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Assessing the Impact of Soil Humic Substances, Textural Fractions on the Sorption of Heavy Metals (Cd, Pb)

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Abstract: This study examined the sorption of heavy metals in selected soils (e.g., Andosol, Cambisol, Planosol) in Slovakia, focusing on the kind and quantity of humic materials as well as the soil's characteristics. Heavy metals were detected using GT AAS, while UV-Vis spectroscopy was used to determine humic substances' colour quotients. The impact of the total organic carbon on the total cadmium, bioavailable lead, and cadmium was highlighted. The results reveal positive correlations among humic substances and bioavailable forms of Cd (r = 0.692) and Pb (r = 0.709). A relationship was discovered between FAs and the bioavailable forms of Pb (r = 0.743) and Cd (r = 0.700) and between the level of HSs and the bioavailable content of Cd (r = 0.499). Bioavailable heavy metals showed a positive correlation with clay fraction and a negative correlation with heavy metal content. Correlations were found between the bioavailable heavy metal forms and the colour quotients of humic substances and humic acids. Heavy metals in bioavailable forms decreased with the levels of the condensation and dispersion of humic substances. From clay to silt, the amounts of Cd and Pb increased. This study' results provide insights into the relationships between soil properties, humic substances, and the sorption of the studied elements.

Keywords: contamination; bioaccessibility; metalloids; humic substances; UV-Vis spectroscopy

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1. Introduction

The input of exogenous organic materials effectively improves soil organic matter [1]. The leading causes of grassland degradation are both human and natural factors [2–4]. Human factors include overgrazing, over cultivation, indiscriminate digging and mining, mineral resource development, infrastructure construction and use, and tourism development [2,3]. Environmental pollution by heavy metals is not only determined by the total volume, but also by the forms of occurrence because different chemical forms of heavy metals in the soil display different environmental behaviours (climate change, wildlife destruction, pests, etc.) and biological effects [2–4]. The presence and behaviour of heavy metals in soil are influenced by many complex factors [5]. Understanding these factors is crucial for assessing the potential risks posed by heavy metal contamination and implementing effective remediation strategies. The complex effects of various factors depend on the pH of the soil, the content of organic substances, soil texture, redox conditions, moisture and drainage, and anthropogenic activities. Overall, complex interactions between soil properties, environmental conditions, and anthropogenic activities determine the fate and behaviour of heavy metals in the soil [3,6,7].

Human activities have an essential part in introducing toxic elements in the soil environment and creating potentially harmful concentrations of Cd and Pb. These heavy metals are often introduced into the soil as byproducts of various industrial processes,

including mining activities, metal production and processing, and chemical and electronic manufacturing. The use of fertilisers, pesticides, and contaminated wastewater from agricultural and industrial sources is another way heavy metals contaminate the soil. The most significant aspect of these contaminants are their abilities to persist in the soil environment for long periods and gradually accumulate in the soil and plants [8]. Heavy metals can also have adverse effects on the soil ecosystem as a whole, e.g., they can inhibit plant growth and development, disrupt soil microbial activity, and alter nutrient availability for plants. These negative effects can have broader implications for the ecosystem, including changes in biodiversity and the loss of soil functions.

In adsorbing heavy metals and creating stable complexes with humic substances, organic additions like composts and peat, which have a high proportion of humified organic matter (OM) [9], might reduce the bioaccessibility of heavy metals in soil. One of the most common, omnipresent, and reactive elements of biological matter in nature is humic substance (*HS*) [10]. Some toxic elements that are fundamentally soluble and changeable can be immobilised by adding humic compounds and can profoundly affect the environmental behaviour of metals. Humic acids (HAs) contain acidic groups such as carboxyl and phenolic (-OH) functional groups [11] and, therefore, provide organic macromolecules with an essential role in the transport, bioaccessibility, and solubility of heavy metals [12]. The primary factors influencing the movements and circulation of metals (Cd, Pb) in nature include plant type, soil formation, and property procedures such as volcanic eruptions, stone deterioration, and climate [13]. Prior research has demonstrated the dependence of toxic elements' chemical forms and bioaccessibility on environmental factors such soil pH, cation exchange capacity (CEC), and DOC, as well as on the measurements of other soil indicators [14–19]. Humic substances (HSs) are the most abundant among organic macromolecules occurring in various components of the natural environment, including soil, water, composts, mires, peats, sapropels, and mineral deposits such as brown and black-brown coal, leonardite, and shale [20–23]. HSs are formed in the process of humification, and the most essential products in this process are humic acids because they significantly affect soil properties. According to Zhang et al. [24], plant Cd and Pb accumulation are influenced by many factors, such as soil pH, organic matter content, and soil metal concentration. A direct measurement of soil quality is impossible due to the wide range of integrating factors associated with various soil usages [19]. Metal contamination in soil is now a significant issue on a global scale [25]. Given their influence on the concentration and bioavailability of toxic elements, humic compounds and soil texture were chosen as this study's primary areas of attention. As major constituents of soil organic matter, humic compounds like FAs and HAs can have big effects on the movements and behaviours of toxic soil elements. The availability of heavy metals to plants and other living things can be greatly influenced by their capacity to bind and mobilise them. Additionally, the amounts of clay, silt, and sand in the soil affect not only the physical and chemical characteristics of the soil, but also its ability to bind and release heavy metals. Variations in soil texture-related parameters such as porosity, wetness, and others can have an impact on metal availability to plants and microorganisms.

UV-Vis spectroscopy can determine the colour quotients of humic substances, which are used to measure the quality of humus in soil. Additionally, the impacts of changes in land usage on the composition and structure of humic substances have been noted, emphasising the dynamic nature of soil properties and humus composition. The advantage of a spectrophotometric determination of the colour quotient is that there is no need to extract the constituent fractions of humic substances (HSs) [26]. The absorbance at a wavelength of 465 nm corresponds to the absorption of the radiation of young humic substances at an early stage of the humification process. The value of the absorbance at 665 nm wavelength is indicative of how much radiation is absorbed by mature, well-humified humic compounds. The degrees of condensation, dispersion, and maturity of humic compounds are indicated by their colour quotients [27]. As the molecular weight and condensation degree increase, the value coefficient of $Q4/6$'s humification falls. The small

colour quotient ratio indicates older, humified organic material with a large concentration of condensed, and hence aromatic, chemicals.

On the other hand, a high value of $Q4/6$ suggests a low degree of aromatic condensation but also indicates a higher proportion of aliphatic compounds and is typical for new, small-scale humified humic acid that has just been supplied with organic materials. Studies on the chemical characteristics of humic acids, their combination of elements, and the content of carboxyl, aliphatic, and aromatic groups accurately characterise the stability of humic substances and humification degree of soil organic matter [28]. For the purpose of conducting a thorough assessment of the effects on soil fertility, it is imperative that the reactions of soil parameters, such as *TOC*, pH, etc., be thoroughly studied [1].

The aim was to characterise the sorption of heavy metals (Cd and Pb) in Andosol, Cambisol, and Planosol in specific soil types of neovulcanites from the Kremnické vrchy Mountains in Slovakia by identifying the kinds and amounts of humic compounds in the soil, as well as the characteristics of the textures of the soil types. This research was oriented toward the interactions between soil properties, humic substances, and heavy metal sorption, especially in diverse geological and environmental conditions. By focusing on the specific soil types and selected regions in Slovakia, this study aimed to provide insights into the relationships between soil composition, HSs, and the sorption of toxic elements. Significant changes in soil properties can result from both natural and human-caused management. The orientation of this study on humic substances and soil texture was chosen to better understand the mechanisms influencing the contents and bioavailability of heavy metals in soil and their impact on the environment. For this reason, soil monitoring and analyses were necessary, along with the right choice of a collection of indication information for an accurate soil quality evaluation.

