Environ Geochem Health (2025) 47:389
https://doi.org/10.1007/s10653-025-02686-4

Exhibit TL-JK-2

ORIGINAL PAPER

Impact of photovoltaics on soil and water by metal(loid)s including technology critical elements: preliminary study

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Received: 22 April 2025 / Accepted: 22 July 2025 / Published online: 15 August 2025

Abstract The increasing adoption of photovoltaic farms is driven by the growing demand for clean, renewable energy. As advancements in solar technology continue and costs decrease, large-scale solar farms are becoming essential for reducing carbon emissions and enhancing energy security. While PV farms offer a sustainable energy solution, they also pose environmental risks. During their operational lifetime, PV panels can be damaged, potentially releasing hazardous materials into the environment. Additionally, stormwater runoff from solar installations may carry pollutants into soil and water sources. Mitigating these risks is crucial to ensuring that solar energy remains both sustainable and environmentally responsible. This work aims to evaluate PV panels' environmental impact, especially on the soil in one of the oldest PV installations in Poland, comparing it with other sources of pollution in the region, such as mining. Therefore, soil and water samples underwent chemical analysis, statistical analysis, pollution indices assessment, and geospatial analysis to determine potential pollution sources for the observed elemental chemical matrix. Also, the chemical composition of PV material was analyzed. The results indicate that In and Sb are emerging pollutants at moderate levels, potentially originating from long-term use of PV installations. In contrast, elements such as Cd, Cr, Pb, and Zn, which come from mining and smelting activities, present significantly higher environmental risks. This study suggests conducting further similar research across various geological backgrounds to draw broader conclusions. Besides, it is vital to develop experiments that assess the impact of PV panels as hazardous waste materials on soil and water.

Keywords Heavy metals · Emerging pollutants · Geospatial analysis · Environmental impact · PCA · PV material

Introduction

To reduce greenhouse gas emissions in the transport, electricity and industry sectors, all of which are highly dependent on fossil fuels, the European Union has decided to implement the Green Deal paradigm (The European Green Deal, 2024). Wind and solar power are planned to generate 40% of the world's electricity by 2030 and almost 70% by 2050, even though they currently account for only 10% of the

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Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10653-025-02686-4.

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global energy supply (Wiatros-Motyka et al., 2024). Consequently, the EU emphasizes the need to increase photovoltaic (PV) installations and wind turbines to harness the power of solar and wind energy (European Commission, 2022). The worldwide adoption of renewable energy sources (RES) is continuously rising, driven in part by the sharp growth in energy demand from previously less developed nations (Gnatowska & Moryń-Kucharczyk, 2021). Solar energy provides a more environmentally friendly power option while helping to reduce the effects of climate change (Shah, 2020). Large photovoltaic (PV) plants are being swiftly constructed and integrated into the grid in numerous countries worldwide, elevating solar PV energy to the level of a utility-scale power source. Clean energy technologies are gaining popularity due to their potential to lower energy consumption and reduce greenhouse gas emissions. According to Greenpeace's Advanced Energy [R]evolution scenario (Teske et al., 2011), PV capacity is projected to grow from its 2014 levels to 9.3 TW by 2050.

Photovoltaic cells are engineered to minimize the release of potentially harmful substances by being encased in glass or a polymer layer. This protective layer safeguards the cells from UV light, moisture, and oxygen exposure (Weimar, 2024). However, extended exposure to UV radiation can cause the polymer layer to degrade over time. Additionally, improper handling can compromise the physical integrity of the layer, potentially releasing materials into the environment (Mik et al., 2021). The environmental impact of operational photovoltaic panels is not well understood. While photovoltaics are generally regarded as safe for the environment, the report Technical Risks in PV Projects (Moser et al., 2016), part of the EU's Solar Bankability project Horizon 2020, highlights that glass breakage and "snail trails"—microcracks and discoloration of the silver paste on the busbars are the most common defects in solar modules.

The photovoltaic panel market is currently dominated by first- and second-generation technologies. Thin-film solar cells, a second-generation innovation, are created using thin-film technologies that deposit one or more layers of photovoltaic material, only a few micrometers thick, onto substrates like glass, plastic, or metal. This production method allows manufacturers to produce solar panels at a lower cost. Common second-generation cells use materials such as copper indium (CuIn), cadmium telluride (CdTe), gallium arsenide (GaAs), gallium diselenide (CIGS), and amorphous thin-film silicon. Their flexibility makes them particularly well-suited for applications in integrated PV systems in "smart cities" (Mondal & Bhattacharyya, 2023).

The global market for CIGS thin-film solar cells is expected to experience significant growth during the 2024–2031 forecast period. Additionally, the increasing adoption of CIGS thin-film solar technology in various sectors is anticipated to drive further market expansion in the coming years (Muteri et al., 2020). While photovoltaic panels offer numerous environmental advantages, they can also present some challenges (Preet & Smith, 2024). Key benefits include the reduction of emissions, as PV panels generate electricity without releasing carbon dioxide or other harmful greenhouse gases, contributing to the mitigation of global warming. Solar power is also a renewable and sustainable energy source that does not deplete finite resources like coal, oil, or natural gas. Moreover, PV panels do not produce air pollution during normal operation, unlike fossil fuel-based power plants. The installation of PV panels is expected to positively influence several soil properties, including enhanced stability of soil aggregates, increased organic matter content, and greater development of the microbial community (Dvořáčková et al., 2024).

However, there are some negative environmental impacts associated with PV panels (Nain & Kumar, 2020). The study of Choi et al. (2020) shows that the carbon and nitrogen content of the photovoltaic soil was lower than that of the reference soil and contained a higher fraction of coarse particles. They also found that the photovoltaic modules introduced heterogeneity in the soil moisture distribution. However, Yue et al. (2021) found that the soil temperature and moisture at sites under PV shading were significantly affected compared with those at sites without shading. PV panels have positive effects on soil moisture. Study of soil contamination near Fence photovoltaic installations shows an increase in cadmium concentrations (Yousuf et al., 2024).

The manufacturing process consumes energy and raw materials, potentially resulting in the emission of greenhouse gases and pollutants. Additionally, water consumption during production can be significant, posing challenges in regions where water is scarce.

End-of-life disposal of PV panels can lead to electronic waste and environmental pollution if not properly managed. Finally, large-scale PV installations can occupy vast areas of land, potentially leading to land-use conflicts and disruptions to local wildlife.

Several trace elements, once regarded as mere laboratory curiosities, have now become essential components in advancing new technologies. However, for many of these elements, current knowledge about their concentrations, transformations, and movement across various environmental compartments remains limited or inconsistent (Filella & Rodríguez-Murillo, 2017). Photovoltaic panels placed on residential buildings (Trimmel et al., 2024), especially large photovoltaic farms, can be a source of uncontrolled emissions of pollutants to water, soil and dust emissions. Metals, including critical elements and other organic compounds, are characterized by a high supply risk and high economic importance for Europe (Nuss & Blengini, 2018). Thus, although photovoltaic panels are considered a relatively clean energy source, their production and use involve some negative environmental impacts. However, when compared to conventional fossil fuel-based energy sources, they generally compare favorably in environmental terms. It is also important to develop photovoltaic technologies towards sustainable use of raw materials, energy efficiency and recycling to minimize their negative environmental impact (Almosni et al., 2018). Photovoltaic panels include many elements, including technology-critical elements.

