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Soil development and contents of selected trace elements in Technosols on dumps of historical iron ore mines in the Jaworzynka Valley, Tatra Mountains, southern Poland

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Abstract

From the Middle Ages until the 19th century, the Tatra Mountains were an important centre for the extraction and processing of metal ores. Technosols developing in the areas of historical mining in the Tatra Mountains are still poorly recognized, therefore this study aimed to determine the properties and mineral composition to classify the soils and find the effects of early pedogenic processes in Technosols on dumps of historical iron ore mining in the Jaworzynka Valley in the Tatra Mountains, south Poland. Another purpose of this investigation was to determine the total contents of Fe, Mn, and potentially toxic trace elements (As, Cd, Co, Cr, Cu, Ni, Pb, Zn) in these soils to assess the degree of contamination with these elements. Four soil profiles representing meadow plant communities (three profiles) and a spruce forest (one profile) were examined. The soils studied showed poor morphological development, characterized by the predominance of stony technogenic soil substrate (in C horizons) constituting carbonate-rich mine wastes, and the occurrence of the thin (up to several centimeters) O and A (or AC) horizons in the topsoil. The texture of the soil fine earth was loamy. The highest content of total organic carbon (TOC) and total nitrogen (TN) was recorded in the O horizons and in the A and AC horizons, which was related to soil organic matter (SOM) accumulation in the topsoil. The soils had a high pH (7.3 on average) in the subsoil. However, the topsoil had a lower pH (6.6 on average). The topsoil of a profile developed in a spruce forest had the lowest pH (4.5 on average). The studied Technosols contained carbonates throughout soil profiles (up to 57.6%). However, the profile developed in a spruce forest did not contain carbonates in the topsoil, which was most likely related to the leaching of carbonates due to strong acidification. The mineral composition of Technosols was diverse, with quartz, dolomite, and calcite as the most abundant phases. Magnetic susceptibility (χ) ranged from 2.5 to 49.4 $\times 10^{-8} \cdot m^3 \cdot kg^{-1}$, and frequency-dependent magnetic susceptibility (χ_{fd}) was in the range of 1.6–8.6%. Both χ, and χ_{fd} were the highest in the topsoil. Therefore, it is likely that some transformations of Fe-bearing minerals related to the advancement of soil-forming processes led to the magnetic enhancement of the topsoil. The total concentrations of potentially toxic trace elements (As, Cd, Co, Cr, Cu, Ni, Pb, Zn) in the soils were variable. However, their contents were low and generally did not exceed the permissible levels determined in Polish law. The studies showed that pedogenesis in the Technosols was in its initial stage and was the most advanced in the topsoil. The first manifestations of soil-forming processes in the investigated Technosols are: the accumulation of SOM in the surface soil horizons, topsoil acidification related to the SOM transformation, leaching of carbonates from the topsoil of the most acidified soils, and the magnetic susceptibility enhancement of the topsoil.

1. Introduction

The Tatra Mountains (the Tatras) are the highest mountain range of the Western Carpathians. They are located in the north-western part of the Carpathian ridge, on the border of Poland and Slovakia, Central Europe. They have an alpine character, distinguishing them from other parts of the Polish part of the Carpathians regarding relief, climatic conditions, and plant cover (Skrzydłowski, 2019). A complex geological structure and diverse geomorphological forms characterize the Tatras (Piotrowska, 2014, 2015). Based on geological and geomorphological features, they have been divided into three parts: the Western Tatras, the High Tatras, and the Bielskie Tatras (Moździerz and Skawiński, 2015).

Although the Tatras are now a protected area (Tatrzański Park Narodowy in Poland and Tatranský Národný Park in Slovakia, both are protected under the UNESCO World Network of Biosphere Reserves), in the past, these mountains were an important center for metal ore mining and smelting (Rączkowska, 2019). The first period of industrial development in the Tatras fell in the Middle Ages and lasted until the 18th century. At that time, the focus was primarily on extracting copper and silver ores (Jost, 1962; Molenda, 1989; Osika, 1987). The extraction of these metals stopped due to the scarcity of the ore deposits. The second period (from the second half of the 18th century until the end of the 19th century) was associated with the discovery and exploitation of iron and manganese ores, which initiated the intensification of mining and metallurgy in the Tatras (Jost, 1962). The largest mining centers in the Tatras occurred in the Kościeliska Valley, Chochołowska Valley, as well as in the Jaworzynka Valley and the Białego Valley. The major metallurgical centers were located in Old Kościelisko, on the Huciska Glade, and in Kuźnice. Mining and metallurgical activity in the Tatras ended in the 19th century (Jost, 2004).

Industrial wastes generated by mining and metallurgical activities were stored on the land surface near the mine or metallurgical plants. Mining waste consisted mainly of extracted rocks, which were unsuitable for further processing, while metallurgical waste was mainly slag and other by-products of ore smelting. Over time, the dumps of historical mining and metallurgy were overgrown with plants, which initiated the formation of technogenic soils (Technosols) on the surface of the waste disposal sites.

Technosols are currently one of the most intensively studied groups of soils (Leguédois et al., 2016; Daniell and van Deventer, 2018). These soils are formed, among others, from industrial wastes and are distinguished by specific properties and soil-forming processes that reflect their anthropogenic origin (Lal and Stewart, 2017; Rate, 2022; IUSS Working Group WRB, 2022). Technogenic soils occur, among others, in areas strongly modified by humans and are known under the acronym SUITMA (soils of urban, industrial, transport, mining, and military areas). The majority of previous studies have focused on the study of Technosols in urban and industrial areas in lowland and upland landscapes (Frouz et al., 2008; Huot et al., 2015; Uzarowicz et al., 2020a), whereas the properties, directions of soil-forming processes and the evolution of Technosols in the high-mountain environment, including the Tatra Mountains, are still poorly understood and require further research. Recent studies (Tarnawczyk et al., 2024) provide information on soil-forming factors controlling the properties of technogenic soils in the Tatras. However, these studies did not take into account the areas of historical iron ore mining in the Jaworzynka Valley.

Post-industrial wastes deposited on the land surface are often contaminated with potentially toxic trace elements (Karczewska and Bogda, 2006; Lottermoser, 2010; Karczewska and Kabała, 2017). The presence of large amounts of these elements in areas of historical mining can lead to contamination of the surrounding soils and groundwater. In addition, plants can take up these elements on a disposal site and incorporate them into the local trophic chain (Kabata-Pendias, 2010). Based on a few studies, the soils in the Tatra Mountains contain low concentrations of Cd, Co, Cr, Cu, Ni, Pb, and Zn, with Zn concentrations generally the highest among these elements (Korzeniowska and Krąż, 2020; Ciarkowska and Miechówka, 2022). Their contents and chemical forms vary with altitude, soil type, vegetation, and anthropogenic influence, with some ecological risks identified mainly from Cd, Pb, and Zn contamination (Kwapuliński et al., 2012; Paprotny et al., 2024). The contents of As in the Tatra Mountains' soils were poorly documented. Parent rock was the most important factor affecting the concentration of Zn, Pb and Cd in soils from the Polish Tatra Mountains (Ciarkowska and Miechówka, 2022). Although the concentrations of trace elements in non-anthropogenic soils were determined, the degree of contamination of technogenic soils in the Tatra Mountains has not been identified in detail so far (Ciarkowska and Miechówka, 2022). For this reason, and due to the occurrence of mine wastes in the Tatra Mountains, which can pose a threat to the local environment, there is still a need for such studies.