2. Materials and Methods

2.1. Area of Study

The research was carried out in specific regions of Slovakia, focusing on soil types found in the Kremnické vrchy Mountains. Soil samples were collected for analysis from selected sites at two distinct locations (Locality I—Jastrabská vrchovina Mts., Locality II—Kunešovská hornatina Mts.) in the Kremnické vrchy Mountains. The measurements were conducted on Slovakia's rocks of lava at varying depths in the centre part of the Western Carpathians (Figure 1).

We determined the soil types of Eutric Cambisols, Eutric Andosols, and Eutric Planosols from the meadows (xerothermic and mowed) (Figure 1, Table 1). These soil types represent the diverse geological and environmental conditions present in the Kremnické vrchy Mountains, offering a valuable opportunity to investigate the sorption of heavy metals in different soil profiles. The Kremnické vrchy Mountains, known for their geological diversity and unique soil formations, provide an ideal setting for studying the interactions between soil properties, humic substances, and heavy metal sorption. The region's varying topography, vegetation, and geological composition contribute to the distinct characteristics of the soil types under investigation. By focusing on these specific soil types and regions, this study aimed to learn more about how toxic elements (Cd and Pb) sorb in diverse soil profiles, each with its unique textural and compositional properties. This approach allowed for a comprehensive assessment of the impact of soil characteristics on the bioaccessibility and mobility of heavy metals, providing valuable information for understanding the environmental dynamics of heavy metal sorption in the context of different soil types within the Kremnické vrchy Mountains. Soil sampling was conducted as open dug wells taken between autumn 2020 and spring 2021 (Table 1). Materials from every genetic horizon were obtained using standard protocols, and the World References Base taxonomy was used to make the diagnosis [29]. The data in Table 1 present the characteristics of the soil horizons [30]. We concentrated on regions within a single district (Žiar nad Hronom) to highlight variations in metal element concentrations and also other properties of meadow soils. Localities P1–P2 and P4–P5 have the type of land that has

mowed meadows and the positions slope with the following slope reliefs: P1, 12–17°; P2, 17–25°; P4, 7–12°; P5, 3–7°. Locality P3 has a type of land with a xerothermic meadow, and the positions saddle with the following relief: P3, 12–17°.

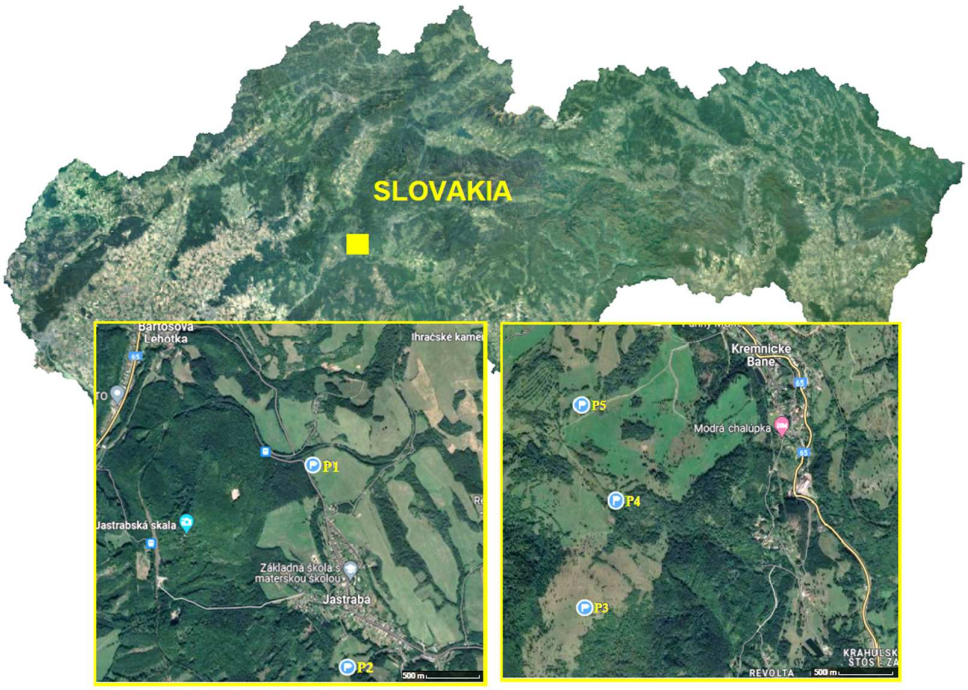


Figure 1. Jastrabská vrchovina Mts. (Locality I; P1–P2; altitude from 430 m a.s.l. to 696 m a.s.l.) and Kunešovská hornatina Mts. (Locality II; P3–P5; altitude from 808 m a.s.l. to 944 m a.s.l.): localities of soil samples.

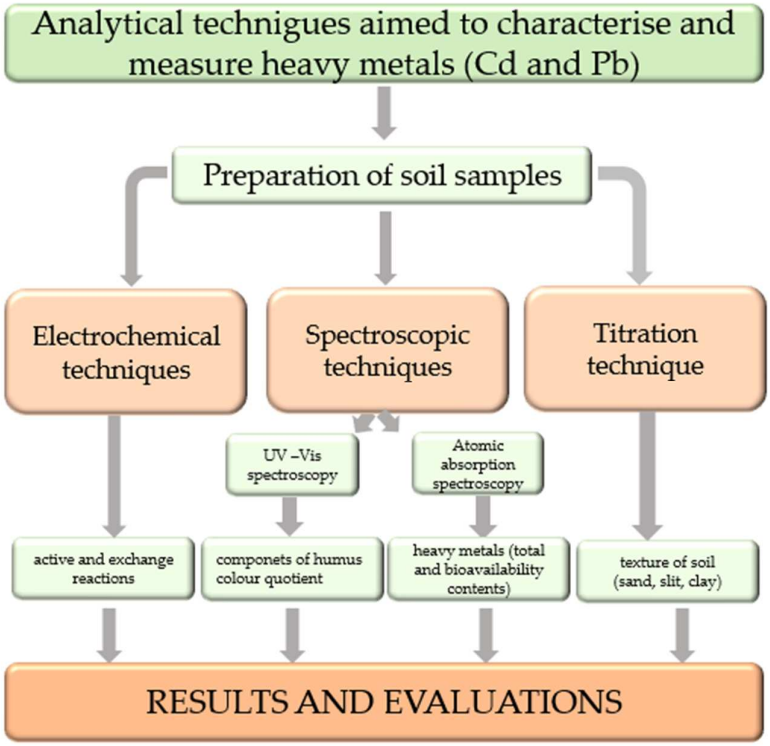
Table 1. Properties of the locations for the sampling and identification of soil horizons in soils.

Profiles/Localities/Soil Units Based on BPEJ [1]	Identification [2]	Depth [m]	Coordinates
P1/Locality I/Eutric Cambisol (EC)	Ao Bv C	0.0–0.12 0.12–0.35 >0.35	48°38′35.4″ E 18°55′46.3″ E
P2/Locality I/Eutric Cambisol (EC)	Ao Bv C	0.0–0.07 0.07–0.36 >0.36	48°37′41.8″ N 18°56′00.2″ E
P3/Locality II/Eutric Andosol (EA)	Ol Aau Bva	0.0–0.06 0.06–0.09 >0.09	48°43′13.7″ N 18°53′23.0″ E
P4/Locality II/Eutric Cambisol (EC)	Ao A/Bv Bv C	0.0–0.06 0.06–0.20 0.20–0.50 >0.50	48°43′38.0″ N 18°53′34.0″ E
P5/Locality II/Eutric Planosol (EC)	Ao A/En En Bmv	0.0–0.15 0.15–0.30 0.30–0.60 >0.60	48°43′59.7″ N 18°53′22.0″ E

[1] Soil unit designation in compliance with BPEJ [31]. [2] Munsell Soil Color Charts 2009 [30].