Environmental research conducted by Robinson and Meindl (2019) on soil samples collected from beneath photovoltaic modules has confirmed elevated levels of Se, Sr, Li, Ni, and Ba in areas near PV systems. Photovoltaic panels can contribute to soil contamination due to heavy metals like Cd, Pb, Ni, and As present in them (Falfushynska, 2024). Rainfall can expose these panels to become a source of heavy metal soil contamination (Yoon et al., 2021). Solar PV infrastructure impact on soil physical and chemical properties. This suggests that lesser-studied metals such as germanium, gallium, tellurium and indium may also be released into the environment around "active" photovoltaic panels, including those used by private consumers and on farms. Currently, there is no available literature addressing the effects of photovoltaic panels on the surrounding environment in relation to metals like Ge, Ga, Te, and In.

In our initial research, we selected one of the oldest photovoltaic farm in Upper Silesia, Poland, which has been operating continuously since 2012. We took samples of water flowing from the panels and soil in the immediate vicinity of the panels. We studied elements V, Co, Cd, Mo, Ni, Pb, Mn, Cu, Zn, Sb, Ga, In, As, Tl, Ag, Sn, Cr, Ge and Te using Inductively Coupled Plasma Mass Spectroscopy (ICP-MS). Our research aimed to identify the elements that may leach into water and soil from operational PV panels. Over time, under real-world operating conditions, the likelihood of leaching TCEs such as Ge, Ga, Te and In, as well as other metals, increases. This process is primarily driven by the formation and progression of microcracks, one of the most common defects in PV panels. These microcracks deteriorate further over time due to exposure to atmospheric conditions. As a result, wet precipitation, often acidic, may penetrate these microstructures, mobilize the embedded metals, and transport them into the surrounding soil.

Material and methods

Sampling and study area

Soil samples for this study were taken from the area surrounding the photovoltaic farm using an Egner's stick sampler to collect undisturbed 20 cm soil cores (two from each place). The farm located in Ruda Śląska (Upper Silesia, Poland) has 1296 photovoltaic panels with a power of 240 W each (totaling approximately 311 kW), made using monocrystalline technology, with a total active surface of 2146.19 m^2. Water samples were taken directly as runoff from the panel surface. Soil sampling points are distributed to capture spatial variability across different locations within the study area (see Fig. 1). Samples from S1 to S10 were collected around the entire farm, and in the northerly direction (the prevailing wind direction in this area), they were extended to cover three levels of terraces downward (e.g., S11, S12, S13), with approximately 5 m between each terrace and the next. The background soil sample was taken in Rybnik in an area not subjected to any impact. Runoff water from the panels was collected directly in the rain by placing a container under the panel.

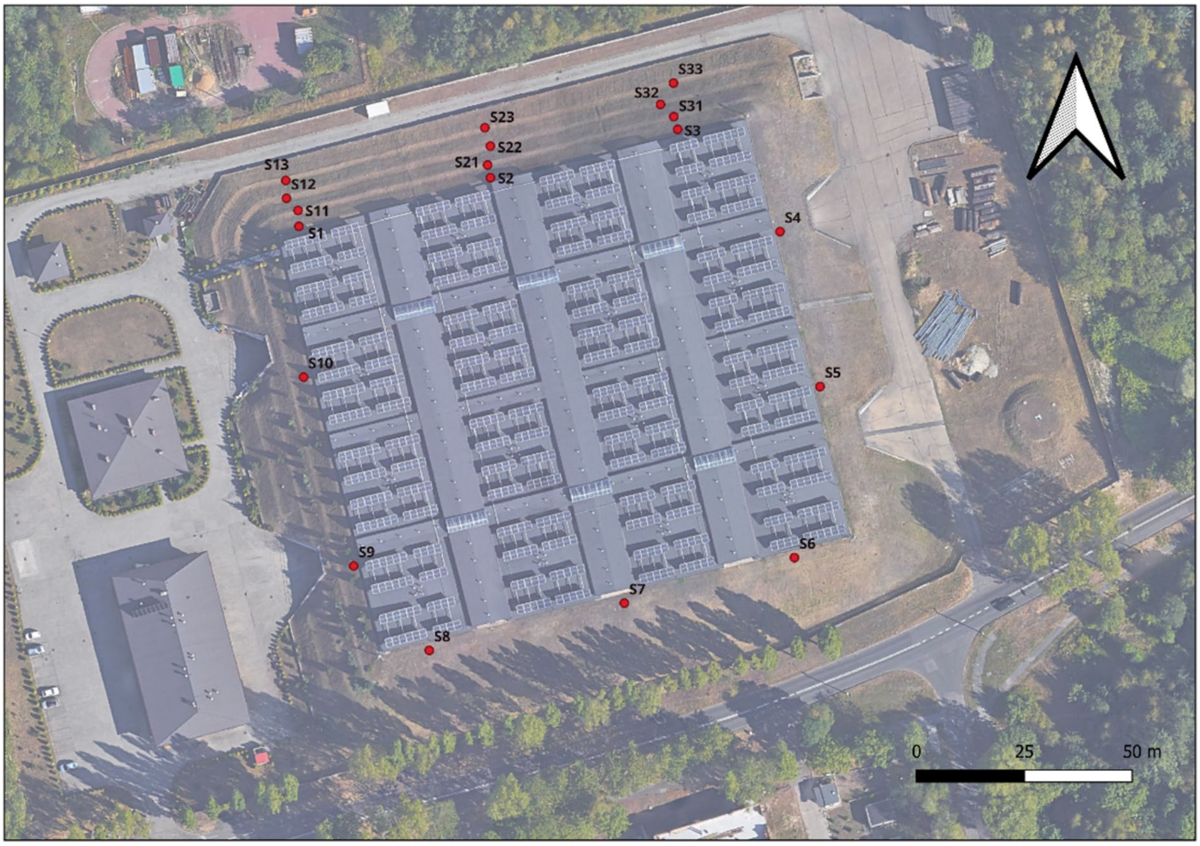


Fig. 1 Study area and sampling points

Sample preparation

Water samples from the panel surface were collected in polypropylene (PP) containers and immediately transported to the laboratory. The physicochemical parameters were measured using a CX-401 multimeter (Elmetron, Poland). The pH was measured with an ERH-111 glass electrode (Elmetron, Poland), redox potential (Eh) was determined using an ERPt-111 platinum electrode (Hydromet, Poland), and CD-2 conductometric sensor (Hydromet, Poland) was used to measure electrolytic conductivity (EC). For the total element quantification water samples were filtered through 0.22 µm polyethersulfone filters (PES), acidified with HNO_3 and stored at 4 °C in the dark until analysis.

