JEE Journal of Ecological Engineering

Journal of Ecological Engineering, 2025, 26(10), 416–425
https://doi.org/10.12911/22998993/205938
ISSN 2299–8993, License CC-BY 4.0

Received: 2025.05.23
Accepted: 2025.07.15
Published: 2025.07.25

Impacts of railway transportation on the enrichment of heavy metals in hortisols of allotment gardens in the city of Zawadzkie

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ABSTRACT

For many years, research has been conducted on the impact of transportation on soils in adjacent areas. An important component of transportation infrastructure is the railway network, which constitutes a significant source of environmental pollution. Of particular importance is the identification of potential threats posed by railway transport to the quality of soils intended for plant production. Such areas include allotment gardens, which occupy a special place in urbanized zones due to their location and function. This study aimed to assess the impact of a railway line on the soil quality of the "Hutnik" family allotment gardens in Zawadzkie, with particular emphasis on heavy metal content. A total of 20 research plots were designated, located in the vicinity of a forest complex (reference material) and near railway infrastructure (a potential emission source). Soil samples were collected from a depth of 0–25 cm.The total content of zinc (Zn), copper (Cu), lead (Pb), chromium (Cr), and nickel (Ni) in the analyzed soils showed variation between the reference plots and those exposed to the influence of the railway line. Elevated concentrations of Cu, Zn, and Pb were found in soils located close to the railway line. Based on the chemical analysis data, it was concluded that railway transport may pose a greater threat to the natural environment than previously expected.

Keywords: hortisols, railway, heavy metals, family allotment gardens.

INTRODUCTION

Anthropogenic activity causes a range of negative effects on all components of the environment, contributing to changes in soil chemistry in areas adjacent to pollution sources (Mielke, 2016). One significant source of contamination is railway lines (Liu et al., 2009). The environmental threat posed by railway infrastructure operation affects all elements of the environment—the atmosphere, lithosphere, hydrosphere, and biosphere (Wierzbicka et al., 2015; Stojic et al., 2017; Samarska et al., 2020; Radziemska et al., 2021). Existing literature has mainly focused on the impact of railway lines on soils and plants located in the immediate vicinity of railway lines, considering land use types (Baltrėnas et al., 2009; Zhang et al., 2012; Tomczyk-Wydrych et al., 2021). The main pollutants emitted by railway transport include, for example, heavy metals, PAHs, PCBs, oil-derived products, and pesticides (Gehrig et al., 2007; Burkhardt et al., 2008).

Of particular concern are emissions of heavy metals, which tend to bioaccumulate and pose a threat to the entire biosphere (Chen et al., 2014; Kim et al., 2014; Malone and Shakya, 2024). Excessive amounts of xenobiotics can lead to environmental degradation and induce abiotic stress. The growing anthropogenic pressure, especially related to the accumulation of heavy metals and soil acidification, contributes significantly to the decline in soil productivity and fertility (Barthel et al., 2010; Mielke, 2016). Elevated concentrations of heavy metals enter the food chain, negatively affecting all elements of the biosphere, and can accumulate in plant tissues, thus posing a risk to consumers (Kabata-Pendias and Pendias, 1999). Soil contamination with heavy metals in agriculturally used areas, including allotment gardens, is an important factor influencing the potential transformation of land from food production to solely recreational use (Kim et al., 2014; Malone and Shakya, 2024).

Family allotment gardens (FAG), which are a vital element of urban landscapes, serve many socio-cultural functions (Bellows, 2004; Pawlikowska-Piechocka, 2011; Kaiser et al., 2015; Bell et al., 2016; Klepacki and Kujawska, 2018). These areas fulfill recreational and leisure needs, promote social integration, and enhance the ecological standards of their surroundings (Barthel and Isendahl, 2013; Bendt et al., 2013). Despite the care and ecological awareness of their users, allotment gardens are exposed to a range of environmental threats resulting from both improper use and the impact of transportation and industrial pollution (Rubino, 2007). Plant cultivation on hortisols depends primarily on soil properties, including texture, pH, salinity, and macro- and micronutrient content. These factors affect crop yield, however, an extremely important issue is the quality of the food produced, especially regarding the risk of contamination, for example, by heavy metals.