2.2. Methods of Analysis of Physico-Chemical Characteristics and Tools

The analysis of soil samples and materials included a number of measurements, including soil texture, pH, *TOC*, *HS*, *HA*, *FA*, Q_{HS}, and selected heavy metals using AAS (atomic absorption spectroscopy) analysis (Scheme 1).



Scheme 1. An overview of techniques aimed to characterise cadmium and lead.

The materials of soil included 180 samples from two chosen locations (three different soil types) that were collected and analysed. Samples of soil were collected at various depths (up to 0.60 m; refer to Table 1). All soil sample analyses were performed three times, including those for pH and *TOC* and heavy metals (Cd and Pb). Additional analyses were performed twice, including those for silt, sand, and clay fractions. The arithmetic mean values are the data that are displayed in the tables.

The total amounts and bioaccessibility forms of cadmium and lead in the examined soil samples were the outcome. Furthermore, a comparison of the metallic element contents under various land uses, soil types, and depths was conducted. To prevent combining two distinct soil strata, soil samples were taken from each soil horizon using an Edelman soil auger and open soil probes. In order to detect contamination, at least one average sample (i.e., nine sampling points or places) was taken from each of the 10 ha in the area under investigation [32].

This study employed UV-Vis spectroscopy as a key method for determining the colour quotients of humic substances, which is instrumental in assessing the quality of humus in the soil. This spectroscopic technique allows for the quantitative analysis of the absorbance values at specific wavelengths, such as 465 nm and 665 nm, to characterise the composition and maturity of humic substances. Additionally, this study utilised methods for extracting and quantifying HSs, containing HAs and FAs, to assess their content and composition in the soil. These methods involved group composition analysis and the determination of colour quotients for HAs and FAs, contributing to a comprehensive characterisation of the humic substances present in the soil samples. Furthermore, the research involved quantitatively determining heavy metals, such as lead and cadmium, using the ET-AAS technique on an atomic absorption spectrometer. This analytical method allowed for assessing the

total and bioaccessible types of selected soil metals, providing crucial data for understanding the sorption and circulation of cadmium and lead in different soil types. Overall, the combination of UV-Vis spectroscopy (Specord 50 Plus, Analytik Jena, Germany), the extraction and quantification of humic substances, and the quantitative determination of heavy metals enabled a comprehensive analysis of the connections between the characteristics of the soil, humic substances, and the sorption of analysed metals in the study area.

2.2.1. Analytical Techniques—Analysing the Heavy Metals and Agrochemical Indicator Contents

Limit values were applied to air-dried soil samples to determine the heavy metals analytically. Soil samples were processed as fine earth I (average particle size: 2 mm) and fine earth II (average particle size: 0.125 mm) for heavy metal determination measurements using the atomic absorption spectrometry method to ascertain agrochemical properties.

Active and Exchange Reactions of Soils

Soil pH, or the soil response, is a crucial factor affecting several different soil processes and qualities. It fundamentally impacts microbial activity, nutrient availability, and the solubility of Cd and Pb found in soil. The sorption and mobility of heavy metals, as well as the availability of vital nutrients for plant development, can all be strongly impacted by the pH of the soil. The measurement unveils crucial insights into the ecosystem's health and functionality. pH values were determined based on a water-to-soil ratio of 2.5:1, v:m [33]. The pH(H_2O)—the active soil reaction—was gauged in distilled water, whereas the pH(KCl)—the exchange soil reaction—was appraised in a 1 mol.dm^{-3} KCl solution (Centralchem, Ltd., Bratislava, Slovakia). A Unimax 2010 horizontal shaker (Heidolph Instrument GmbH, Schwabach, Germany) was used to ensure uniform suspension of the soil samples for 20 min. Subsequently, pH values were determined using an ino-Lab Multi 9310 pH meter (Labo SK, Ltd., Bratislava, Slovakia).

Total Organic Carbon

We measured the total organic carbon content (*TOC*) in soil samples and the various separated fractions using the Nikitina-modified Tyurin method [34]. By utilising the Tyurin method modified by Nikitina according to Orlov and Grišina for *TOC* determination, this study ensured a standardised and reliable approach to quantifying the soil samples' levels of organic carbon. This information was crucial for understanding the soil's organic matter composition and its potential influence on heavy metal sorption and other soil properties.

Components of Humus—Isolation of FA and HA Fractions

Humus was extracted into $Na_4P_2O_7$ with c = 0.1 mol dm^{-3} and NaOH to get the pH down to 13 (c = 1.0 mol dm^{-3}). Soil samples were infused for 24 h. A spectrum analyser (Specord 50 Plus, Analytik Jena, Germany) was used to examine UV/VIs spectra from 300 nm to 700 nm. We calculated the content of humus using Equation (1) [35]:

$$Hum = TOC \times 1.724 \quad (1)$$

Hum (%) = the humus content in the soil
TOC (%) = the total organic carbon
1.724 is the valid conversion coefficient, assuming that the humus contains 58% carbon (e.g., 100/58 = 1.724)

The group composition of humus substances (HSs) was used to determine their content using the Belčiková–Kononová technique [36]. In general, HSs can be fractionated into three principal groups, depending on their solubility in an aqueous environment at various pHs. These fractions include humins (HUs)—generally insoluble at any pH, fulvic acids (FAs)—soluble in every pH [37,38], and humic acids (HAs)—soluble in alkaline media, which precipitate at pH below 2.0 [39].

A $Na_4P_2O_7$ solution (c = 0.1 mol·dm^{-3}) was applied to extract the samples for a full day (24 h) at 22 °C with periodic shaking to measure metal concentrations bound to humic and fulvic fractions. In order to quantify the amounts of metals bonded to the humic and fulvic fractions, the samples were extracted for 24 h at 22 °C with intermittent shaking using the $Na_4P_2O_7$ mixture (c = 0.1 mol·dm^{-3}). Centrifugation at 3000 rpm was used to remove any undissolved material [36]. *FA* and *HA* were separated from the mixture by filtering and acidifying with H_2SO_4. Thermal 0.05 mol.dm^{-3} NaOH was used to dissolve the remaining *HA*. After filtering, all solutions were mixed with 0.1 mol·dm^{-3} H_2SO_4 and NaOH to achieve a pH of 6.

In using the Belčiková–Kononová technique, the group consisting of humic substances was used to calculate the quantity of humic compounds as well as the ratio *c(HK)/c(FK)* [36], according to Equation (2):

$$c(HA)/c(FA) = \frac{(a-b) \times 0.0003 \times f \times 1,17 \times 100}{n} \quad (2)$$

c(HA), c(FA) is the whole carbon of HSs and HAs (%);
a is the usage of 0.1 mol·dm^{-3} Mohr's salt per centilitre in measured blank;
b is the application of 0.1 mol·dm^{-3} Mohr's salt per centilitre in sample titration;
0.0003 is the carbon factor of conversion;
f is the salt titration factor of Mohr;
n is the calculated weigh of soil sample (g)

A Varian Cary 50 spectrophotometer (Specord 50 Plus, Analytik Jena, Jena, Germany) operating in the 300 nm to 700 nm wavelength range was used to measure the UV-Vis spectra. According to Michalska et al. [10], UV-Vis spectroscopy may be recognised as a cost-effective approach for the preliminary characterisation of HSs [10].