Soil samples (approximately 500 g) were collected from the surface layer at each designated sampling point. The soil samples were carefully transferred into labeled plastic containers and immediately transported to the laboratory for further preparation. In the laboratory, the samples were air-dried at room temperature until constant weight was reached. Any visible plant material, stones, or debris were manually removed to ensure the purity of the samples. After drying, the samples were sieved through a 2 mm mesh to ensure uniform particle size. This standardized preparation process ensures that the samples are adequately prepared for consistent pH analysis and accurate measurements of other soil properties. The conductivity and pH parameters were measured using the CX-401 multi-meter, along with the electrodes mentioned above according to PN-EN ISO 10390:2022–09 procedure (Soil, treated bio-waste and sewage sludge—Determination of pH) (ISO, 2005), while conductivity parameter according to PN-ISO 11265:1997 procedure (Soil quality – Determination of electrical conductivity).

Soil samples were digested under acidic conditions in an Anton Paar 5000 microwave oven (Austria) using a digestion mixture of 6 ml HNO_3, 2 ml H_2O_2, and 3 ml HF. A 0.2 g air-dried soil sample was placed in a digestion vessel and treated according to the following program: ramp I: 170℃/ 25 min.; ramp II: 210℃/ 15 min; hold: 210℃/ 25 min. After digestion, the solution was transferred to a polypropylene volumetric flask and diluted to a final volume of 50 ml. For quality control purposes, the certified soil reference material 73,324 (China National Analysis Center for Iron and Steel, Beijing, China) was diluted using the same procedure applied to the soil samples.

Chemical analysis

For the determination of V^{51}, Co^{59}, Cd^{114}, Mo^{98}, Ni^{60}, Pb^{208}, Mn^{55}, Cu^{65}, Zn^{66}, Sb^{121}, Ga^{69}, In^{115}, As^{75}, Tl^{205}, Ag^{107}, Sn^{118}, Cr^{53}, Ge^{74}, Te^{126} concentration Elan 6100 DRC-e ICP-MS (PerkinElmer, USA) fitted with cross-flow nebulizer, Scott-type spray chamber, nickel sampler and skimmer cones, and collision/reaction cell was used. The spectrometer was daily tuned with a 10-μg L^{-1} solution (Mg, Cu, Rh, Cd, In, Ba, Ce, Pb, and U in 1% HNO_3) to optimize the instrumental performance. To improve the accuracy and precision of quantitative measurements rhodium was used as internal standard in analysis of each element. In Ge^{74} determination a collision chamber with methane (CH_4) as the auxiliary gas was used to eliminate numerous polyatomic interferences and the correction equation $-0.1385 \times Se82$ was applied. The determination of Te was performed using correction equation $-0.003404 \times Xe129$ mode.

The research into Al, Ca, Fe, K, Mg, Na, P, S, Si elements content was conducted using a PerkinElmer Avio 200 inductively coupled plasma optical emission spectrometer. The ICP-OES spectrometer was equipped with a quartz torch, cross-flow nebulizer and Scott-type spray chamber.

The concentrations of Li^+, Na^+, NH^{4+}, K^+, Mg^{2+}, and Ca^{2+} ions were quantified using a Thermo Scientific Dionex ICS-1100 ion chromatograph. For the determination of F^-, Cl^-, NO^{2-}, NO^{3-}, $PO_4{}^{3-}$, and $SO_4{}^{2-}$ ions, a Thermo Scientific Dionex ICS-6000 ion chromatograph was employed. Ion analysis was performed following the standards PN-EN ISO 14911:2002 and PN-EN ISO 10304–1:2009, using soil samples extracts in a ratio 1to 10 (m/v) prepared according to the PN-EN 12457–2 procedure.

Preparation and chemical analysis for solar panel material

PV samples preparation for chemical component analysis, the process begins with carefully cutting the PV crystalline silicon module into manageable pieces (4 cm^2) using a heavy-duty tin snip. These pieces were then subjected to grinding using a mechanical grinder (Retsch SK 100) to achieve a fine, uniform particle size. The ground material was sieved using a mesh with a pore size of 0.5 mm to separate smaller fractions suitable for digestion. Particles passing through the sieve are collected, while larger particles are reground to ensure consistency. The sieved fraction, less than 0.5 mm in size, undergoes acid digestion using a mixture of concentrated acids, such as nitric and hydrochloric acid, to dissolve the material and release the target chemical components. The resulting solution was filtered to remove any undissolved residue and prepared for further analysis using techniques such as ICP-MS, ensuring precise quantification of the chemical constituents.

Geospatial analysis

To create maps and carry out spatial analysis, QGIS software (version 3.30.1—'s-Hertogenbosch) was utilized. The Inverse Distance Weighted (IDW) method was employed to interpolate elemental concentration data into a graphical representation of the location. all maps were produced using EPSG:4326—WGS 84 coordination reference system.

Assessment of environmental pollution

Three fundamental environmental indices were used to assess the elements present in the soil samples. Furthermore, background information for these elements was sourced from Salminen et al. (2006) and, for germanium (Ge), from Négrel et al. (2016) to represent the background value for a location closest to the study area.

Geoaccumulation Index (I_{geo}), introduced by Müller (1986), is the most used indicator for assessing the geoaccumulation of pollutants. The calculation is expressed in Eq. (1), where $C_{mSample}$ represents the measured concentration of the element in the sample, and $C_{mBackground}$ refers to the geochemical background concentration of the element. The value of 1.5 represents the correction constant applied to account for natural fluctuations in element levels and mitigate the effects of human activities on the element concentrations (Jabłońska-Czapla et al., 2024; Nawrot et al., 2021).

$$I_{geo} = \log_2\left(\frac{C_{mSample}}{1.5 \times C_{mBackground}}\right) \tag{1}$$

($I_{geo} < 1$) indicates no pollution; ($1 \leq I_{geo} < 2$) shows moderate contamination; ($2 \leq I_{geo} < 3$) signifies moderate to heavy pollution; and ($3 \leq I_{geo} < 4$) represents heavy contamination.

The Pollution Index (PI) is used to evaluate the level of contamination in soils, sediments, or water bodies, by comparing the measured concentrations of elements to established background values (Eq. 2). The PI has been widely adopted in environmental studies to monitor the impacts of industrial, agricultural, and urban activities on ecosystems (El Morabet et al., 2024; Jabłońska-Czapla et al., 2024; Nawrot et al., 2021).

$$P_I = \frac{C_{mSample}}{C_{mBackground}} \tag{2}$$

($PI < 1$) indicates no pollution; ($1 \leq PI < 3$) reflect moderate contamination; and ($3 \leq PI$) represents heavy contamination.

The Enrichment Factor (EF) is a metric used in environmental science to assess the degree of anthropogenic (human-made) influence on the concentration of elements in soils, sediments, or atmospheric particles. The EF is calculated by normalizing the concentration of an element of interest against a reference element (Eq. 3) that is assumed to have a stable, natural background concentration such as Al (De Paula et al., 2015; Jabłońska-Czapla et al., 2024; Nawrot et al., 2021).

$$EF = \frac{\left(\frac{Me}{MeRef}\right)Sample}{\left(\frac{Me}{MeRef}\right)Background} \tag{3}$$

($EF < 2$) indicates no to minimal enrichment; ($2 \leq EF < 5$) reflect moderate enrichment; and ($5 \leq EF < 20$) represents significant enrichment.