The aim of the study was (1) to determine physical and chemical properties, mineral composition, and classify technogenic soils (Technosols) on dumps of historical iron ore mining in the Jaworzynka Valley, Western Tatras, and (2) to determine the total contents of Fe, Mn, and potentially toxic trace elements (As, Cd, Co, Cr, Cu, Ni, Pb, Zn) in these soils. The obtained results (1) allowed for the identification of the first manifestations of soil-forming processes in the studied soils and (2) allowed for the assessment of the degree of their contamination with selected trace elements. The hypotheses assumed that (1) the studied technogenic soils show the initial stage of development, but the first manifestations of soil-forming processes can be found, and (2) the soils are not rich in potentially toxic trace elements.

2. Study area

2.1. Tatra Mountains characterization

The Tatras are characterized by the vertical climatic-plant zonality resulting from diverse climatic conditions depending on the altitude (Mirek and Piękoś-Mirkowa, 1992; Hess, 1996). The lowest vegetation-altitude zone is the lower montane zone (in Polish: regiel dolny), reaching up to about 1250 m a.s.l., characterized by the dominance of beech (*Fagus silvatica* L.) and fir (*Abies alba* Mill.), as well as spruce (*Picea abies* (L.) H.Karst), which is an effect of former forest management (Skrzydłowski, 2019). The lower montane zone is characterized by the mean annual air temperature (MAAT) from 6°C in the lower part to 4°C in the upper part. Snow cover lasts for 140 days per year on average, and the annual rainfall is about 1400 mm. At an altitude of 1250–1550 m a.s.l., the upper montane zone (in Polish: regiel górny) extends, where the dominant tree species is spruce. This zone is characterized by the MAAT of 4°C at the lower part and 2°C at the upper timberline. Mean annual precipitation amounts to about 1600 mm, and snow cover lasts, on average, for 180 days per year. The dwarf pine (*Pinus mugo* Turra) shrubs spread above the upper forest line in the so-called subalpine zone at an altitude of 1550 to 1800 m a.s.l. This zone is characterized by the MAAT from 2°C at the forest line to 0°C. Snow cover lasts about 215 days per year, and annual precipitation amounts to about 1800 mm (Skrzydłowski, 2019). The alpine zone extends at altitudes from 1800 to 2300 m a.s.l. It is characterized by the MAAT of about –2°C. Snow cover remains in this zone for about 250 days per year, and the annual precipitation reaches 1750 mm. The vegetation in this zone is represented by high-mountain grasslands. Above 2300 m a.s.l., there is a subnival zone, where the MAAT is –4°C, and snow cover lasts for 290 days. Mosses and lichens are the predominant vegetation in the subnival zone (Piękoś-Mirkowa and Mirek, 1996). The highest peak of the Tatras is Gerlach (2655 m a.s.l.) located in Slovakia, while on the Polish side it is Rysy (2503 m a.s.l.).

The soil cover of the Tatras and its spatial differentiation mainly depend on the bedrock, plant cover, as well as geomorphological settings, and the intensity of morphogenetic processes (Komornicki and Skiba, 1996; Drewnik, 2008). The typical bedrock in the Tatras comprises of igneous rocks (granitoid), sedimentary rocks (e.g., limestones, dolomites, shales, sandstones), and metamorphic rocks (e.g., gneisses). In places where geomorphological processes are particularly active, usually above the upper forest line, the soil cover is characterized by fragmentation (Komornicki and Skiba, 1996; Skiba, 1996). In the lower parts of the Western Tatras, in places where carbonate rocks occur, rendzinas (Rendzic Leptosols) and brown soils (Cambisols) are formed, constituting fertile habitats for mountain beech and fir forests (Oleksynowa et al., 1977; Miechówka and Drewnik, 2018; Ciarkowska and Miechówka, 2022). In the higher parts of the mountains, podzolic soils (Podzols) are formed on non-carbonate rocks (Komornicki and Skiba, 1996). In the subalpine zone, where a large amount of needles is supplied, acidic (pH 3.5–4.0) organic horizons are formed in the upper parts of the soil profiles, which are formed regardless of the bedrock (Miechówka and Ciarkowska, 1998; Wasak and Drewnik, 2012, 2015). They are characterized by significant thickness and consist of poorly decomposed organic matter. The slower decomposition of needles results from harsh climatic conditions, which cause low microbiological activity (Wasak and Drewnik, 2012; Wasak, 2014). Initial soils, including Leptosols and Regosols, predominate above the timberline. Additionally, remnants of cryogenic soils formed due to processes occurring during former cold periods can be found in the alpine and subnival zones of the Tatras (Oleksynowa and Skiba, 1977).

2.2. Jaworzynka Valley

The study area was located in the upper part of the Jaworzynka Valley (Fig. 1) in the Western Tatras. This valley is characterized by a vegetation distribution reflecting the climatic and plant zonation of the Tatras. The majority of the valley is located in the forest montane zone of the Tatras, at an altitude of about 1000–1500 m a.s.l. Predominating types of forest include mixed and coniferous forests, in which the main tree species is spruce, and in the lower parts, there are also fir and beech (Piękoś-Mirkowa and Mirek, 1996). At about 1400 m a.s.l., dense spruce stands change into dense thickets of dwarf pine, which form a natural boundary between the upper montane zone and the subalpine zone. In the past, intensive sheep grazing was carried out in the Jaworzynka Valley, which transformed the local vegetation cover (Ciurzycki, 2003; Wasak and Drewnik, 2015; Skrzydłowski, 2019).

In the upper part of the Jaworzynka Valley, in the so-called Żleb pod Czerwienicą, intensive mining activity was carried out in the years 1766–1871. The most productive iron ore mines in the Tatras occurred there. About 300–400 tons of ore with 30–32% iron content were extracted annually from the mines (Jost, 1962). The remnants of old mines in the Jaworzynka Valley are few, but still clearly visible in the landscape. These are primarily old mining routes (in Polish: Drogi Hawiarskie) and mine waste dumps (Jost, 1962). The dumps are currently overgrown with vegetation from natural plant succession.

Shepherding and mining have destroyed the soil cover in the Jaworzynka Valley (Wasak and Drewnik, 2015). In some parts of the valley, including the slopes of Skupniowy Upłaz, there are numerous larch (*Larix decidua* Mill.) plantings, the purpose of which is to stabilize the ground on the slopes and protect the soil from erosion (Skrzydłowski, 2019).