Degree of Humification and Colour Quotient

The proportion of the Vis spectra's values for absorbance at 465 nm and 665 nm was used to calculate the colour quotients of humus components (Q_{HS}) [40]. We calculated the colour quotients of humus components (Q_{HS}) and humus acids following Equations (3) and (4):

$$Q4/6_{HS\frac{Q_{465}}{Q_{665}}} \quad (3)$$

$$Q4/6_{HA\frac{Q_{465}}{Q_{665}}} \quad (4)$$

1. *Q4/6_HS* is the colour quotients of humus components
2. *Q4/6_HA* is the colour quotients of humus acids

The lower the values of these parameters, the more condensed and mature the humic acids are. While the absorbance at 665 nm relates to the absorbing capacity of mature and well-humified humic compounds, the absorbance at 465 nm corresponds to the radiation absorbing of immature humic compounds that are in the early phases of humification. The colour quotients of humic substances can be calculated by measuring these absorbance values, providing insights into the humic compounds' maturity, condensation level, and soil dispersion. The colour quotient was calculated via Vis spectrometry (Specord 50 Plus, Analytik Jena, Germany, glass cuvette). The humified compounds' humification degree *(DH)* was determined using Equation (5) [41]:

$$[\%] \cdot DH = \frac{c_{HA}}{TOC \times 100} \quad (5)$$

Soil Texture

We used the pipetting technique to determine the silt, sand, and clay fractions [33].

Analysis of Metals That Are Heavy

The AAS method was employed to determine heavy metals' total and bioaccessible forms. In using a GTA 120 Graphite Tube Atomizer from Agilent Technologies (Hermes LabSystems, Ltd., Bratislava, Slovakia) and an atomic absorption spectrometer, the GT-AAS approach was used to quantitatively determine the presence of heavy metals (lead and cadmium). In order to quantify the heavy elements that were analysed, soil samples were tested in three replicates. With an equipped Ethos One (Chromspec Slovakia, Ltd., Šaľa, Slovakia), samples of soil were processed before analysis. To ascertain the cadmium and lead contents, the samples of soil were processed in aqua regia (the compounds were from Sigma Aldrich, Ltd., Bratislava, Slovakia; HCl = 37%; HNO_3 p.a. $\geq$ 65%). The samples were processed according to the legislation and laws [32].

Forms of lead (Pb) and cadmium (Cd) that may be bioaccessible were separated using a 2:10 (soil/nitric acid) solution containing 2 mol·L^{-1}. Aqua regia, a method of extracting that uses a ratio of HCl to HNO_3 (3/1), was utilised to assess the overall concentration of heavy metals. A total of 3 g of soil sample was digested for 2 h at 180 °C [42].

The results obtained from the GT AAS analysis were crucial for evaluating the potential environmental impact of heavy metal contamination and understanding the sorption behaviours of these metals in different soil types.

Chemical reagents (ACS grade) were dissolved in distilled and deionised (DDI) water from a MilliporeSigma™ Synergy™ Ultrapure Water Purification System (Merck Millipore, Bedford, MA, USA) in all experiments.

2.2.2. Statistical Analysis and Data

In this study, a data analysis was conducted using statistical methods to explore the relationships between soil properties, humic substances, textural fractions, and the content of cadmium and lead in the soil. As was previously indicated, a few statistical techniques were used to examine the measured values that were taken from the soil samples. The degree of dependency between the observed variables was determined using Spearman's rank correlation coefficient. By applying correlation analysis, this study aimed to assess the degree of association between factors such as the total organic carbon, humic substances, humic acids, fulvic acids, textural fractions, and the content of heavy metals (Cd and Pb) in the soil samples. The statistical analysis involved testing the significance of the correlation coefficients at specific confidence levels (e.g., $p < 0.05$ and $p < 0.01$) to determine the reliability and strength of the observed relationships. This approach provided a quantitative basis for understanding the interplay between soil characteristics, humic substances, texture, and heavy metal sorption. The STATISTICA application 9.0 Standard Plus CZ (StatSoft Inc., Tulsa, OK, USA) was used to carry out the computations.

3. Results and Discussion

The relationship between the study soils and the presence of cadmium (Cd) and lead (Pb) is a critical aspect of the research, as it directly influences the potential environmental impact of toxic metal contamination. The specific soil types and their unique attributes, including pH and organic matter concentration, and textural properties can significantly influence the behaviour, mobility, and bioaccessibility of cadmium and lead.

3.1. Carbon Parameters

At Localities I (P1–P2) through II (P3–P4), soil samples were gathered in the autumn and spring. As previously indicated, the soil samples were tested for pH(H_2O), pH(KCl), *TOC*, *c(HS)*, *c(HA)*, and *c(FA)* (Table 2). The monitoring parameters, for example, the soil's pH level, can impact the solubility and mobility of lead and cadmium, potentially affecting their bioaccessibility and potential for leaching into the environment. Additionally, the soil's organic matter content and textural fractions can influence these heavy metals' adsorption and desorption processes, further shaping their distribution and potential impact on the surrounding ecosystem. The Andosol soil (P3: xerothermic meadow) had the

most significant proportion of humic compounds (3.6%), whereas the Cambisol soil had the lowest average value. Given the high concentration of fulvic acids in the soils, which are poorer in carbon than humic acids, HSs isolated from the soil samples suggest humus of poor quality (Table 2). The content of the humified and condensed component known as soil humus in our soil averaged around 1.5–3.5% and is responsible for soil fertility and production performance [43]. The process of humus formation is very demanding and lengthy, depending on the type of vegetation, climatic conditions, air and water content in the soil, parent rock or soil-forming substrate, and human activity. Despite the continuous processes of formation and deposition, there are also continuous losses. Therefore, the humus content often remains constant or even decreases rapidly. Humic substances, the main organic component of soil, contain humic acids, fulvic acids, and humins [44,45]. Their lignin content is very high, derived from organic materials and plant waste, and is often associated with quite high degrees of humification [46]. Although they make up a small percentage of soil isolation, they play a variety of crucial functions in the availability of nutrients, the carbon–nitrogen cycle, and the metabolic processes that mobilise harmful organic and inorganic compounds [47]. Humic acids are complex acids with ion groups organised so that chelate complexes can form. Humic acids can control the bioaccessibility of metal ions in a plant's development environment thanks to chelate complexes. When the pH of the water is more than two, humic acids dissolve in it. Their shades range from dark brown to black. Humic acid binds minerals into easily absorbable organic compounds, makes the soil more permeable and able to retain more water, reduces the presence of toxins in the soil, and greatly reduces the amount of pollutant that can reach the roots of plants. Long molecular chains, a dark brown colour, and solubility in an alkaline solution are characteristics of HA that may help it retain its form, structure, and nutrients in the soil. Humic acids are highly mobile in the soil. Their salts, Cd and Pb, are soluble in water.

Table 2. Carbon parameters' average values in soil profiles.

Localities	Profile	Depth [m]	*TOC*	HSs	HAs	FAs	*c(HA)/c(FA)*
			[%]				
Locality I	P1	0.0–0.12	3.14	0.93	0.26	0.68	0.60
		0.12–0.35	0.91	0.26	0.04	0.23	0.16
		>0.35	0.13	0.14	0.01	0.13	0.04
	P2	0.0–0.07	5.37	1.85	0.37	1.48	0.25
		0.07–0.36	0.66	0.63	0.10	0.52	0.20
		>0.36	0.88	0.26	0.14	0.12	1.18
Locality II	P3	0.0–0.06	14.77	6.84	1.22	5.63	0.22
		0.06–0.09	12.41	6.37	0.46	5.91	0.08
		>0.09	4.28	2.40	0.27	2.13	0.12
	P4	0.0–0.06	5.01	1.85	0.38	1.47	0.26
		0.06–0.20	1.58	0.86	0.21	0.65	0.32
		0.20–0.50	1.63	0.48	0.17	0.31	0.53
		>0.50	1.35	0.59	0.13	0.46	0.27
	P5	0.0–0.15	2.85	1.64	0.61	1.03	0.59
		0.15–0.30	2.81	0.92	0.38	0.55	0.69
		0.30–0.60	1.25	0.92	0.18	0.74	0.24
		>0.60	1.10	0.67	0.21	0.46	0.45

TOC—total organic carbon, HSs—humic substances, HAs—humic acids, FAs—fulvic acids.