Statistical and data analyses

Principal Component Analysis (PCA) and k-means clustering were utilized to examine the relationships between element concentrations. Additionally, a Spearman correlation matrix was generated to assess the relationships between element concentrations and various soil parameters, including pH and conductivity. Finally, a statistical difference analysis was conducted on select elements of interest using one-way ANOVA or the Kruskal–Wallis tests, based on the test's assumptions in each case analyzed. The analysis was performed using R software (R Core Team, 2024). The specific packages used were factoextra (Kassambara & Mundt, 2020) and corrplot (Wei & Simko, 2021).

Results and discussion

Chemical analysis of soil, water and PV panel

In our preliminary study, we collected 19 soil samples and 7 water samples draining from the panels. This pioneering study was conducted to preliminarily evaluate the potential influence of operating PV panels on the soils in their immediate surroundings. First, we analyzed the photovoltaic panel itself. Table S1 presents the total chemical composition of a silicon-based (c-Si) photovoltaic panel. This type of photovoltaic panel was installed on the studied photovoltaic farm. Among the metals, the highest concentrations were measured for antimony (2123 mg/kg) and copper (1832 mg/kg). Additionally, the material contained tin (965.0 mg/kg), lead (685 mg/kg), titanium (468.0 mg/kg), silver (481.2 mg/kg), cobalt (13.45 mg/kg), and nickel (247.8 mg/kg). Among the TCEs the panel contained 18.61 mg/kg of gallium, 5.52 mg/kg of germanium, 3.5962 mg/kg of indium, and 1.97 mg/kg of tellurium.

The results of the qualitative and quantitative analysis of soils collected around the operating panels are presented in Tables S2 and S3. To compare the obtained values of metal content in the soils, we collected a soil sample from Rybnik, an area not affected by the pollutants present at the study site. As shown in Table S3, the soil sample from Rybnik contains only trace amounts of metals/metalloids. In comparison, the samples collected in Ruda Śląska from the area surrounding the photovoltaic farm contain significantly higher amounts of metals.

According to Salminen et al. (2006), the indium concentration in Poland, particularly in the Upper Silesia region, ranges between 0.01 and 0.03 mg/kg. In our study, the indium concentration in the soil ranged from 0.04 to 0.11 mg/kg, indicating higher values. Notably, in the soil from the unaffected area in Rybnik (Upper Silesia), the indium concentration was 0.01 mg/kg. The antimony concentration in the topsoil in Poland, as reported by Salminen et al. (2006), falls within the range of 0.39–0.83 mg/kg, whereas in the soil samples collected around the photovoltaic farm, it ranged from 1.21 to 2.82 mg/kg. The Sb concentrations in the collected soils were elevated. Gallium in the soils from the sampling area is expected to be present at concentrations ranging from 3.5 to 10.7 mg/kg. However, in the soil samples collected during our study, the average gallium content was 22.38 mg/kg. The concentration of gallium in the soil samples was significantly elevated compared to the levels of this TCE in soils not subjected to anthropogenic pressure.

Our earlier research showed that the germanium concentration in the area around the WEEE plant was as high as 7.64 mg/kg, with an average concentration of 3.51 mg/kg (Jabłońska-Czapla et al., 2023). Other studies on Saxony soils indicated that the germanium concentrations in two different soils were 1.5 and 1.6 mg/kg (Wiche & Heilmeier, 2016). Analysis of soil samples showed that the germanium concentration ranged from 1.51 to 2.46 mg/kg, which was elevated, similar to the area around the WEEE processing plant. This suggests that photovoltaics influence the germanium content in soils surrounding active PV panels. However, it should be noted that the photovoltaic farm was located in Upper Silesia, a region with a well-developed mining industry. In contrast, a study of the mining area of Freiberg (Germany) showed that the total concentration of Ge in soil varied considerably, ranging from 1.0 to 4.3 mg/kg (mean 1.9 mg/kg) (Wiche et al., 2017). Therefore, further research should include analyses of soils in areas under photovoltaic pressure but without the influence of industries such as mining or metallurgy.

The concentration of tellurium in the analyzed soils was low, averaging 0.02 mg/kg, indicating no impact of photovoltaics (crystalline PV panels) on the content of this element in soils. According to the literature, tellurium is a naturally occurring element found in its pure state in the Earth's crust in amounts ranging from 0.001 to 0.01 mg/kg (Kabata-Pendias & Pendias, 1999). However, our earlier results have shown that the concentration of tellurium in soils around the WEEE processing plant can be up to 10 times higher, reaching 0.166 mg/kg (Grygoyć & Jabłońska-Czapla, 2021).

In the soil samples collected for this study, significantly elevated concentrations of metals were observed, including lead (ranging from 67.60 to 237.69 mg/kg), chromium (38.14 to 165.41 mg/kg), cadmium (1.82 to 6.87 mg/kg), copper (19.06 to 38.67 mg/kg), cobalt (6.32 to 13.64 mg/kg), nickel (maximum concentration of 53.08 mg/kg), manganese (347.82 to 5283.61 mg/kg), and vanadium (40.77 to 87.39 mg/kg).

The results of the panel runoff water tests are shown in Table S4. Runoff water from the PV panels (in the form of precipitation) did not have elevated concentrations of elements critical to the technology. Table S4 shows the concentrations of V, Co, Cd, Mo, Ni, Pb, Mn, Cu, Zn, Sb, Ga, In, As, Tl, Ag, Sn, Cr, Ge and Te. For elements such as Mo, In, Tl, Ag, Sn, Cr, Ge and Te, concentrations were low, below the limit of quantification. Of the elements tested, only the concentration of cadmium exceeded the permissible concentration in drinkable water (above 5 µg/L). The problem of water health safety in Poland is regulated by the Regulation of the Minister of Health of 7 December 2017 (Minister of Health, 2017) on the quality of water intended for human consumption, taking into account the provisions of European Union Council Directive 98/83/EC. On the other hand, if one refers the results obtained to the Regulation of the Minister of Maritime and Inland Navigation (Min. Mar. Econ. & Inland Navig. 2019) on substances particularly harmful to the aquatic environment and the conditions to be met when discharging waste water into waters or into the ground, as well as when discharging rainwater or snowmelt into waters or into water facilities, the obtained results indicate that there are no exceedances of the permissible concentrations of metals.