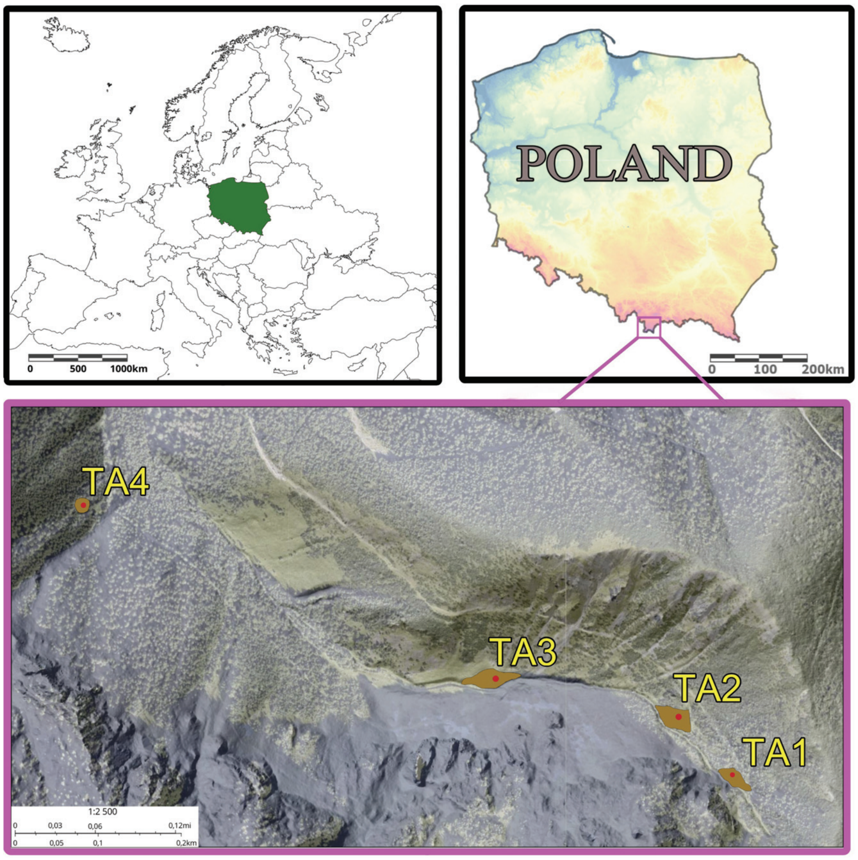

Fig. 1. Location of the study area and soil profiles (source: https://geologia.pgi.gov.pl/haldy/)

3. Materials and methods

Four research sites were selected for the study in the upper part of the Jaworzynka Valley (Fig. 2). The sites were located on small dumps in the area of abandoned iron ore mines. Field works included the excavation of four soil profiles on the dumps (profiles TA1, TA2, TA3, TA4). The locations of the soil profiles were determined after prior field reconnaissance. Each of the four soils representing four separate dumps was described and sampled according to the guidelines of the World Reference Base for Soil Resources (IUSS Working Group WRB, 2022). In each soil profile, soil horizons were identified, from which soil samples were taken for laboratory analyses.

In the laboratory, soil samples were stripped of plant residues (living roots, branches, and organic debris) and then dried at room temperature. After drying, soil samples were sieved through a 2 mm sieve to separate rock fragments (>2 mm) from the fine earth (<2 mm). Small aliquots of fine earth from each soil sample were ground in a zirconium mortar.

The physical and chemical analyses described below were performed on the fine earth soil materials. The texture was determined using the Bouyoucos hydrometer method modified by Casagrande and Prószyński (Warzyński et al., 2018). Soil textural classes were determined according to the USDA classification (Soil Science Division Staff, 2017). Soil pH was measured using the potentiometric method in H_2O and 1M KCl (Pansu and Gautheyrou, 2006). The Scheibler volumetric method was used to determine the percentage of calcium carbonate equivalent. The total organic carbon (TOC) content in the Oi, Oe, and Oa, as well as total nitrogen (TN) and total sulphur (TS) in all soil samples, was determined by CHNS elemental analyzer (the vario MACRO cube, Elementar). The TOC concentration in mineral (i.e., A, AC, Bw and C) horizons was analyzed using the dichromate oxidation technique (modified Tyurin method; digestion reagent: $K_2Cr_2O_7$ and H_2SO_4; titrant: $FeSO_4·7H_2O$). The C/N ratio was calculated based on the TOC and TN content.

Total potential acidity (TPA) (so-called hydrolytic acidity) was determined according to the Kappen method (extraction using 1 mol·dm^{-3} calcium acetate and titration using 0.1 mol·dm^{-3} NaOH). Exchangeable bases (Ca^{2+}, Mg^{2+}, K^+, and Na^+) were extracted using ammonium chloride (pH = 8.2) (Ostrowska et al., 1991). Content of exchangeable bases (Ca^{2+}, Mg^{2+}, K^+, and Na^+) in extracts was determined using the inductively coupled plasma – optical emission spectrometry (ICP–OES) method (Perkin Elmer, Avio 200). The sum of exchangeable bases (EB) was then calculated. Cation exchange capacity (CEC) was obtained as the sum of TPA and EB. Base saturation (BS) was calculated as a percentage of EB in CEC.

The mass-specific magnetic susceptibility (χ), i.e., volume magnetic susceptibility (κ) normalized by a mass unit, was measured using a multifunction Kappabridge MFK1-FA (AGICO, Brno, Czech Republic) at two frequencies of magnetic field (976 and 15,600 Hz) with an intensity of 200 Am^{-1}. The mass of parameter was measured three times for each sample, and the average value was calculated. The samples were measured with an accuracy of ±1 mg to calculate χ. The percentage of frequency-dependent magnetic susceptibility (χ_{fd} given in %) was calculated from the χ values measured at low and high frequencies of the magnetic field. The apparatus ratio (set at 0.8), which depends on the frequencies at which the MFK1-FA operates, was included in the final calculation of χ_{fd} (Hrouda, 2011). The χ_{fd} parameter was then utilized to assess the contribution of ultrafine superparamagnetic grains (SP) with a size of < 0.03 μm, which can reflect the development of pedogenic processes in soil. The magnetic analyses were performed at the Department of Magnetism, Institute of Geophysics, Polish Academy of Sciences, Warsaw.