Fulvic acids are natural chelators. After adding the necessary micronutrients, fulvic acids form chemical bonds that prevent reactions with other ions. Nutrients bound to a chelate are efficiently transferred from the roots to other tissues; chelation increases the bioaccessibility of otherwise insoluble nutrients by making them soluble. Understanding the relationship between studies and the presence of lead/cadmium is critical to assessing the potential environmental risks associated with heavy metal contamination. Examining

how specific soil types influence the behaviour and fate of lead and cadmium can reveal potential interactions and overall impacts on soil quality and environmental health. This understanding is essential for developing effective management strategies. Fulvic acids are soluble in alkaline and acidic solutions, i.e., they are highly mobile in the soil [48]. Their salts, Cd and Pb, are soluble in water. With ferric and aluminium hydroxide, fulvic acids form soluble complex compounds. This property is important for the movement of minerals in the soil, and they are important in podzolisation processes. The increased content of fulvic acids in the soil (typical of more acidic soils) makes these elements available in forms acceptable to plants. Fulvic acids are a type of humic acid with a low molecular weight and oxygen content [49]. Fulvic acids are fairly light in colour, from yellow to a light brown.

The values of carbon parameters, such as *TOC*, FAs, HSs, and HAs, in soil profiles are shown in Table 2.

The humus's composition can be roughly determined using the senses—by colour (the darker the better), the structure of the decomposition of organic matter, the type of soil, and the soil reaction. Furthermore, it can also be determined using the ratio of humus to fulvic acids (*HA*/*FA*), poor quality humus: 0.5 or less (podzol soil, peaty soil).

The top layers of the soil's profile are where the greatest concentrations of organic matter, mostly from vegetation, concentrate in natural ecosystems. In specific monitoring locations and soil types, we examined how each correlation value depended on the sampling depth (Table 2). As the depth increased, the transformation cycles' overall nature shifted. Fermentation processes replace oxidation processes, which cause soil carbon to be lost. The amount of the total organic carbon (*TOC*) content is a fundamental measure of the organic carbon present in the soil and may be attributed to the influences of many factors, including climate conditions, soil properties, etc. [50]. It serves as an indicator of the soil's organic matter content, reflecting the quantity of carbon stored in organic compounds within the soil [51,52]. The *TOC* content is crucial for assessing soil fertility, nutrient availability, and the potential for carbon sequestration. Changes in *TOC* content can provide insights into alterations in land use, management practices, and environmental conditions, making it a valuable parameter for evaluating soil health and productivity [53,54]. The main elements of soil organic matter are HSs, which include FAs and HAs [55]. They are essential in soil structure, nutrient retention, and the complexation of toxic elements. The contents of *HS*, *HA*, and *FA* in the soil profiles provide valuable information about the quality and composition of organic matter, influencing soil fertility and the availability of essential nutrients for plant growth [45]. The TOC and other organic materials reduced as soil depth increased, which agrees with the claim of Wang et al. [50]. The TOC content in the Cambisol soil type (P1, P2, P4) ranged from 0.13% to 5.37%, and the average value for the soil types studied was 1.530%. The averaged value for Andosol (P3) was 7.432%, and that for the Planosol soil type (P5) had a value of 2.653% (Table 2).

Figure 2 provides a comprehensive overview of the carbon parameters in soil profiles, colour quotient of humic substances (Q_{HS}), colour quotient of humic acids (QHA), colour quotient of fulvic acids (QFA), and the humification degree (DH). These parameters are essential for understanding the composition and quality of organic matter in the soil.

In the Cambisol and Planosol soils, there is a higher concentration of condensed compounds and an increased level of humification, as shown by the measured values of the colour quotient of humic substances. There was no discernible variation in the colour values of the humic substance quotient among these two categories of soil. The average values of the detected humic substances' colour quotient in Cambisol were lower (in the range from 2.36 to 2.71) than that in Planosol (Q_{HS} = 3.10). The greatest average value of the colour quotient was found in the P3 profile (the Andosol in the xerothermic meadow), with varied degrees of organic matter decomposition on the soil's surface and a steady supply of dead plant material generating the underlying organic horizon. The low-humified HAs that were supplied with a new source of organic materials had a greater colour quotient. The use of land resources has an impact on the amount of soil HSs. Since the absorbance at 465 nm, which is typical for these young humic compounds, was greatest for Andosol, the UV-Vis

spectrum indicates that the Andosol soil observed in profile P3 had numerous juvenile humic substances at the very beginning of humification. Figure 2 shows that the colour quotient values for HAs ranged from 2.08 to 5.97, while those for FAs ranged from 5.66 to 13.84. The present findings are consistent with those of Petrášová and Pospíšilová [27].

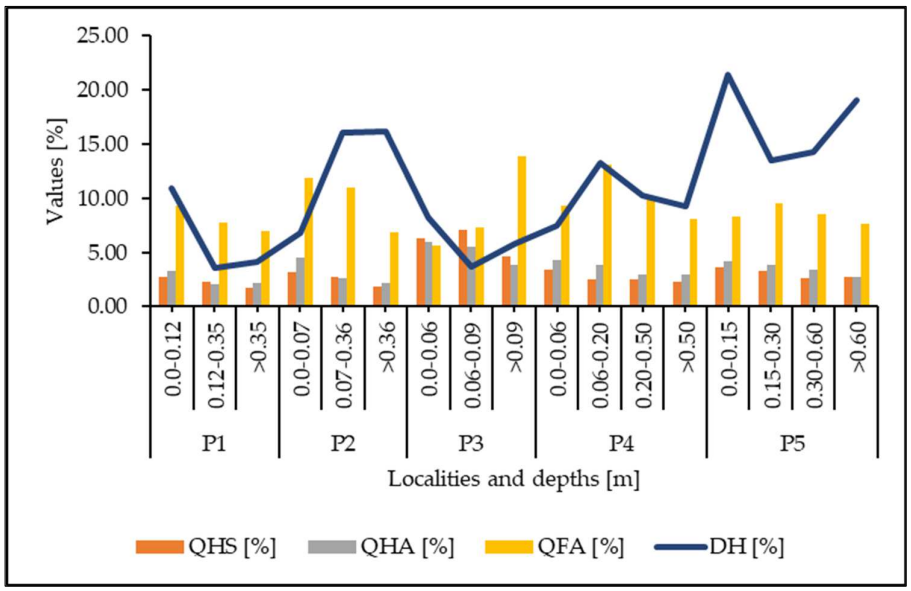


Figure 2. Colour quotients and humification degrees (Q_{HS}—colour quotient of HSs, QHA—colour quotient of HAs, QFA—colour quotient of FAs, DH—humification degree).