The mechanical properties of silicon PV cells make them prone to fracturing and brittleness. This susceptibility can lead to the formation of cracks and microcracks during manufacturing, transportation, installation of PV, and under weathering conditions, such as heavy snow pressure. Additionally, these microcracks can cause thermal insulation, which raises the temperature near the defective cells. This increased temperature may lead to electrical inactivation, ultimately affecting the overall efficiency of the PV module (Paggi & Sapora, 2013). Aghaei et al. (2022) conducted a comprehensive review of weathering factors contributing to PV degradation during the aging process, including irradiation, temperature, moisture, and other environmental stresses. For example, ultraviolet radiation—particularly in the 280–315 nm range—has a damaging effect by degrading the polymer layer. Elevated temperatures further accelerate the degradation of both the polymer and backsheet layers and promote corrosion of metallized components, consistent with the Arrhenius model. Moreover, extreme temperatures can compromise the structural integrity of critical PV components such as cells, solder joints, and ribbons. Finally, moisture plays a critical role in the degradation of PV components. Prolonged exposure to near-saturation water levels can deteriorate adhesive layers, weakening the overall structure. Additionally, hydraulic pressure and the expansion of freezing water introduce mechanical stresses that further exacerbate damage. Over time, these processes contribute to the formation and propagation of microcracks, which in turn facilitate deeper moisture ingress and accelerate degradation.

It is worth mentioning that partial shading of a PV module can cause localized overheating, as shaded cells in a series string are forced into reverse bias and dissipate power as heat, leading to the formation of hot spots and potential damage over time. Sepulveda-Oviedo (2025) reported that 60% to 70% of PV efficiency is lost due to dust accumulation, temperature fluctuations, and shading factors in extreme conditions. The study proposed a set of metrics to evaluate the extent of PV degradation during the aging process. These metrics include the degradation rate, cleanliness index, performance ratio, and performance loss rate. These metrics are essential not only for the economic management of PV facilities but also for assessing the environmental susceptibility of aging PV materials. However, the lack of data needed to calculate these metrics for commercial confidential reasons, along with limited regular environmental monitoring in relevant locations, may hinder the progress of such research.

Geochemical sources analysis

This analysis explores the intricate dynamics of trace element migration within natural systems by examining their pathways and interaction patterns. It integrates geochemical parameters, ion interactions, and environmental variables to trace element sources and understand their behaviour.

Patterns and pathways of trace element migration

After performing PCA and k-means clustering, we identified four main clusters based on the PCA scores. These clusters were highlighted within the PCA coordinate space, and the rotated loadings were represented as arrows radiating from the center of variance (Fig. 2). This analysis captured 80.3% of the total variance in the data. The total variance is distributed across orthogonal principal components: Dimension 1 (Dim1) accounts for 48.3%, Dimension 2 (Dim2) accounts for 22.9%, and Dimension 3 (Dim3) accounts for 9.1% of the total variance. In summary, all elements except Te exhibit a negative correlation with Dim1, as illustrated in Fig. 2. Four categories of elements can be established based on the distribution of elements among clusters of sampling points and PCA dimensions. The first category includes Ge, Mn, and Te, which are attributed to Dim3 variance. In this context, S13 has a significant influence on Ge and Mn, showing the highest values (in Dim3), while Te exhibits the weakest correlation with Dim1, yet it displays a slight tendency towards cluster group number 1. The other categories are distinguished based on the differences between Dim1 and Dim2, where Co, Cr, Mo, and V (second category) are negatively correlated with Dim2 and strongly associated with cluster number 2. On the other hand, the third category consists of Ag, As, Cd, Pb, Tl, and Zn, is positively affiliated with Dim2 and cluster number 4. Finally, although the fourth category (Cu, Ga, In, Sb, and Sn) shares many similarities with the third category, it is firmly aligned with Dim1 and weakly aligned with Dim2.

Upper Silesia is regarded as one of the most heavily exploited regions in Poland, primarily due to its extensive mining and smelting activities. This region

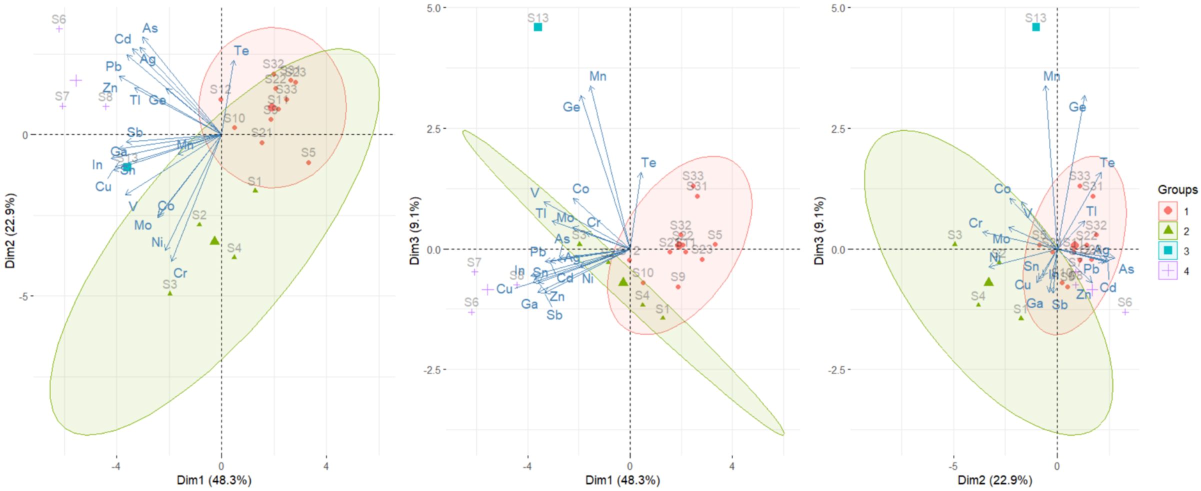


Fig. 2 PCA biplots for soil samples and geochemical composition with k-mean clusters

is geologically significant and hosts a variety of economically valuable ore deposits, including coal and non-ferrous metals (particularly zinc and lead ores). Hence, it has experienced severe contamination through a century of excessive mining (Jabłońska-Czapla et al., 2024; Lewińska-Preis et al., 2021; Parzentny, 2020; Swęd et al., 2022).

Pasieczna et al. (2020) studied anthropogenic and geogenic contamination in Upper Silesia, including in Ruda Śląska. They analyzed topsoil and subsoil samples and identified several elements that fall into the third category, particularly Ag, As, Cd, Pb, S, and Zn. These elements are mainly associated with the mining and smelting of Zn-Pb ores, which began in the nineteenth century. Additionally, Co and V may originate geogenically from both Quaternary glacial tills and Carboniferous mudstones and claystones, while Cr, Mo, and Ni are linked to iron and steel production. In the same region, Parzentny (2020) analyzed trace metal content in the coal and coal ash to conclude that despite elements from the second category, especially Co, Cr, Ni, and V, exist in lower amounts compared to other trace metals such as Ba, Mn, Pb, Sr, and Zn, they are still essential for understanding the source and quality of coal. Co, Cr, Ni, and V may also originate from a range of soil types, including proper soils, Fluvic Cambisols, Eutric/Epidystric Cambisols, Gleyic/Stagnic Phaeozems and Chernozems, Fluvic Phaeozems, Podzols, Dystric Cambisols, Luvisols, Dolomitic/Calcaric Cambisols, Haplic Chernozems, and Gleyic/Stagnic Phaeozems (Tomczyk et al., 2023).