To assess the potential threat of anthropogenic contamination in garden soils, 20 research plots were designated within the "Hutnik" Family Allotment Gardens in Zawadzkie, which have been part of the urban structure since 1956. Their location near railway infrastructure, a small wastewater treatment plant, and the "Andrzej" Pipe Rolling Mill Ltd. indicates the potential influence of anthropogenic factors.

This study presents anthropogenic threats resulting from the spatial distribution of the examined hortisols in an industrial area and along transportation routes, with particular emphasis on the level of soil contamination with heavy metals.

Methodology

Characteristics of the research site

The study plots were located in the "Hutnik" Family Allotment Gardens (FAG), situated in the southwestern part of the town of Zawadzkie, along Voivodeship Road No. 901, in the vicinity of Railway Line No. 144, which runs from east to west across Poland, connecting Zawadzkie with Opole. The research area is separated from the railway line by a strip of shrubs and tree vegetation. Nearby, there are both a voivodeship road and a county road, and to the south, a dirt road. The closest industrial facilities bordering the "Hutnik" allotment gardens include a small wastewater treatment plant located to the south and a gasworks situated to the east.

Soil sampling

Twenty plots measuring 10 × 10 m were designated in the study area (Figure 1), from which composite soil samples were collected from the 0–25 cm layer in accordance with the PN-E-04031 standard. Samples were taken during two periods: March 2023 and October 2023. Sampling locations were arranged in transects to enable analysis of the potential influence of various anthropogenic factors on the examined soils. Plots numbered 1, 2, 3, 4, 9, 10, 17, 18, 19, and 20 were located in close proximity to a forested area, while plots numbered 5, 6, 7, 8, 11, 12, 13, 14, 15, and 16 were situated along the railway line.

After being transported to the laboratory, soil samples were dried at a temperature of 25 °C. The soil material was then homogenized and sieved through a 2 mm mesh. The following analyses were performed on the collected samples:

- granulometric composition using the hydrometer method of Bouyoucos, modified by Casagrande and Prószyński (PN-04032:1998);
- pH in KCl solutions at a soil-to-solution ratio of 1:2.5, measured potentiometrically (BN-75/9180-03);
- electrical conductivity at a soil-to-water ratio of 1:5, measured by the conductometric method (PN-ISO 11265:1997);
- organic matter content by dry combustion after prior removal of carbonates (PN-ISO 10694:2002);
- calcium carbonate content using the Scheibler volumetric method (PN-EN ISO 14688-1);
- content of Zn, Cu, Pb, Cr, and Ni after mineralization in a mixture of nitric and perchloric acids (1:3), determined by atomic absorption spectroscopy (AAS) using a Philips PU 9100X spectrometer.

Statistical analysis

The statistical analysis of the results was conducted using the Statistica 13.3 software. In order to assess the potential impact of anthropogenic factors on selected soil parameters, the following statistical tests were performed: the