Planosol from a mowed meadow showed the greatest levels of humification, the concentration of the aromatic core, and as a result, the humic compounds' quality (Figure 2). Profile P3 had the least amount of humification that we could find with the new availability of organic matter and the greatest amount of *TOC* and HSs (Table 2, Figure 2). As a result, the smaller degrees of humic material dispersal and condensate, the lower the contents of the bioavailability forms of selected metals. The principal functional groups in humic materials include carboxylic acid, phenolic and alcoholic hydroxyl, ketone, and quinone groups. Alkyl/aromatic units form the backbone of humic compounds, which are mostly cross-linked by the presence of nitrogen and oxygen [56]. Dube et al. [57] stated that the functional groups that contain oxygen found in humic and fulvic acids, such as carboxylic, phenolic, and carbonylic groups, are primarily responsible for their capacity to complex. Chelate compounds are particularly significant. As ligands, the fulvic and humic functional groups are involved. Each of the groups has the ability to build closed rings by occupying two or more coordinating places around metal ions. Particularly on volcanic substrate, the humic substances of Andosol were distinguished by a significant level of humification. A larger ratio of *c(HK):c(FK)* is linked to greater humification characteristics of HSs (Figure 2).

The colour quotients of humic substances (Q_{HS}), humic acids (QHA), and fulvic acids (QFA) are measures of the colour intensity of these organic components. These parameters are indicative of the maturity and degree of humification of the organic matter in the soil, providing insights into the decomposition and transformation of organic compounds over time. The humification degree (DH) represents the extent of humification, reflecting the degree of transformation of organic matter into humic substances. This parameter offers valuable information about the stability and maturity of the organic matter in the soil, influencing its interactions with heavy metals and also other soil properties. By analysing these carbon parameters (Table 2), we gained a comprehensive understanding of the soil profile characteristics, which contributed to a more thorough assessment of the soil's fertility and other soil properties. These parameters were essential for understanding the composition and organic matter present in the soil.

The content of the *TOC* is a crucial indicator of the soil's organic matter content, representing the quantity of carbon sequestered in organic compounds within the soil. It serves as a key measure of soil fertility, nutrient availability, and the potential for carbon sequestration. The values of *TOC* in topsoil did not vary between profiles P1–P2 and P4 (Cambisols) and P5 (Planosol) (Table 2). The *TOC* content provides insights into the soil's ability to support microbial activity, retain moisture, and sustain plant growth. Additionally, changes in *TOC* content can reflect alterations in land use, management practices, and environmental conditions, making it a valuable parameter for assessing soil health and productivity. A comprehensive picture of the organic composition was obtained by analysing the *TOC* content in conjunction with other carbon metrics (Table 2 and Figure 2), which aided in a more thorough assessment of the capacity for storing carbon and any potential interactions with heavy metals.

3.2. Cadmium and Lead Pseudo-Total Levels in the Soil Samples

The soil's total cadmium and lead levels ranged from 1.40 mg kg^{-1} to 5.30 mg kg^{-1} and 30.10 mg kg^{-1} to 65.30 mg kg^{-1}, respectively (Table 3). In all samples, the limit value was not surpassed (Table 3). Given the environmental concerns of Cd and Pb, chemical characterisations and property assessments of these elements, and potentially also of their bioavailable forms, are particularly warranted, as well as an analysis of the heavy metal contents in the solution. However, 2 M HNO_3 highlights the low content of potential bioavailable forms of lead and cadmium in soil, below the limit parameters. Despite the high content level of the metals being observed, the proportion of acceptable forms of Cd (0.05–0.27 mg·kg^{-1}) and Pb (10.80–38.10 mg·kg^{-1}) in the soil were low, demonstrating a minimal chance of these components getting into the biomass of the plant. We agree with Sun et al.'s [25] claim that human behaviours, such as fuel heating, transport, and manufacturing, are the major sources of Cd and Pb contamination. The results of Liu et al. [58] showed that Pb is reasonably stable and has little chance of migration (a reduced potential migratory ability, the lowest bioavailability, and the highest stability).

Table 3. Some soil properties.

Profiles	Depth [m]	pH_{H2O}	pH_{KCl}	Cadmium [mg kg^{-1}]		Lead [mg kg^{-1}]	
				Total Content	Bioaccessibile Form	Total Content	Bioaccessibile Forms
P1	0.0–0.12	6.6	5.8	5.30	0.23	65.30	25.20
	0.12–0.35	7.1	6.2	4.90	0.13	58.90	23.50
	>0.35	7.3	5.7	4.20	0.12	30.40	19.80
P2	0.0–0.07	5.6	5.0	4.80	0.25	57.30	24.20
	0.07–0.36	5.7	5.1	2.40	0.19	51.20	19.60
	>0.36	6.0	5.3	2.20	0.14	43.30	13.40
P3	0.0–0.06	5.1	3.7	4.50	0.25	47.60	25.30
	0.06–0.09	3.9	3.7	4.90	0.27	63.10	38.10
	>0.09	6.0	4.4	5.10	0.19	39.50	24.03
P4	0.0–0.06	6.2	4.5	3.40	0.16	49.40	18.70
	0.06–0.20	6.1	4.2	2.90	0.13	47.80	17.30
	0.20–0.50	6.2	4.2	2.70	0.12	42.70	15.80
	>0.50	6.1	4.1	2.10	0.08	41.00	13.10
P5	0.0–0.15	6.4	4.8	2.40	0.13	65.10	17.80
	0.15–0.30	6.2	4.4	2.10	0.11	49.90	16.00
	0.30–0.60	6.0	4.1	1.90	0.08	38.30	12.40
	>0.60	6.1	4.4	1.40	0.05	30.10	10.80

pH_{H2O}—active reaction of soil, pH_{KCl}—exchange reaction of soil.

In addition, the measurement of soil pH offered insightful information on the chemical properties of the soil and its potential to influence heavy metal sorption and other soil processes (Table 3). This information adds to a more thorough comprehension of the environment's shifting dynamics and possible dangers connected to soil contaminated with toxic elements [59].

The soil reaction, often measured as the pH of soil, was an important element that affects the availability and mobility of toxic metals such as cadmium and lead in the soil samples. The soil's pH level can significantly impact the solubility and bioaccessibility of HMs, thereby affecting their potential for plant uptake and environmental mobility. According to Sungur et al. [60], in acidic soils, the solubility of lead and cadmium increases, potentially leading to higher levels of bioaccessible lead and cadmium. Conversely, in alkaline soils, the solubility of lead and cadmium decreases, which may reduce their bioaccessibility, and a reduced soil pH may improve mobility and lessen the adsorption of heavy metals [60]. Therefore, understanding the soil reaction or pH is essential for assessing the potential risk of lead and cadmium contamination and their impact on the environment. The relationship between the reaction of soil and the amount of Cd/Pb was crucial for evaluating the potential environmental impact of contamination. By analysing this relationship, this study aimed to provide perceptions of the variables impacting the distribution and bioaccessibility of lead (cadmium) in the soil, contributing to a comprehensive understanding of the environmental dynamics of contamination. Soil pH affected carbonate production and dissolution, and pH and carbonate-bound toxic metal contents were positively correlated [61]. A high soil pH was advantageous for the synthesis of Fe–Mn oxides [62].

Understanding the relationship between the study soils and the presence of lead and cadmium is crucial for assessing the potential environmental dangers posed by toxic element pollution. Investigating how the specific soil types influence the behaviour and fate of cadmium/lead can show the potential interactions and the overall impact on soil quality and environmental health. This understanding is essential for developing effective strategies for managing and mitigating the environmental impact of heavy metal contamination in soil.

3.3. Soil Texture

The transformation of organic materials depended on the texture of the soil. When analysing data, we evaluated the interdependence of individual outcomes at different soil sample locations in certain profiles and soil types regarding the relationship among soil texture (Figure 3).