Local comparative assessment of Cu, Ga, In, Sb, and Sn

Nadłonek et al. (2024) analyzed the polluted soils resulting from mining and metallurgical waste in Park Czykowskiego, which is approximately 2.6 km from our sampling location in Ruda Śląska. The study found that historic Zn-Pb ore mining and Zn and Fe metallurgy had caused significant chemical transformation of the soils in this region, particularly affecting the levels of As, Sb, and S. Therefore, data (N = 13) from Nadłonek et al. (2024) were used to analyze the statistical differences of elements across various local sites. Additionally, soil samples were collected from a private PV unit located in Zabrze city (N = 4), which is almost 9 km away from Ruda Śląska. Accordingly, the Kruskal–Wallis test, followed by Dunn's multiple comparison with the Benjamini–Hochberg adjustment, indicated that the observed elements (Cu, In, Sb, and Sn) showed significant differences in their concentrations between Park Czykowskiego and Ruda Śląska (Figure S1). This suggests that the concentrations of these elements vary significantly between the previous mining locations and the PV farm located in Ruda Śląska. In contrast, samples from the Zabrze location did not show any significant differences when compared to other locations, except for Sn, where a difference was noted with the PV farm in Ruda Śląska. Additionally, a significant difference in Ga concentration was observed between Zabrze and Ruda Śląska, as determined by a one-way ANOVA followed by Tukey's HSD post-hoc test. In summary, Cu, In, and Sb tend to be found in much lower concentrations in soil samples from PV facilities compared to those previously associated with mining and smelting operations. On the other hand, Ga and Sn show varying concentrations in different PV locations.

Ion interactions and parameters

The analysis of ion concentration in soil is vital for comprehensively understanding soil health, nutrient availability, and potential contamination. This assessment is instrumental in evaluating the impact of pollutants, such as heavy metals, on soil quality. In the field of environmental studies, ion analysis plays a critical role in monitoring contamination arising from industrial activities, agricultural runoff, or infrastructure such as PV farms, where metals from panels might leach into the soil over time. Two main outcomes can be derived from the Spearman correlation matrix shown in Fig. 3. Firstly, it confirms the relationships found in each category identified through PCA. Secondly, it highlights the correlations between major ions and trace elements.

It is important to note that there was no strong or significant correlation between the elements in the first two categories and the observed major ions. The most significant correlations were between the major ions and the elements in the third and fourth

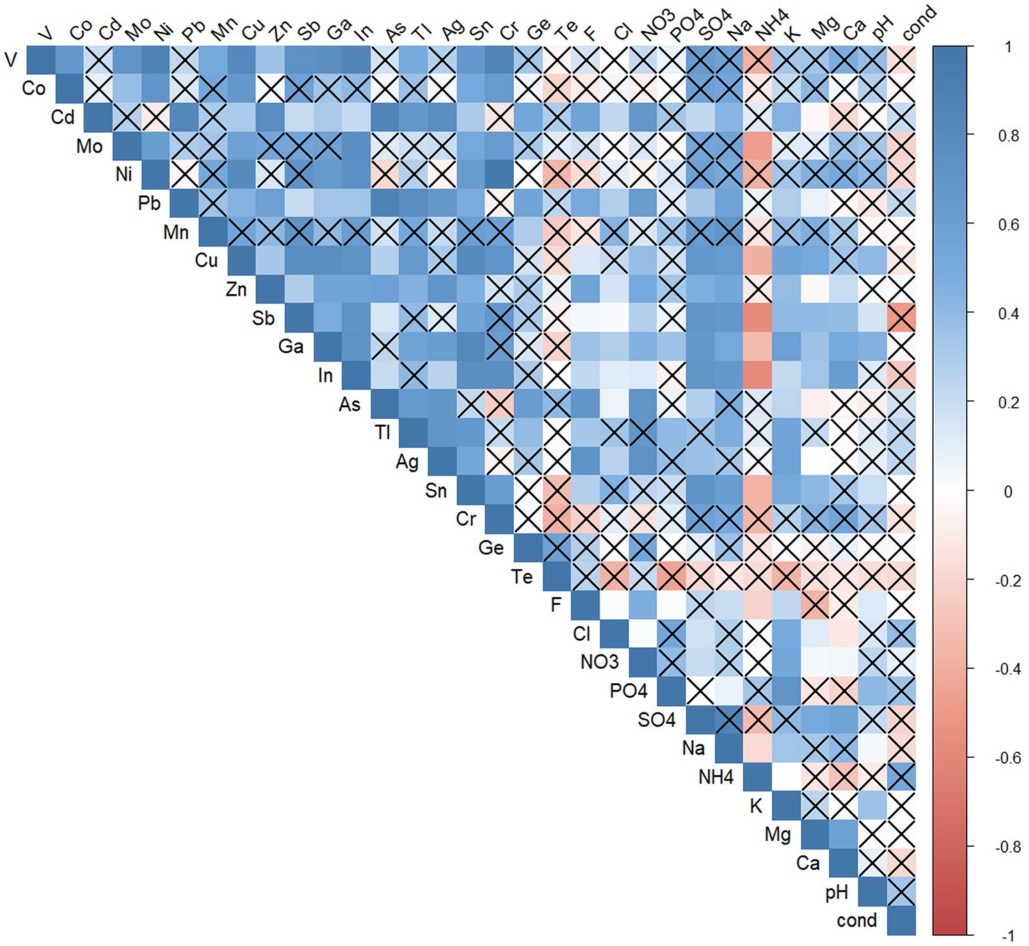


Fig. 3 Spearman correlation matrix

categories. For illustration, a strong correlation is noted between F^- and NO_3^- with elements from the third category, including arsenic As, Ag, Cd, Pb, and Zn. Additionally, SO_4^{2-} shows a strong correlation with elements in the fourth category, such as Cu, Ga, In, Sb, and Sn. Ca and Mg also display higher correlations with In and Cu, respectively.

In contrast to the other ions, NH_4^+ shows only a significant negative correlation, primarily with In and Sb. Further, no valid relationship has been found with Cl^- and PO_4^{3-}. Finally, considering both parameters (pH and conductivity), only pH exhibited a moderately positive correlation with both Cu and Ga.