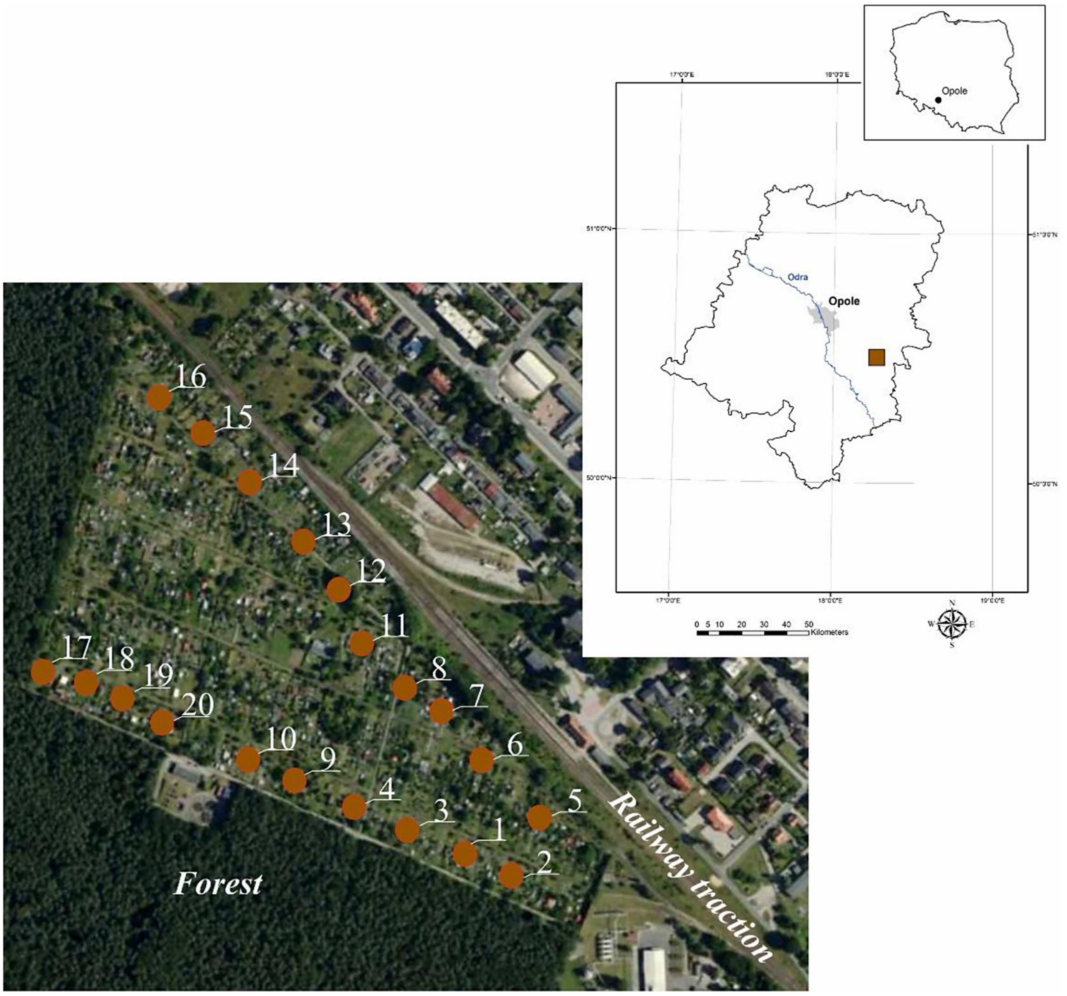

Figure 1. Places for collecting soil samples and their location in family allotment gardens in the city of Zawadzkie

Mann–Whitney U test, and principal component analysis (PCA).

RESULT AND DISCUSSION

All analyzed soils were characterized by a sandy granulometric composition, with varying amounts of clay fraction, which allowed them to be classified as loose sands, slightly loamy sands, and loamy sands.

The analysis of pH_{KCl} values in the studied soils indicates slight variation. The pH ranged from slightly acidic to neutral. The results of the Mann–Whitney U test showed no significant differences between the study plots located along the forest and those situated along the railway line in both sampling periods (Figure 2). The soils of all study sites were characterized by a low calcium carbonate content (non-calcareous soils).

The electrical conductivity (EC) of the analyzed soils ranged from 36.4 $\mu S \cdot cm^{-1}$ to 257.8 $\mu S \cdot cm^{-1}$ in the spring season and from 62.1 $\mu S \cdot cm^{-1}$ to 173.3 $\mu S \cdot cm^{-1}$ in the autumn season (Figure 3). Statistical analyses did not indicate significant differences in this parameter depending on the location of the study plots (Student's t-test for independent samples, $p = 0.5698$). At the adopted significance level ($\alpha = 0.05$), the test confirms no significant differences between the samples. Additionally, none of the tested soils exceeded the threshold value for plants of 2 $mS \cdot cm^{-1}$ (Jackson, 1958). At salinity levels above this threshold, most plant species in natural environments begin to die off.

The total content of heavy metals in soils of urban and industrial areas is a useful indicator of anthropogenic pressure and a marker of potential environmental contamination, allowing for the assessment of soil degradation and the estimation