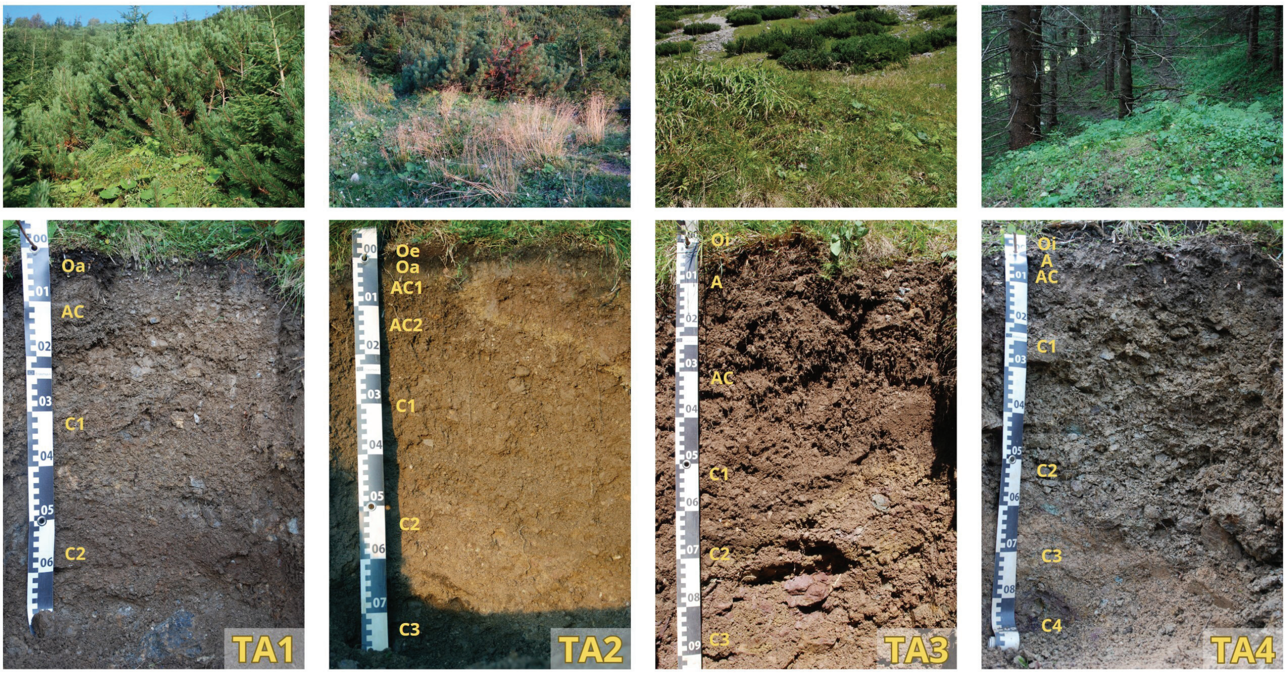

Fig. 2. Morphology of the studied soil profiles and their surroundings

Fine-earth (<2 mm) sample bulk mineral composition was determined using the powder X-ray diffraction method (XRD). The samples were powdered in an agate mortar prior to analyses. The Bruker AXS D5005 diffractometer was used. It was equipped with the KRISTALLOFLEX® 760 X-ray generator, vertical goniometer, 1 mm divergence slit, 2 mm anti-scatter slit, 0.6 mm detector slit, a graphite diffracted-beam monochromator, and a detector (scintillation counter). The CoKα radiation was applied with a voltage of 40 kV and 30 mA current. Random mounts of the ground materials were scanned from 3 to 70°2θ at a counting time of 1 s per 0.02° step on a rotating stage. XRD analyses were performed in the Department of Soil Science, Warsaw University of Life Sciences – SGGW (WULS–SGGW), Poland. Mineral symbols were used in accordance with international standards (Warr, 2021).

Total phosphorus (TP) and selected element contents (Fe, Mn, Zn, Pb, Cu, Cd, Ni, Co, Cr, As) were determined in soil samples. The samples were digested by microwave mineralization (Milestone Ethos UP) in the following acids: 2 ml HF + 2 ml HNO_3 + 6 ml HCl. Concentrations of elements in the extracts were measured by ICP–OES (Perkin Elmer Avio 200). The analyses and blanks were conducted in duplicates.

4. Results

4.1. Soil morphology, physical and chemical properties, and soil classification

The O and A horizons occurred in the upper parts of the soil profiles (Table 2). The major soil substrates of the studied Technosols were mine wastes from iron ore mines. Lithological discontinuities were distinguished in the subsoil of TA1 and TA4 profiles (Fig. 2) at about 40–50 cm and 60–70 cm, respectively. Moreover, a layering was typical of the TA2 profile (Fig. 2). The fine earth of soils had a texture of sandy loam and loam (Table 2).

The pH_{H2O} values of the studied soils ranged from 4.3 to 8.5 (Table 3). High pH_{H2O} (up to 8.5) was characteristic of soils in the TA1, TA2, and TA3 profiles. The exception was profile TA4, which showed strong acidification (pH_{H2O} ranging from 4.4 to 4.9) in surface soil horizons, whereas it had high pH_{H2O} (6.3–8.4) in the subsoil. The carbonate content in the studied soils was up to 57.6% (profile TA2, C2 horizon). A high carbonate content was found in the TA1, TA2, and TA3 profiles, whereas in profile TA4, carbonates occurred only at a depth below 60 cm. The TOC content in the O horizons ranged from 12.4 to 30.9%, while in the mineral horizons (A, AC, and C) it was from 0.01 to 3.1% (Table 3). Total nitrogen (TN) content in the studied soils ranged from 0.03% to 1.46%. The C/N ratio in litter was 15.3, on average, while in mineral horizons, it was 4.4, on average. The exception was the AC2 horizon in the TA2 profile, which had a C:N ratio equal to 50. Such a high C:N ratio indicates that the AC2 horizon in the TA2 profile might contain some charcoals, which, however, were not clearly identified in the soil sample. Total sulphur (TS) and total phosphorus (TP) contents ranged from 0.01 to 0.17% and from 0.07 to 0.29%, respectively (Table 3).

The soils studied were classified according to the WRB classification as different variants of Spolic Technosols (Table 1).

4.2. Magnetic susceptibility of soil

The magnetic susceptibility of the investigated soils ranged from 2.5 to 49.4 × 10^{-8} $m^3 kg^{-1}$ (Table 2). In each profile, the highest values of χ were observed in the topsoil. The frequency-de-

Table 1
Field settings and classification of the studied soil profiles

Soil profile	Soil classification (WRB 2022)	Geographical position (GPS)	Altitude (m a.s.l.)	Approximate age of soil	Geomorphological settings	Vegetation and predominating plants
TA1	Spolic Technosol (Loamic, Eutric, Dolomitic, Ochric, Hyperartefactic, Skeletic)	49°15.045' N 20°00.138' E	1514	~ 150 years	Slope 30–40°, exposure NW	Meadow in the vicinity of *Pinus mugo* shrubs Predominating plants: *Pinus mugo, Picea abies, Carex nigra, Tussilago farfara, Dryas octopetala, Vaccinium myrtillus, Trifolium repens, Bryophyta*
TA2	Spolic Technosol (Loamic, Eutric, Epidolomitic, Ochric, Hyperartefactic, Skeletic)	49°15.080' N 20°00.089' E	1479	~ 150 years	Slope 25°, exposure W	Meadow in the vicinity of *Pinus mugo* shrubs Predominating plants: *Carex nigra, Tussilago farfara, Trifolium sp., Bryophyta*
TA3	Spolic Technosol (Loamic, Eutric, Epidolomitic, Endocalcaric, Ochric, Hyperartefactic, Skeletic)	49°15.110' N 19°59.908' E	1375	~ 150 years	Slope 40°, exposure S	Alpine meadow Predominating plants: C*arex nigra, Tussilago farfara, Cirsium Mill., Carlina acaulis*
TA4	Spolic Technosol (Loamic, Epidystric, Endoeutric, Humic, Hyperartefactic, Skeletic)	49°15.225' N 19°59.496' E	1270	~ 150 years	Flat area on a dump surface	Spruce forest Predominating plants: *Picea abies*, sparse understory with *Bryophyta, Polypodiopsida Cronquist*

Table 2
Physical properties and magnetic susceptibility of the studied soils

Profile	Horizon	Depth (in cm)	Munsell colour (moist)	% of rock fragments	% of fraction			Soil textural class (USDA)	χ_{lf}	χ_{hf}	χ_{fd} (%)
					2.0–0.05 mm	0.05–0.002 mm	< 0.002 mm		($\times10^{-8}\cdot m^3\cdot kg^{-1}$)		
TA1	Oa	5–0	7.5YR 2.5/2	–	–	–	–	–	19.1	18.1	4.1
	AC	0–10	7.5YR 4/2	74.4	51	36	15	L	7.2	6.8	4.6
	C1	10–40	7.5YR 4/4	68.4	62	27	15	SL	8.5	8.2	2.4
	C2	40–65	7.5YR 3/3	66.4	55	29	16	SL	11.3	11.0	1.7
TA2	Oe	4–2	7.5YR 2.5/3	–	–	–	–	–	49.4	47.1	3.8
	Oa	2–0	7.5YR 2.5/2	–	–	–	–	–	23.7	22.6	4.1
	AC1	0–4	7.5YR 2.5/3	56.0	60	30	10	SL	6.6	6.4	3.0
	AC2	4–15	7.5YR 3/4	48.4	55	35	10	SL	4.0	3.9	3.5
	C1	15–35	7.5YR 3/4	64.9	66	19	15	SL	6.7	6.6	1.6
	C2	35–65	7.5YR 3/4	59.3	72	17	11	SL	5.8	5.6	2.0
	C3	65–75	7.5YR 3/3	69.2	59	26	15	SL	10.6	10.4	1.7
TA3	Oi	2–0	–	–	–	–	–	–	–	–	–
	A	0–15	10YR 3/4	60.8	59	30	11	SL	8.4	8.1	3.5
	AC	15–45	10YR 4/4	67.3	65	25	10	SL	5.4	5.2	3.1
	C1	45–60	7.5YR 4/4	68.9	61	29	10	SL	5.9	5.7	3.3
	C2	60–80	7.5YR 4/3 and 10YR 5/4	64.7	54	31	15	SL	5.7	5.6	1.9
	C3	80–105	5YR 4/3. 7.5YR 4/3 and 10YR 5/4	65.5	59	26	15	SL	6.2	6.0	1.7
TA4	Oi	1–0	–	–	–	–	–	–	–	–	–
	A	0–5	10YR 3/2	58.9	71	21	8	SL	40.2	36.0	8.6
	AC	5–10	10YR 3/3	66.7	68	22	10	SL	33.8	30.8	7.5
	C1	10–40	2.5Y 5/4	69.5	67	22	11	SL	4.5	4.4	2.1
	C2	40–60	2.5Y 5/3	82.5	72	21	11	SL	3.7	3.6	1.6
	C3	60–80	10YR 5/4	46.3	68	21	11	SL	2.5	2.4	2.4
	C4	80–90	5YR 4/3	61.3	68	21	11	SL	6.5	6.4	1.9