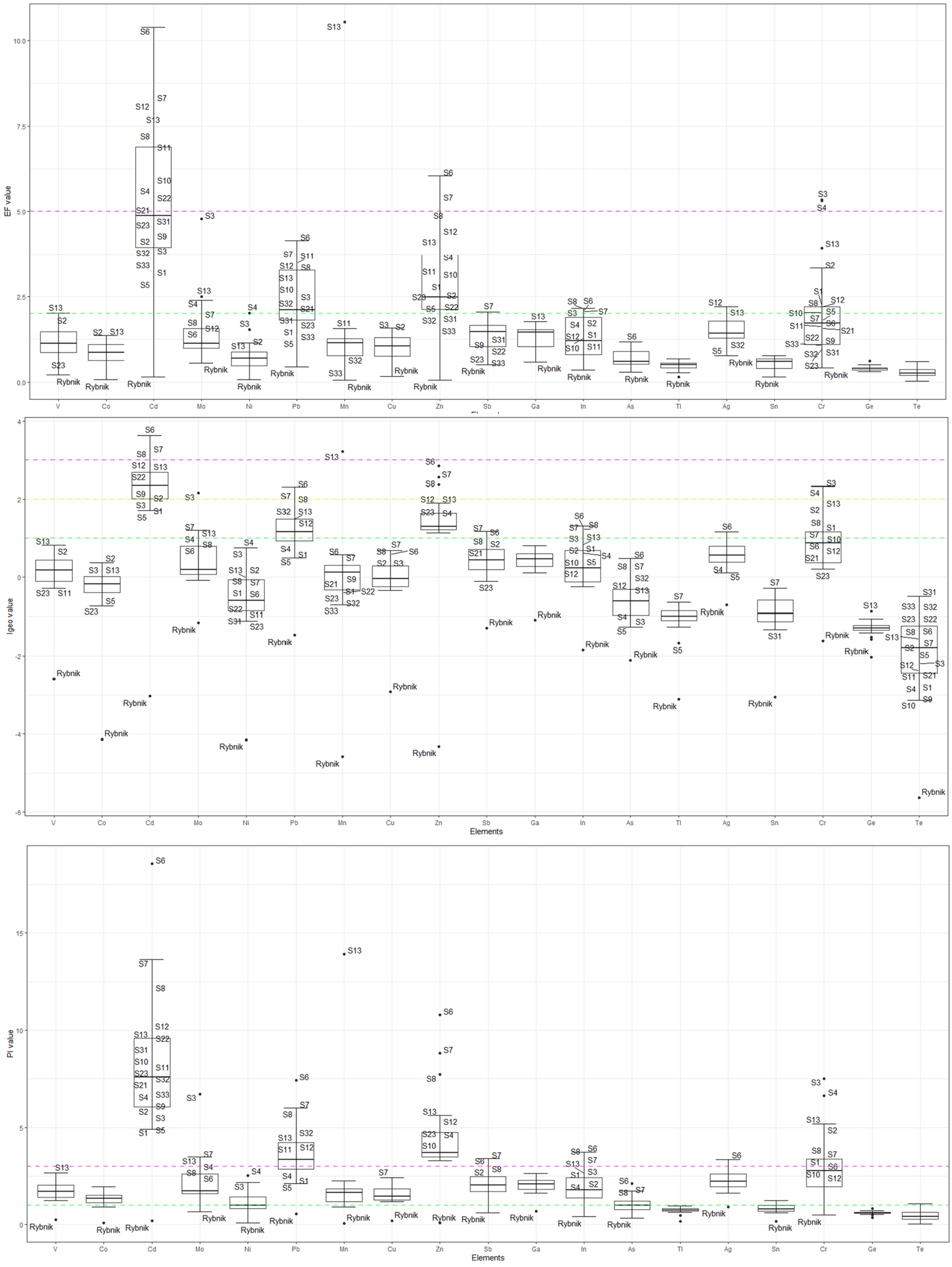
According to the Environmental Protection Agency (EPA, 1994), chloride, fluoride, nitrate, sodium, and sulphate could exist in mining wastewater due to various processing activities related to Zn-Pb ores extraction, such as blasting, mill operations, flotation, smelting, and refining of concentrates. Kamewada and Ooshima (2024) modelled the interaction of SO_4^{2-} ions with heavy metals in Japanese paddy soils. They found that sulphide-forming metals, including chalcocite (Cu_2S), greenockite (CdS), sphalerite (ZnS), galena (PbS), and chalcopyrite (CuFeS), dominate as a reflex to decreasing redox potential conditions. Consequently, the concentration of sulphate ions is significantly reduced to equilibrate the redox potential levels. Liu et al. (2010) identified a significant correlation between sulphate and antimony during their investigation of antimony speciation in the Xikuangshan mining area of China. This relationship was associated with the presence of stibnite (Sb_2S_3) ores, which release both components, and sulphide is oxidized to sulphate. On the other hand, Nyman et al. (2023) investigated the behaviour of various heavy metals and rare earth elements in sulphate-rich soils along the Swedish coastal plains. They found that under oxidized conditions, Cd, Co, Mn, Ni, and Zn are more likely to form soluble compounds with sulphates. In contrast, the concentrations of silver Ag, Cu, In, Sb, Sn, and Te are less susceptible to increasing in acid-sulphate soils that are influenced by water.

Pollution assessment

Pollution indices (I_{geo}, PI, EF) were calculated and displayed as box plots, which included classification threshold lines and corresponding sample points (Fig. 4). Notably, Ge, Te, and Tl showed the lowest levels of contamination and enrichment across all calculated indices. Additionally, the Rybnik sample, regarded as a witness sample, demonstrated no signs of contamination. In contrast, elements such as Cd, Cr, Pb, and Zn exhibited significant heavy contamination and enrichment, suggesting a potential anthropogenic influence on these elements. Generally, PI provides more conservative estimates than I_{geo} and EF, with most elements showing moderate to heavy contamination. Conversely, I_{geo} and EF tend to give more liberal estimates; apart from Cd, Cr, Pb, and Zn, most elements indicate no contamination or enrichment. Furthermore, a clear integration is observed between PCA and pollution indices analysis, where the relationships between samples and elements (scores and loadings) in PCA are illustrated in the box plots of pollution indices as outliers or maximum values. For instance, third-category elements like Cd, Pb, and Zn show higher contamination levels in S6, S7, and S8 samples. In contrast, second-category elements (e.g., Cr, Mo, and Ni) exhibit higher contamination associated with S2, S3, S4, and, to some extent, S13. Finally, it is worth mentioning that fourth-category elements, especially In and Sb, also exhibited higher contamination values in samples S6, S7, and S8.

Tomczyk et al. (2023) evaluated agricultural soils in Poland, including Upper Silesia, using contamination indices. Their findings indicated that the I_{geo} values ranged from moderate to heavy contamination for Cd, Cr, Pb, and Zn. Additionally, the PI ranged from light pollution to serious pollution for Cd, Pb, and Zn. However, they reported much higher EF than our results, especially for Cd, Pb, and Zn, with values exceeding 5. This suggests severe pollution and could be attributed to the different reference metals used in their study (Mn). Liu et al. (2021) studied the elements Ga, In, and Tl in soil profiles near industrial parks in Taiwan. They observed an unexpected increase in EF values at certain surface soil locations, with levels ranging from moderate to significant enrichment. Furthermore, empirical models have been established linking the EDTA-extracted phase as a function of the clay content and total concentrations of Ga or Tl using multivariate linear regression analysis, which reflected the dependency of bioavailability for Ga and Tl on the clay content of soils.