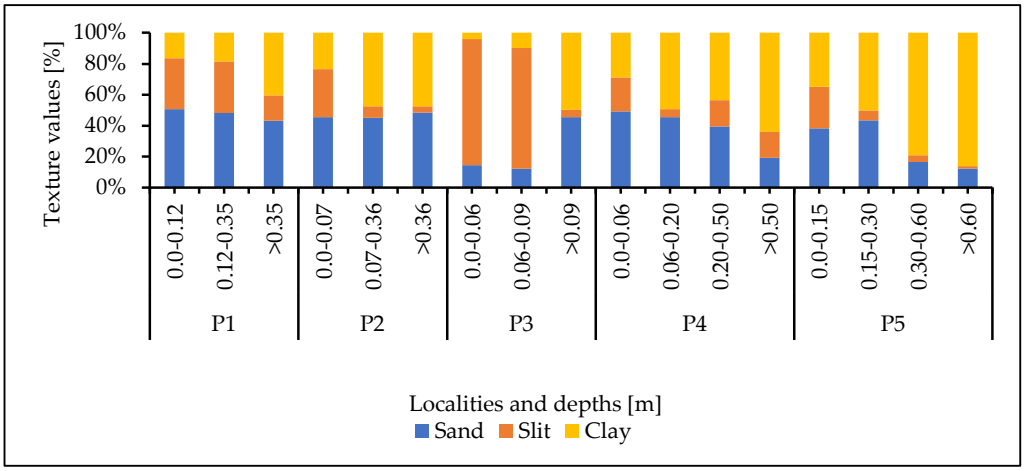


Figure 3. Characteristics of soil texture—average values (sand: 2–0.050 mm, silt: 0.05–0.002 mm, clay: <0.002 mm).

The procedures for transformation are impacted by sand, silt, and clay due to pH and other factors. In selected profiles depending on depth, there were the following textures: P1 loam (0–0.35 m), clay (>0.35 m), P2 loam (0–0.07 m), sand clay (0.07–0.36 m, >0.35 m), P3 silt (0–0.06 m), silt loam (0.06–0.09 m), sand clay (>0.09 m), P4 sandy clay loam (0–0.6 m), sandy clay (0.06–0.20 m), clay (0.20–0.50 m. >0.50 m), P5 clay loam (0–0.15 m), and clay (0.15–0.60 m, >0.60 m). In certain soil types and profiles, we assessed the dependence of individual values in Figure 3 at soil sample locations.

According to Rodríguez-Bocanegra et al. [63], the subsoil's increased particles, clay (loam), fine texture, and organic materials may contribute to decreased heavy metal concentrations in plant shoots (subsoil at root depth). Clay (loam) can form strong connections with toxic elements in the soil from biomass addition based on various types of land uses, rates of decomposition, and plant materials, which reduces the metals' availability to plants [64]. Furthermore, rather than being a homogenous structure, the soil is a matrix with a variety of microenvironments, which can cause environments and components in various soil components (such as aggregate fractions) to react differently to changes in the surrounding environment. The selected samples for soil mineralogy investigations differ in terms of their mineralogy, particle size, and cohesiveness; for example, alluvial and clay souls are more cohesive than quartz-based sands [65].

This raises the question of whether heavy metal forms in soil aggregates of different particle sizes respond differently to microplastics (the small-sized particles < 5 mm) [66,67]. This response mechanism warrants investigation, given its expected importance in guiding soil management [67].

A positive association was observed between the chemical components of humic substances and the percentage features and heavy metal concentration in the soil, as shown through statistical testing using Spearman's correlation (Table 4). Table 4 shows that there was a positive connection (r = 0.887, $p < 0.01$) between the *TOC* and the silt fraction and a negative correlation (r = −0.667, $p < 0.01$) with the clay fraction. Tobiašová, Barančíková, and Gömöryová [68] stated that there is a positive association between the clay fraction and the amount of soil organic matter. Table 4 indicates a favourable association between the total organic carbon and the overall concentration of cadmium (r = 0.493, $p < 0.05$), as well as between the total organic carbon and the bioaccessible forms of Pb (r = 0.708, $p < 0.01$) and cadmium (r = 0.734, $p < 0.01$). In comparison to lead, cadmium had the highest sorption property in terms of the *TOC*, according to the correlation analysis. Deka and Sarma [69] found a slight negative correlation among the levels of soil organic matter (SOM) and heavy metals, particularly lead. Lead has the greatest sorption characteristic in terms of the *TOC* (r = 0.941, $p < 0.01$) in comparison to Cd (r = 0.718, $p < 0.05$), according to Hudec et al. [70].

Table 4. Correlation relationships among the chemical components of HSs and the soil's textural characteristics, heavy metal concentrations, and other parameters.

		TOC	*HS*	*HA*	*FA*	Q_{HS}	Q_{HA}	*c(HA)/c(FA)*
pH(H_2O)		−0.757 **	−0.795 **	−0.507 *	−0.813 **	−0.804 **	−0.726 **	0.140
pH(KCl)		−0.521 *	−0.568 *	−0.496 *	−0.559 *	−0.585 *	−0.656 **	0.153
Cd	total content	0.493 *	0.448	0.214	0.471	0.429	0.331	−0.443
Pb		0.344	0.299	0.299	0.290	−0.443	0.400	0. 075
Cd	bioaccessibility form	0.734 **	0.692 **	0.499 *	0.700 **	0.664 **	0.625 **	−0.228
Pb		0.708 **	0.709 **	0.352	0.743 **	0.734 **	0.566 *	−0.448
Sand		−0.442	−0.516 *	0.372	−0.521 *	−0.469	−0.384	0.260
Silt		0.887 **	0.864 **	0.702 **	0.861 **	0.774 **	0.704 **	−0.315
Clay		−0.669 **	−0.596	−0.526 *	−0.587 *	−0.540 *	−0.526 *	0.133

* $p < 0.05$, ** $p < 0.01$, pH(H_2O)—active reaction of soil, pH(KCl)—exchange reaction of soil, Pb—lead, Cd—cadmium, *TOC*—total organic carbon, *HS*—humic substance, *HA*—humic acid, *FA*—fulvic acid, Q_{HS}—colour quotient of humic substances, QHA—colour quotient of humic acids, QFA—colour quotient of fulvic acids, DH—degree of humification.

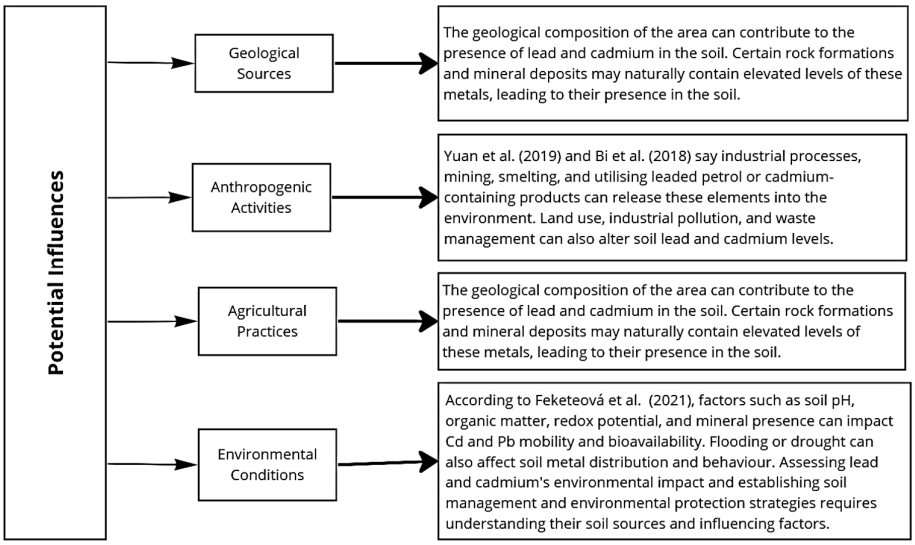
There was a noteworthy correlation found among the concentration of humic substances and the bioaccessible forms of Cd (r = 0.734, $p < 0.01$) and Pb (r = 0.709, $p < 0.01$). Table 4 displays the association among the bioaccessible forms of Cd and Pb as well as the levels of fulvic and humic acids. The results show that Pb is relatively stable and has weak migration potential [64].