Explanations: – not analysed; L – Loam; SL – Sandy Loam; χ_{lf} – magnetic susceptibility measured in 976 Hz; χ_{hf} – magnetic susceptibility measured in 15616 Hz; χ_{fd} – the frequency-dependent magnetic susceptibility.

pendent magnetic susceptibility ranged from 1.6 to 8.6% and showed the highest values in the upper parts of the soil profiles. The highest values of $\chi_{fd\%}$, ranging from 7.5 to 8.6%, were observed in the topsoil of the TA4 profile.

4.3. Sorption properties

The highest TPA was measured in the upper part of the TA4 profile (12.6 and 15.2 cmol(+)·kg^{-1}), while TPA did not exceed 1.09 cmol(+)·kg^{-1} in the TA1, TA2 and TA3 profiles and in the subsoil of the TA4 profile (Table 4). The EB ranged from 3.69 to 19.74 cmol(+)·kg^{-1}. The predominant base cations in the soils studied were calcium and magnesium, followed by potassium and sodium. The cation exchangeable capacity (CEC) of the analysed soils ranged from 4.89 to 20.26 cmol(+)·kg^{-1}. Base saturation (BS) in most soil horizons exceeded 90%. Only in the topsoil (A and AC) of the TA4 profile BS was relatively low (about 28%).

4.4. Mineral composition

Quartz was the predominant mineral in all soils studied. In some horizons (e.g., in the upper parts of profiles TA1 and TA2), the dominant mineral was dolomite (Table 5). Calcite was also an important mineral in the investigated soils. Technosols examined contained admixtures of muscovite,

Table 3
Chemical properties of the studied soils

Profile	Horizon	Depth (in cm)	pH_{H2O}	eq. $CaCO_3$ (%)	TOC (%)	TN (%)	C/N	TS (%)	TP (%)
TA1	Oa	5–0	6.8	–	12.35	0.66	18.7	0.07	0.18
	AC	0–10	7.5	47.3	1.51	0.18	8.4	0.03	0.15
	C1	10–40	8.0	19.6	0.43	0.09	4.8	0.02	0.17
	C2	40–65	8.1	31.2	0.01	0.04	0.3	0.01	0.11
TA2	Oe	4–2	6.6	–	30.90	2.27	13.6	0.17	0.29
	Oa	2–0	6.6	–	19.91	1.46	13.6	0.13	0.23
	AC1	0–4	7.7	50.5	0.83	0.11	7.5	0.03	0.10
	AC2	4–15	8.1	19.3	2.50	0.05	50.0	0.02	0.07
	C1	15–35	8.2	17.5	0.04	0.05	0.8	0.02	0.10
	C2	35–65	8.5	57.6	0.01	0.03	0.3	0.02	0.11
	C3	65–75	8.3	8.3	0.02	0.04	0.5	0.03	0.13
TA3	Oi	2–0	–	–	–	–	–	–	–
	A	0–15	7.5	16.4	1.27	0.14	9.1	0.03	0.17
	AC	15–45	8.1	16.4	0.53	0.08	6.6	0.02	0.14
	C1	45–60	8.1	20.1	0.65	0.10	6.5	0.03	0.16
	C2	60–80	8.5	15.5	0.14	0.04	3.5	0.02	0.13
	C3	80–105	8.5	11.6	0.11	0.04	2.8	0.03	0.14
TA4	Oi	0–1	4.9	–	–	–	–	–	–
	A	0–5	4.3	–	3.13	0.34	9.2	0.06	0.18
	AC	5–10	4.4	–	2.07	0.24	8.6	0.07	0.17
	C1	10–40	6.3	<	0.13	0.05	2.6	0.07	0.21
	C2	40–60	6.7	<	0.09	0.05	1.8	0.08	0.14
	C3	60–80	8.1	2.1	0.09	0.03	3.0	0.05	0.15
	C4	80–90	8.4	7.3	0.16	0.05	3.2	0.03	0.17

Explanations: – not analyzed; < – below detection limit; TOC – total organic carbon; TN – total nitrogen; TS – total sulphur; C/N – the TOC to TN ratio.

chlorite, Fe oxyhydroxides (goethite and lepidocrocite), and orthoclase. Pyrite and jarosite were likely in some soil horizons (Table 5).

4.5. Total concentrations of selected elements

Iron was present in all soil profiles, and its content was in the range of 20277–132095 mg·kg^{-1} (43111 mg·kg^{-1}, on average). The total content of Mn was from 823 to 21601 mg·kg^{-1}. Manganese reached the highest concentration in the C3 horizon of the TA2 profile. Arsenic was present only in some horizons of TA1 and TA2 profiles, with a maximum concentration of 41.1 mg·kg^{-1} (Table 6). Cadmium occurred throughout the TA1 and TA2 profiles, but it was not detected in the subsoils of TA3 and TA4 profiles. Concentrations of Cd were from 0.1 to 7.8 mg·kg^{-1}. Cobalt content in the studied Technosols was in the range of 6.5–16.8 mg·kg^{-1}. The highest concentration was measured in the C1 horizon of the TA1 profile. Chromium was present in all the soil profiles studied (18–79.7 mg·kg^{-1}). Copper content was in the range of 0.4–38.1 mg·kg^{-1}. Copper was absent in the C1 horizon of the TA3 profile and in the C1, C2, C3 and C4 horizons of the TA4 profile. Nickel contents ranged from 12.5 to 43.9 mg·kg^{-1}, and reached the maximum value in the C3 horizon of the TA2 profile. The concentrations of Pb were from 4.3 to 118.9 mg·kg^{-1}. The highest Pb content was recorded in the C1 horizon of the TA1 profile. Zinc was present in contents from 0.8 to 479.3 mg·kg^{-1}. The highest Zn content was measured in the C3 horizon of the TA2 profile, while in the TA4 profile, it was not detected in the C1 and C2 horizons (Table 6).