It is crucial to exercise caution when comparing contamination indices from other studies, as the


EF value
10.0
7.5
5.0
2.5
0.0
Igeo value
4
2
0
-2
-4
-6
PI value
15
10
5
0
V
Co
Cd
Mo
Ni
Pb
Mn
Cu
Zn
Sb
Ga
In
As
Tl
Ag
Sn
Cr
Ge
Te
Elements
Rybnik

◂**Fig. 4** Boxplots of Pollution Indices by Sample and Pollution Levels

varying reference metals and background values used in calculations significantly influence the results and interpretations of each study. TCE has received less attention concerning its environmental implications than typical heavy metals. This is evident in the limited research on estimating contamination indices for certain elements, such as Ga, Ge, In, Sb, Te, and Tl. Several factors contribute to this negligence: these elements often occur in low concentrations in soil and water, some are challenging to measure due to low limits of detection (LOD), and there is a lack of certified reference materials for them. Furthermore, there remains a significant gap in assessing their health impacts. For example, calculating the Ecological Risk Index is problematic because these elements do not have well-established Toxic Response Factor coefficients (Rezanul et al., 2023; Yandem & Jabłońska-Czapla, 2024). Overall, when relying on the results of geochemical indices, several important considerations must be taken into account. One critical factor influencing the reliability of these indices is the selection of the proper background concentration for the area being studied. This can involve using local geochemical surveys, pre-industrial baselines, or global averages. It's important to note that changes to the chosen baseline can significantly alter the index, sometimes by orders of magnitude.

For example, while the I_{geo} index employs a 1.5 multiplier to partially correct for lithogenic variability, this constant is empirical and may not be suitable for every region, particularly those with significant geological heterogeneity. Alternatively, the Enrichment Factor (EF) assumes that a normalizing element like aluminum is immobile, which helps to account for grain-size and mineralogical effects. However, if the normalizing element is itself susceptible to remobilization (due to acidic conditions or redox changes) or influenced by anthropogenic inputs, the EF may misrepresent the concentration of the target metal (Fang et al., 2019). Additionally, geochemical indices often overlook speciation, bioavailability, and ecological context. Typically, these indices rely on total metal concentrations; however, the ecological risk posed by a metal is determined by the more dynamic water-soluble or exchangeable fractions that organisms can actually absorb. Furthermore, the bioavailability of a metal is influenced not only by its total concentration but also by various environmental factors such as pH, redox conditions, and the presence of organic matter, all of which can either amplify or mitigate its potential toxicity (Nawrot et al., 2021).

Geospatial distribution of soil pollution

The geospatial maps (Figure S2) illustrate the concentrations of each element within the study area using IDW interpolation. This analysis reveals not only the differences among elements but also the variations in the concentration of each element across different zones. However, It is important to note that some elements exhibited considerable concentration ranges, particularly Mn, Zn, Pb, and Cr, while others had limited ranges, including Te, In, Tl, Ag, and Ge. The maps created from the geospatial analysis are consistent with the results of the PCA, for instance, elements within the third and fourth clusters show a notably higher concentration in the southern region, particularly around S6, S7, and S8. Hence, it is essential to consider the proximity to roads and buildings as an influencing factor. Interestingly, Ge, Mn, and Te (the first cluster) are evident in the northern region, particularly around samples found in the lower terraces, such as S13 and S33. This observation supports the idea that the mobility of these elements may be affected by runoff, leading to their accumulation in certain areas. Finally, elements from the second cluster (Co, Cr, Mo, Ni, and V) exhibit varying distributions among S1, S2, S3, and S4 samples, except for V, which showed relatively higher concentrations in the S13 sample. According to the analysis of pollution indices, the elements Ag, Cd, Cr, In, Mn, Mo, Pb, and Zn pose the highest environmental risks; despite Cd, Cr, Pb, and Zn present a broad spatial spread of contamination, some other elements have a limited spatial impact. For example, Mn demonstrates severe contamination only at S13, while Mo shows significant contamination mainly at S3, S4, S7, and S13. Additionally, indium has moderate contamination at S3, S6, S7, S8, and S13.

Conclusions

This study seeks to assess the environmental impact of PV panels, with a particular focus on their effects on soil quality at one of the oldest PV installations in Poland. The evaluation will include a comparison of these effects to other sources of pollution in the region, such as mining and smelting activities. Consequently, the following conclusions may be drawn:

- The PCA analysis identifies four major patterns related to soil chemical composition, including elements such as Ag, As, Cd, Pb, Tl, and Zn. These elements primarily originate from extensive mining and smelting activities in the Upper Silesia region. Additionally, Co, Cr, Mo, Ni, and V may derive from various types of agricultural soils in Poland. Elements like Cu, Ga, In, Sb, and Sn can come from e-waste and are also considered by-products of Zn-Pb ores, particularly found in slags. Finally, Ge, Mn, and Te might emanate from coal ash. Thus, there are potential confounding aspects related to various sources of pollution.
- The assessment of pollution indices (I_{geo}, PI, EF) reveals significant heavy contamination and enrichment of the elements Cd, Cr, Pb, and Zn, indicating a likely anthropogenic influence. Notably, Cd, Pb, and Zn exhibit higher contamination levels in samples S6, S7, and S8, while Cr shows more pronounced contamination in samples S2, S3, and S4, suggesting different sources of pollution. Additionally, In and Sb display moderate to higher contamination levels, but only in samples S6, S7, and S8.
- The close relationship between certain ions and trace metals may indicate a common potential source or result from competitive chemical interactions that lead to the formation of various chemical species in the environment. For instance, F^- and NO_3^- are closely connected to As, Ag, Cd, Pb, and Zn, while SO_4^{2-} demonstrates a strong association with Cu, Ga, In, Sb, and Sn. Additionally, an inverse relationship is observed between NH_4^+ with both In and Sb.
- The geospatial analysis implies that elements with high pollution indices, such as Cd, Cr, Pb, and Zn, are widely distributed throughout the study area. In contrast, the elements In, Mn, and Mo exhibit high pollution indices but have a more limited and localized distribution.

This study highlights the necessity of conducting additional research in the future across diverse geological contexts to generalize the findings on a larger scale and obtain more comprehensive closure. Furthermore, it is essential to design experiments that evaluate the impact of PV panels, as hazardous waste materials, on soil and water quality.

Acknowledgements The research was carried out in the frame of project which received funding from statutory research of the Institute of Environmental Engineering, Polish Academy of Sciences, for 2024, No. 1A-149/24

Author contributions M.J.C. Conceptualization, Supervision, Funding acquisition, Project administration, Methodology, Investigation, Writing-Original draft preparation, Writing- Reviewing and Editing. G.Y. Data curation, Investigation, Software, Formal analysis, Writing- Original draft preparation, Visualization, Writing- Reviewing and Editing. K.G. Investigation, Formal analysis, Writing- Original draft preparation, Writing- Reviewing and Editing. All authors reviewed the manuscript.

Funding The research was carried out in the frame of project which received funding from statutory research of the Institute of Environmental Engineering, Polish Academy of Sciences, for 2024, No. 1A-149/24.

Data availability The datasets are attached to the supplementary materials and are available from the authors.

Declarations

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.The authors declare no competing interests.

Ethical approval The Authors confirm that the manuscript entitled “Impact of photovoltaics on soil and water by metal(loid)s including TCEs contamination: preliminary study” has not been published previously and is not under consideration for publication elsewhere.

Consent to participate Informed consent was obtained from all authors to participate in the study.

Consent for publication All authors have given their consent for publication. The availability of data and materials is not applicable.

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