The relationship between Cd and Pb in soil is complex and multifaceted. Both lead and cadmium are heavy metals that can coexist in soil environments, and their interactions can have significant implications for environmental quality and human health [71]. In some cases, lead contamination in soil can influence the behaviour and mobility of cadmium and vice versa. For example, these metals' adsorption and desorption processes can be interrelated, affecting their bioaccessibility and potential for leaching into groundwater. Additionally, one metal's existence may affect another's absorption and buildup by plants and other organisms in the soil environment.

Furthermore, the capacities to dissolve and transport cadmium and lead are influenced by soil properties and the minerals [59]. Changes in these soil properties can affect the interactions between cadmium and lead, potentially altering their distribution and bioaccessibility in the soil. Understanding the relationship between cadmium and lead in soil is crucial for assessing the possible dangers to the environment connected with heavy metal contamination. By investigating the interplay between these metals, we can gain insights into their behaviour, possible interactions, and the overall impact on soil quality, environmental health, and the mitigation of the environmental effects of soil that has been exposed to toxic elements. QHSs and QHAs were shown to correlate with the bioaccessible forms of heavy metals (Table 4).

The positive connection was discovered by applying the Spearman correlation technique, which statistically assessed the connection of correlation with a high degree between the bioaccessible and total contents of Cd/Pb and the soil silt fraction (Table 4). A negative correlation with high degree was found between the contents of heavy metals and clay fraction on the significance level $\alpha = 0.01$ (Table 4). According to Dube et al. [57], the content of heavy metals usually decreases from clay to coarse silt. The soils with high amounts of clay fraction and organic matter can contribute more to heavy metals than others [57].

The relationship between the total cadmium and lead contents and bioaccessibility monitoring toxic elements in soil is critical for understanding the potential environmental impact of their contamination and implications for meadow plants. The total cadmium and lead contents in soil represent the overall concentrations of lead and cadmium present, including both bioaccessible and non-bioaccessible forms. Bioaccessible cadmium and lead refers to the portion of cadmium and lead that are readily accessible for uptake by plants and other organisms. The bioavailability of cadmium and lead in soil is influenced by a number of variables, such as pH, the amount of organic matter in the soil, and the presence of other minerals. Changes in these soil properties can impact the solubility and mobility of cadmium and lead, affecting their bioavailability to meadow plants. Additionally, the total cadmium and lead contents in the soil can be used to predict the likelihood that plants will absorb these elements and affect their health [72–75]. The values of Cd/Pb in the soils of the monitored localities might have been impacted by a number of variables, including natural geological sources [13], human activities [8], and environmental conditions (Scheme 2).



Scheme 2. Potential influences and their values. (Yuan et al. [8], Bi et al. [76], Feketeová et al. [59]).

Understanding the relationship between total cadmium and lead contents and the bioavailability of cadmium and lead is necessary for assessing the possible dangers brought on by soil contamination. By investigating this relationship, we can gain insights into the factors influencing the availability of cadmium and lead to plants and the potential for cadmium and lead uptake. It provides valuable information for evaluating the environmental impact of Cd/Pb contamination on plant health and ecosystem dynamics. The limit values for these heavy metals in the soil and plants of meadows are regulated by environmental and agricultural authorities [32] to guarantee the preservation of the environment and public health. The World Health Organization (WHO) has established the following guidelines and limits for the amount of Cd/Pb in soil and plants:

- Soil: The WHO has established guidelines for cadmium/lead in soil to safeguard both the environment and human health. These guidelines are designed to prevent soil contamination and to minimise the potential for damage to these metals through breathing or consuming contaminants, or uptake by plants. For example, in the European Union, the limit values for lead and cadmium in soil are regulated under the Soil Framework Directive 2004/107/EC [77].
- Plants: The WHO also provides guidelines for cadmium/lead in food products, including plants grown in agricultural areas. These guidelines were designed to guarantee the security of agricultural goods and minimise the risk of consuming contaminated food through exposure to cadmium/lead. The limit values for lead and cadmium in plants, including those found in meadows, are established to ensure food safety and prevent the accumulation of harmful levels of these metals in edible crops and forage. The limit values for lead and cadmium in plants are based on the maximum permissible levels in food products and were designed to protect human health [13].

The textural fractions (sand, silt, and clay) of soil are crucial in influencing various soil properties, such as water retention, nutrient availability, and the mobility of contaminants, e.g., heavy metals. When analysing data, we evaluated the interdependence of the textural fractions of soils and heavy metals (total and bioaccessibility forms) (Table 5). The relationship between these textural fractions is fundamental for understanding soil's physical and chemical characteristics and its potential impact on plant growth and environmental quality. The texture and structure of the soil were impacted by the quantity and size of the particles (loam, clay, and sand) [55].

Table 5. Correlation relationships between fraction characteristics and heavy metals.

		Sand	Silt	Clay
Cd	total	0.247	0.59 3 *	−0.762 **
Pb	content	0.259	0.512 *	−0.746 **
Cd	bioaccessibility	0.108	0.715 *	−0.832 **
Pb	form	−0.026	0.780 **	−0.800 **

* $p < 0.05$, ** $p < 0.01$.

Sand particles are the largest, followed by silt, and then clay, which has the smallest particle size. The relative proportions of these fractions determine the soil's texture, which in turn influences its water-holding capacity, drainage, and aeration.

Additionally, the textural fractions of soil can impact the adsorption and retention of contaminants, such as heavy metals, affecting their mobility and bioaccessibility (Table 5). For example, clay particles have a higher surface area and greater capacity to adsorb heavy metals than sand particles [13]. The way that plants absorb heavy metals can be altered by clay particles, which also raises the possibility of environmental pollution. Understanding the relationship between the textural fractions of soil is essential for evaluating the quality of the soil, as well as plant growth and health.

The relationship between cadmium and lead (total and bioaccessible forms) and the soil's sand, silt, and clay fractions is crucial for understanding the potential impact of cadmium/lead contamination on meadow plants and the overall ecosystem. The textural soil fractions, including sand, silt, and clay, significantly influence plants' mobility, availability, and the potential uptake of cadmium and lead. The distribution of cadmium/lead within different soil fractions, such as sand, silt, and clay, can impact their bioaccessibility to meadow plants as environmental contaminants in soil [13]. For example, clay particles' adsorption and retention of cadmium/lead can influence their mobility and bioaccessibility, potentially affecting plant uptake. Additionally, the textural soil characteristics may affect the movement and distribution of lead and cadmium, potentially impacting their availability to meadow plants. Assessing the possible dangers associated with cadmium/lead soil pollution and its impact on meadow plants require an understanding of the link between cadmium/lead and the textural fractions of the soil.

4. Conclusions

This study examined the migrations of selected metals in natural settings and how their behaviours are influenced by soil composition. Significant impacts on soil's total organic carbon were found for both cadmium content and the bioaccessible forms of cadmium and lead. Correlations were identified between bioaccessible heavy metal forms and the colour quotients of humic substances, indicating dependency on humic substance condensation levels in the soil. Humic substances' colour quotients ranged from 2 to 6 for humic acids and 6 to 14 for fulvic acids. Humic substances were found to immobilise soluble and replaceable heavy metal forms, affecting their environmental behaviour. Understanding humic substances, particularly humic acids, is crucial for influencing heavy metal transport, bioavailability, and solubility. Positive correlations were observed between bioaccessible forms and total contents of Cd/Pb and the soil silt fraction. In contrast, negative correlations were found with the clay fraction. Moreover, heavy metal content was noted to increase from clay to silt.

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