Table 4
Sorption properties of the studied soils

Profile	Horizon	Depth (in cm)	TPA	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	EB	CEC (TPA+EB)	BS (%)
			$cmol_{(+)} \cdot kg^{-1}$							
TA1	Oa	5–0	1.09	7.78	2.44	0.10	0.026	10.35	11.44	90.50
	AC	0–10	0.64	12.27	3.85	0.15	0.026	16.29	16.93	96.23
	C1	10–40	0.34	11.48	2.77	0.08	0.022	14.36	14.70	97.69
	C2	40–65	0.26	14.82	2.21	0.07	0.026	17.13	17.39	98.49
TA2	Oe	4–2	–	12.43	3.84	0.29	0.030	16.58	16.58	100.03
	Oa	2–0	–	10.25	2.95	0.17	0.039	13.42	13.42	99.97
	AC1	0–4	0.45	13.24	1.70	0.07	0.030	15.04	15.49	97.11
	AC2	4–15	0.34	14.58	1.74	0.03	0.026	16.38	16.72	98.01
	C1	15–35	0.30	7.978	1.18	0.04	0.022	9.21	9.51	96.84
	C2	35–65	0.23	10.09	1.00	0.02	0.013	11.13	11.35	97.98
	C3	65–75	0.53	17.51	2.15	0.05	0.026	19.74	20.26	97.41
TA3	Oi	2–0	–	–	–	–	–	–	–	–
	A	0–15	0.45	11.79	2.01	0.11	0.030	13.94	14.39	96.90
	AC	15–45	0.41	12.56	1.60	0.05	0.013	14.24	14.65	97.15
	C1	45–60	0.41	13.63	2.01	0.08	0.061	15.78	16.19	97.44
	C2	60–80	0.26	16.26	2.12	0.10	0.035	18.53	18.79	98.59
	C3	80–105	0.30	16.47	1.98	0.09	0.039	18.58	18.88	98.43
TA4	Oi	0–1	–	–	–	–	–	–	–	–
	A	0–5	15.15	3.46	0.86	0.14	0.026	4.48	19.63	22.82
	AC	5–10	12.56	2.92	0.67	0.09	0.017	3.69	16.25	22.71
	C1	10–40	0.75	7.64	0.52	0.11	0.052	8.32	9.07	91.68
	C2	40–60	0.68	3.74	0.40	0.04	0.030	4.22	4.89	86.16
	C3	60–80	0.41	6.53	0.48	0.02	0.022	7.05	7.46	94.45
	C4	80–90	0.41	14.06	1.75	0.13	0.043	15.98	16.39	97.50

Explanations: – not analyzed; TPA – total potential acidity (hydrolytic acidity); EB – sum of exchangeable bases; CEC – cation exchange capacity; BS – base saturation.

5. Discussion

5.1. Manifestations of soil-forming processes in the studied soils

Spolic Technosols occurring on surfaces of mine and industrial waste dumps are often young soils. Typically, they have been formed in the last few decades or centuries, in particular in the 20th century. Therefore, typically they are very poorly developed and do not show visible manifestations of pedogenic processes (Neel et al., 2003; Uzarowicz et al., 2017; Ortega et al., 2022). Nevertheless, the first effects of soil-forming processes are observed in Technosols. They are expressed by the accumulation of soil organic matter (Józefowska et al., 2017), changes in the chemical properties of the soil substrate (Huot et al., 2013), mineral transformations (Grünewald et al., 2007; Uzarowicz and Skiba, 2011), as well as an increase in soil biological activity (Pająk et al., 2018; Uzarowicz et al., 2020b). Although soil-forming processes in Spolic Technosols have become increasingly better understood in recent years (Bini and Gaballo, 2006; Huot et al., 2015; Leguédois et al., 2016), new studies are still needed to fully understand the directions and rates of soil-forming processes in Spolic Technosols occurring in different environments on Earth, including high-mountain areas, such as the Tatra Mountains.

Previous studies on Spolic Technosols have focused primarily on urban and post-industrial zones in lowlands and up-

Table 5
Mineral composition of the studied soil profiles based on powder XRD analyses

Profile	Horizon	Depth (in cm)	Minerals
TA1	Oa	5–0	–
	AC	0–10	Dol, Qz, Ms, Cal, Chl
	C1	10–40	Qz, Dol, Ms, Cal, Or
	C2	40–65	Qz, Dol, Cal, Ms, Gth, Lpc
TA2	Oe	4–2	–
	Oa	2–0	–
	AC1	0–4	Dol, Qz, Cal, Ms, Gth, Chl
	AC2	4–15	Dol, Qz, Cal, Ms, Py
	C1	15–35	Qz, Ms
	C2	35–65	Qz, Cal, Dol, Ms
	C3	65–75	Qz, Cal, Dol, Ms, Gth, Lpc
TA3	Oi	2–0	–
	A	0–15	Qz, Dol, Ms, Cal
	AC	15–45	Qz, Dol, Ms, Cal
	C1	45–60	Qz, Dol, Ms, Cal
	C2	60–80	Qz, Cal, Dol, Ms, Chl, Or
	C3	80–105	Qz, Cal, Ms, Chl, Dol, Or
TA4	Oi	0–1	–
	A	0–5	Qz, Ms
	AC	5–10	Qz, Ms, Jrs
	C1	10–40	Qz, Ms, Jrs
	C2	40–60	Qz, Ms, Jrs
	C3	60–80	Qz, Ms, Dol
	C4	80–90	Qz, Ms, Dol, Cal

Explanations: – not analysed. Mineral symbols: Cal – calcite, Chl – chlorite, Dol – dolomite, Gth – goethite, Jrs – jarosite, Lpc – lepidocrocite, Ms – muscovite, Or – orthoclase, Py – pyrite, Qz – quartz.

lands (Huot et al., 2015; Uzarowicz et al., 2020a). One of the first studies on the genesis of Spolic Technosols in high mountains was the study by Tarnawczyk et al. (2024), in which the authors focused on determining soil-forming factors that control the properties and processes occurring in high-mountain Technosols, using the soils from the Tatras as an example. The studies presented herein supplement the aforementioned investigation with soils occurring in the area of the abandoned iron ore mines in the Jaworzynka Valley. Tarnawczyk et al. (2024) divided the soils occurring in the areas of historical mining and metallurgy in the Tatra Mountains into groups based on their chemical properties and mineral composition. The soils found on the dumps of historical iron ore mining in the Jaworzynka Valley have the features of Technosols from group I, because the soils studied were characterized by a large share of limestone fragments, high pH_{H2O} (average 7.3), carbonate content (20% on average) due to the occurrence of carbonates (dolomite and calcite) in the mineral composition, as well as high base saturation (88.7% on average). Taking into account these properties, the studied Technosols have very much in common with rendzina soils (Rendzic Leptosols) occurring naturally on the outcrops of carbonate rocks in the Tatras (Miechówka, 1989; Komornicki and Skiba, 1996; Miechówka and Ciarkowska, 1998; Miechówka and Drewnik, 2018).

