable or slightly lower than those at 30 cm, confirming a discrete vertical gradient of transfer. The range of 0.002–0.037 indicates limited effective mobility at this depth, with no major differences between the years analyzed. The fact that the values do not increase significantly in 2024 and 2025 at 50 cm suggests that the intensified mobilization processes in these years were concentrated predominantly in the upper root zone, without a marked propagation in depth.

At the depth horizon, the indicator maintains values like those at 50 cm or slightly lower, confirming a minimal contribution of the deep horizon to the accumulation process in the fruit.

From a temporal perspective, there is a progressive increase in AMTF-Cd values from 2023 to 2025 at most points, but this increase does not change the transfer class. Thus, although the legislative analysis indicated exceedances of the 0.05 mg/kg threshold in fruit in 2024 and 2025, the AMTF-based classification keeps Cd in the very low transfer category, highlighting the difference between the specific regulatory non-compliance and the integrated intensity of the transfer process in the soil profile.

In a comparative approach, the analysis of AMTF-Pb and AMTF-Cd values highlights consistent differences between the two elements in terms of the intensity and significance of transfer in the soil–plant–fruit system. For Pb, spatial and vertical variability is more pronounced, with occasional occurrences in the high transfer class (0.55-0.89), especially at a depth of 30 cm in 2024, in areas with significant historical contamination. This behavior indicates local episodes of intensified mobilization, without reaching the very high or extreme transfer classes, suggesting the existence of effective soil immobilization mechanisms that limit the actual transfer to the fruit.

A different pattern is observed for Cd, AMTF values remain consistently in the very low transfer class (AMTF < 0.10), with a uniform distribution across the profile and moderate interannual variations. Although fruit concentrations exceeded the legislative threshold in 2024 and 2025, the integrative indicator did not show a structural intensification of transfer, indicating a dissociation between normative pressure and the procedural intensity of mobilization in the soil.

Thus, comparatively, Pb reflects a more pronounced edaphic pressure and greater variability in transfer, while Cd exhibits high process stability but increased normative vulnerability, determined by the low legislative threshold. This differentiation confirms the ability of the AMTF indicator to integrate mobility, accumulation in fruit, and normative reference into a coherent assessment of the intensity of metal transfer in the investigated fruit tree ecosystems.

CONCLUSIONS

Heavy metal content in soil. The results obtained highlight the persistence of historical contamination with Pb and, to a lesser extent, with Cd in the soils of the investigated area. For Pb, exceedances of the maximum permissible limit were frequent and distributed over several depths (30–100 cm in Baia Mare; 5–30 cm in Tăuții de Sus), confirming both surface accumulation and migration in the profile. In the case of Cd, exceedances were less numerous and more localized (Baia Mare and Tăuții de Sus), indicating lower edaphic pressure compared to Pb.

Heavy metal content in fruits. For Pb, the significant difference between the national threshold and the European/international threshold generates discrepancies in the

interpretation of compliance. Although the European threshold was exceeded in 2024, the values remained below the national limit, and a partial reduction was observed in 2025. For Cd, the uniform and more restrictive limit led to direct non-compliance in 2024 and 2025, highlighting a higher regulatory vulnerability compared to Pb.

Transfer factor. Analysis of transfer using the AMTF indicator shows that, despite exceedances in soil and isolated non-compliances in fruit, the integrated transfer intensity remains predominantly in the lower classes for both elements. For Pb, isolated occurrences of the high transfer class at 30 cm indicate temporary episodes of mobilization, without reaching the higher classes. For Cd, AMTF values remain constant in the very low transfer class, suggesting that legislative exceedances are more a consequence of the restrictive regulatory threshold than of a structural amplification of mobility in the profile.

From a food safety perspective, the results indicate that the risk is not determined exclusively by the total concentration in the soil, but by the interaction between mobility, pedoclimatic conditions, and the severity of the legislative threshold. In areas with historical anthropogenic impact, even moderate variations in the mobile fraction can lead to exceedances of the permissible limits, especially for Cd.

Therefore, it is necessary to implement a periodic monitoring system that integrates the analysis of the mobile fraction and the assessment of transfer through synthetic indicators such as AMTF, to anticipate potential non-compliance and protect consumer health.

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