The studied Technosols are young (about 150 years) (Table 1) and represent soils in the initial stage of pedogenesis. It is corroborated by the simple morphology of soil profiles (A or AC horizons in the topsoil and C horizons in the subsoil)

Table 6
Total concentrations of Fe and selected trace elements in the studied soils (in mg·kg^{-1})

Profile	Horizon	Depth (in cm)	As	Cd	Co	Cr	Cu	Fe	Mn	Ni	Pb	Zn
*Permissible contents of element**			50	5	50	500	300	–	–	300	500	1000
*Permissible contents of element***			*20*	*3*	*30*	*300*	*150*	–	–	*100*	*100*	*300*
TA1	Oa	5–0	39.6	2.2	10.1	32.7	12.4	42705	4937	15.3	69.3	94.1
	AC	0–10	41.1	1.1	11.5	45.5	9.9	29435	2034	20.0	30.2	82.1
	C1	10–40	15.6	3	16.8	46.5	13	71812	10446	22.5	118.9	34.0
	C2	40–65	< LOQ	4.5	14.8	36.6	11.5	117536	21236	18.8	58.0	20.1
TA2	Oe	4–2	5.4	2.1	6.5	23.6	12	23938	3572	14.0	60.8	159.7
	Oa	2–0	2.9	2.2	8.2	28.2	13.8	39197	4524	16.2	75.0	149.0
	AC1	0–4	21.4	1.8	10	25.8	21.1	48071	9128	20.1	66.2	111.2
	AC2	4–15	< LOQ	1.7	7.1	18.1	13.9	44000	6638	16.9	74.3	97.4
	C1	15–35	4.4	2.2	11.5	23.3	0.4	65853	7890	15.1	< LOQ	57.1
	C2	35–65	< LOQ	1.2	9.3	18.0	1.7	48314	6769	12.5	< LOQ	58.0
	C3	65–75	< LOQ	7.8	15.3	34.2	38.1	132095	21601	43.9	69.2	479.3
TA3	Oi	2–0	–	–	–	–	–	–	–	–	–	–
	A	0–15	< LOQ	1	13.6	43.4	8.2	39016	3965	19.3	39.3	56.7
	AC	15–45	< LOQ	0.5	11	31.6	3.2	29740	2805	16.1	22.4	31.7
	C1	45–60	< LOQ	0.5	13.1	37.4	< LOQ	25740	4707	22.7	46.3	83.9
	C2	60–80	< LOQ	0.1	13.2	51.7	2.3	22345	823	23.0	< LOQ	45.1
	C3	80–105	< LOQ	< LOQ	14.2	50.6	15.3	24060	1022	24.9	4.3	51.0
TA4	Oi	0–1	–	–	–	–	–	–	–	–	–	–
	A	0–5	< LOQ	0.5	13.6	62.6	< LOQ	22150	983	19.7	28.8	62.5
	AC	5–10	< LOQ	0.8	14.7	68.9	1.4	27718	998	22.3	14.3	64.5
	C1	10–40	< LOQ	< LOQ	13.7	56.7	< LOQ	20277	1633	21.1	< LOQ	< LOQ
	C2	40–60	< LOQ	< LOQ	8.7	37.6	< LOQ	21031	1128	12.7	< LOQ	< LOQ
	C3	60–80	< LOQ	< LOQ	10.5	36.7	< LOQ	21065	1117	13.0	< LOQ	0.8
	C4	80–90	< LOQ	< LOQ	13.8	79.7	< LOQ	26416	853	34.5	< LOQ	31.7

Explanations: * for the land group no. II and the depth of 0–25 cm according to the Regulation of the Ministry of Climate and Environment (2024); ** for the land group no. II and the depth below 25 cm according to the Regulation of the Ministry of Climate and Environment (2024); < LOQ – below the limit of quantification.

(Fig. 2). Despite the fact that all the studied soil profiles are characterized by a poor degree of development, they show certain manifestations of soil-forming processes. The most recognizable effect of soil-forming processes is the accumulation of soil organic matter (SOM) in the topsoil, which leads to the formation of humus (A) horizons. This is expressed by the concentration of TOC and TN in the uppermost soil horizons of the studied soils (Table 3). The content of TOC in the studied soils is relatively low in comparison with rendzina soils in the Tatra Mountains (Miechówka and Drewnik, 2018). This fact confirms that the studied Technosols represent an initial stage of development. SOM accumulation is a common process in soils. This is one of the first manifestations of soil-forming processes on freshly deposited sediments, including mine and industrial wastes, which undergo natural plant succession (Badin et al., 2009; Monserie et al., 2009; Séré et al., 2010; Uzarowicz et al., 2017).

Another manifestation of soil-forming processes is the acidification of the topsoil generated by the transformation of SOM in the studied soils. This is a typical process in soils, as the organic matter decomposition results in the production of organic acids, which causes acidification (Alriksson and Olsson, 1995).

The type of organic matter, depending on the vegetation cover, significantly affects the intensity of acidification. The SOM-bearing horizons in Technosols developed under meadows had a circumneutral reaction. This is a feature recognized in part of the rendzina soils in the Tatra Mountains (Miechówka and Drewnik, 2018). On the other hand, the highest acidity in the surface soil horizons was typical of profile TA4 located on a dump covered with spruce. This tree species causes strong acidification even in soils developed from carbonate-rich parent materials, and this is a process recognized in the soils in the Tatras (Wasak and Drewnik, 2012) (Table 3). The needles of coniferous trees show a special ability to soil acidification, as they are characterized by a high content of difficult-to-decompose compounds, such as lignin and cuticular wax (Dziadowiec, 1990). Their decomposition leads to a decrease in soil pH. Plants also contribute to the increase in soil acidity by releasing root exudates into the soil (Wasak and Drewnik, 2012).

Strong soil acidification caused by the decomposition of SOM in the soil causes the leaching of carbonates from the upper parts of soil profiles (Gonet et al., 2015). Carbonates are relatively soluble minerals in the soil environment, and their dissolution/recrystallization cycles and translocation in the soil are the manifestation of soil-forming processes (Zamanian et al., 2016). The leaching of carbonates from the topsoil was likely identified in profile TA4 (Table 3). This phenomenon in that soil is related to the action of organic acids as a result of spruce needle decomposition (Skiba, 1985).

A reliable indicator of soil-forming processes appears to be the magnetic susceptibility (χ), which is dependent on the content of magnetic particles and their mineralogy, as well as the distribution of the size of magnetic grains (domain state) (Thompson and Oldfield, 1986). The χ values in the studied Technosols (Table 2) were relatively low and they are within the ranges for technogenic soils developed in the area of historical Fe and Mn mines at Huciańskie Banie in the Tatra Mountains (Tarnawczyk et al., 2024). As the highest values of χ observed in the surface parts of the studied soil profiles are associated with elevated values of $\chi_{fd\%}$, this suggests the presence of superparamagnetic grains (SP). The increasing contribution of SP grains in the surface horizons, which are enriched in SOM, may indicate the initial stage of pedogenic process development (Dearing et al., 1996; Ouallali et al., 2024). A similar relationship has been observed in other Spolic Technosols (e.g. Uzarowicz et al., 2024, 2025), including those occurring in the Tatra Mountains (Tarnawczyk et al., 2024). The most advanced pedogenic process appears to occur in the topsoil of the TA4 profile developed on a dump covered with a spruce forest (Table 2). According to Dearing et al. (1996), the values of $\chi_{fd\%}$ ranging from 7.7% to 8.6% can indicate a contribution of approximately 50% SP grains, which has a relatively high effect on increasing the χ in the A and AC horizons of the TA4 profile. It can be hypothesized that, in conjunction with the progression of pedogenesis driven by vegetation cover development, the topsoil of the studied Technosols acquires favourable conditions for the formation of pedogenic or biogenic phases characterized by higher magnetic susceptibility than the primary phases inherited from the mine waste.

5.2. Concentrations of selected elements

Spolic Technosols developed on mine waste dumps often contain very high concentrations of potentially toxic trace elements (Karczewska et al., 2018; Ciarkowska and Miechówka, 2022). For this reason, the studied soils in the Jaworzynka Valley may potentially pose a significant threat to the nearby environment.

A comparison of the content of the potentially toxic trace elements (As, Cd, Co, Cr, Cu, Ni, Pb, Zn) measured in the studied soils with the permissible contents specified in the current Regulation of the Minister of Climate and Environment in Poland (Regulation of the Ministry of Climate and Environment, 2024) for the land group no. II (including, for example, national parks and nature reserves) indicates that the concentrations of these elements do not exceed the permissible limits (Table 6). The exception was a subsoil (C4 horizon) of the TA2 profile in which the concentrations of Cd and Zn were higher than the permissible limits (Table 6). Therefore, the results of the analysis confirm that the majority of the analyzed soils do not show contamination with the studied elements in accordance with the applicable provisions of Polish law.

The results obtained can be compared with a few studies focused on the assessment of the degree of soil contamination with trace elements in the Tatra Mountains. According to Ciarkowska and Miechówka (2022), the total concentrations (ranges and means) of Zn, Pb and Cd in soils developed from carbonate rock in the Tatra Mountains were as follows: Zn 80.7–688 $mg \cdot kg^{-1}$ (mean of 227 $mg \cdot kg^{-1}$), Pb 37.9–365 $mg \cdot kg^{-1}$ (mean of 115 $mg \cdot kg^{-1}$), and Cd 0.40–16.31 $mg \cdot kg^{-1}$ (mean of 3.36 $mg \cdot kg^{-1}$). The results for the studied Technosols are within these ranges. Moreover, mean concentrations of the following elements in soils from the Potok Jaworzynka sub-catchment according to Korzeniowska and Krąż (2020) were as follows: Cd 0.9–1.3 $mg \cdot kg^{-1}$, Cr 31.6–49.2 $mg \cdot kg^{-1}$, Cu 6.4–12.9 $mg \cdot kg^{-1}$, Ni 7.7–15.6 $mg \cdot kg^{-1}$, Pb 99.1–117.8 $mg \cdot kg^{-1}$, and Zn 86.0–122.5 $mg \cdot kg^{-1}$. The results for the studied technogenic soils show that the concentrations of Pb are within these ranges, but the contents of Cd, Cr, Cu, Ni, and Zn in the studied Technosols are a bit above the ranges.

6. Conclusions

1. The studied soils located on dumps of historical iron ore mining in the Jaworzynka Valley in the Tatra Mountains were young (about 150 years old) Spolic Technosols, which parent materials were carbonate-bearing mine wastes.
2. The high pH, high carbonate content, as well as high base saturation, make the studied Technosols similar to the rendzina soils (Rendzic Leptosols) developed naturally from carbonate rocks in the Tatra Mountains.
3. Although the studied Technosols are young and represent soils in the initial phase of pedogenesis, they exhibited such manifestations of soil-forming as the accumulation of SOM in the soil surface, topsoil acidification, leaching of carbonates from the superficial soil horizons of the most acidified soils, and the magnetic susceptibility enhancement of the topsoil.

4. The studied Technosols did not contain high contents of potentially toxic trace elements (As, Cd, Co, Cr, Cu, Ni, Pb, Zn), which concentrations are comparable with contents in native soils developed from carbonate rocks in the Tatra Mountains. According to Polish law, the soils were not contaminated with these elements. However, a layer of technogenic materials enriched in Cd and Zn was found in the subsoil of one soil profile.

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Conflict of interest

The authors declare no conflict of interest. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. This research did not involve human or animal subjects.

Author Contributions

Karolina Feluch – Data curation, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Łukasz Uzarowicz** – Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Supervision, Validation, Writing – review & editing. All authors read and approved the final manuscript.

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Rozwój gleb oraz zawartość wybranych pierwiastków śladowych w glebach technogenicznych na hałdach historycznego górnictwa rud żelaza w Dolinie Jaworzynki w Tatrach

Słowa kluczowe

Gleby technogeniczne
Procesy glebotwórcze
Historyczne górnictwo rud żelaza
Tatry

Streszczenie

Od średniowiecza do końca XIX wieku Tatry były ważnym ośrodkiem wydobycia i przetwórstwa rud metali. Technosole rozwijające się na obszarach historycznego górnictwa w Tatrach pozostają wciąż słabo poznane. Celem pracy było określenie właściwości fizykochemicznych oraz składu mineralnego badanych gleb, w celu ich klasyfikacji i identyfikacji procesów glebotwórczych zachodzących w glebach technogenicznych (industriosolach) na hałdach historycznego górnictwa rud żelaza w Dolinie Jaworzynki w Tatrach. Ponadto, celem badań było określenie całkowitej zawartości Fe, Mn i potencjalnie toksycznych pierwiastków śladowych (Zn, Pb, Cu, Cd, Ni, Co, Cr, As) w tych glebach co pozwoliło na ocenę stopnia zanieczyszczenia tymi pierwiastkami. Badano cztery profile glebowe reprezentujące zbiorowiska roślinności łąkowej (trzy profile) i las świerkowy (jeden profil). Podstawowym substratem budującym badane gleby były odpady kopalniane stanowiące utwory kamieniste bogate w węglany. W górnych częściach profili występowały cienkie (do kilku centymetrów) poziomy O i A (lub AC). Części ziemiste gleb charakteryzowały się uziarnieniem gliniastym. Najwyższą zawartość węgla organicznego (TOC) i całkowitego azotu (TN) odnotowano w poziomach O oraz w poziomach A i AC, co było związane z akumulacją materii organicznej w wierzchnich poziomach. Gleby wykazały wysokie pH (średnio 7,3) w dolnych częściach profili glebowych. Wierzchnia warstwa gleby miała niższe pH (średnio 6,6). Najniższe pH występowało w wierzchniej warstwie profilu rozwiniętego w lesie świerkowym (pH=4,5). Badane Technosole zawierały węglany (do 57,6%), natomiast profil znajdujący się w lesie świerkowym nie zawierał węglanów w wierzchniej warstwie gleby, co najprawdopodobniej było związane z wypłukiwaniem węglanów wywołane silnym zakwaszeniem. Skład mineralny Technosoli był zróżnicowany, a dominującymi minerałami był kwarc, dolomit i kalcyt. Podatność magnetyczna (χ) wahała się od 2,5 do 49,4 $\times 10^{-8} \cdot m^3 \cdot kg^{-1}$, natomiast podatność magnetyczna zależna od częstotliwości (χ_{fd}) wynosiła od 1,6 do 8,6%. Zarówno χ, jak i χ_{fd} były najwyższe w wierzchniej warstwie gleby, co związane jest prawdopodobnie z przekształceniami minerałów zawierających Fe, które doprowadziły do zwiększenia wartości podatności magnetycznej wierzchniej warstwy gleby wraz z postępem procesów glebotwórczych w badanych glebach. Całkowita zawartość potencjalnie toksycznych pierwiastków śladowych (As, Cd, Co, Cr, Cu, Ni, Pb, Zn) w badanych glebach była zróżnicowana. Jednak zawartości tych pierwiastków były niskie i nie wskazywały na zanieczyszczenie gleby w świetle obowiązujących przepisów prawa w Polsce. Badania wykazały, że stopień zaawansowania procesów glebotwórczych w badanych glebach technogenicznych był najwyższy w wierzchniej warstwie gleby. Pierwszymi przejawami procesów glebotwórczych w badanych glebach technogenicznych są: (1) akumulacja glebowej materii organicznej w powierzchniowych warstwach gleby, (2) zakwaszenie wierzchniej warstwy gleby, co związane jest z przemianami i rozkładem glebowej materii organicznej, (3) wypłukiwanie węglanów z górnej części profilu glebowego oraz (4) wzrost podatności magnetycznej powierzchniowych poziomów glebowych.