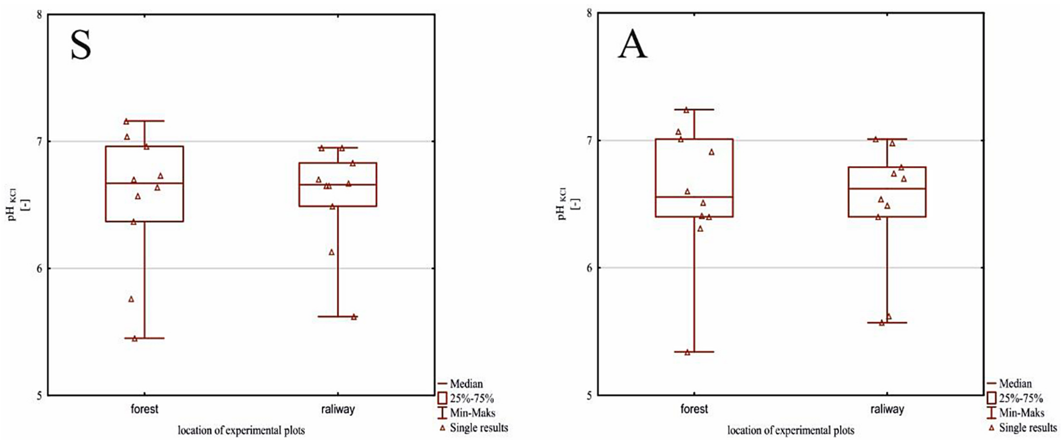

Figure 2. Distribution of pH_{KCl} values in the soils located near the forest and the railway line during the two sampling periods (S – spring, A – autumn)

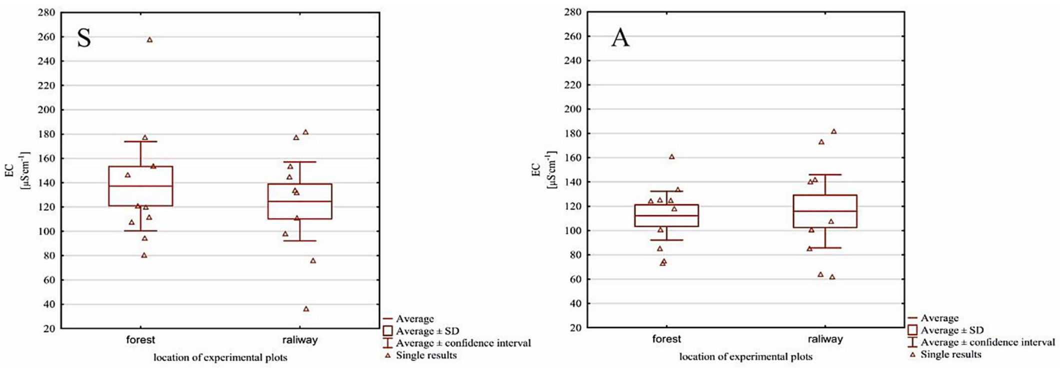

Figure 3. Distribution of electrical conductivity values in the studied soils located near the forest and the railway line during the two sampling periods (S – spring, A – autumn)

of potential bioaccumulation of the analyzed elements. The distributions of the analyzed elements are presented in Figures 4 and 5. It should be also noted that soil moisture dynamics affect the kinetics of heavy metal reactions with soil and the instability of their bonds in metal-organic complexes under field conditions, as clearly emphasized by Lv et al. (2024). The soils of the allotment gardens were subject to different cultivation, fertilization, and irrigation systems. Therefore, the variability in the total forms of heavy metals between the objects showed differentiation expressed by the coefficient of variation, as presented in Table 1.

The Zn content in the studied soils ranged from 46.2 to 282 $mg \cdot kg^{-1}$. The reference soils were characterized by a median Zn content of 92.7 $mg \cdot kg^{-1}$, with relatively low variability. In contrast, soils from the transect located near the railway tracks exhibited significantly higher Zn values – the median increased, and maximum values reached nearly 282 $mg \cdot kg^{-1}$. Zn shows strong enrichment in railway soils, indicating its anthropogenic origin – likely resulting from the wear of metal components, brakes, and rails (Klik et al., 2025). Considering the framework guidelines for agriculture by Kabata-Pendias et al. (1995), an elevated (levels I and II) zinc content was found in all soils of the allotment gardens (Table 1). At the same time, according to the Regulation of the Minister of the Environment of 1 September 2016 on the method of assessing soil contamination (Journal of Laws 2016, item 1395), for allotment garden soils (soil group category II, subgroup II-1), all analyzed soils showed permissible levels of zinc, not indicating an exceedance of the permissible content of this element set at 300 $mg \cdot kg^{-1}$.

The Cu content in the reference soils ranged from 3.85 to 30.4 $mg \cdot kg^{-1}$, with a median value of 11.1 $mg \cdot kg^{-1}$. In contrast to the reference soils, the soils near the railway line had significantly higher Cu concentrations, with some samples exceeding 40 $mg \cdot kg^{-1}$. The median was also higher than in the soils adjacent to the forest. The observed

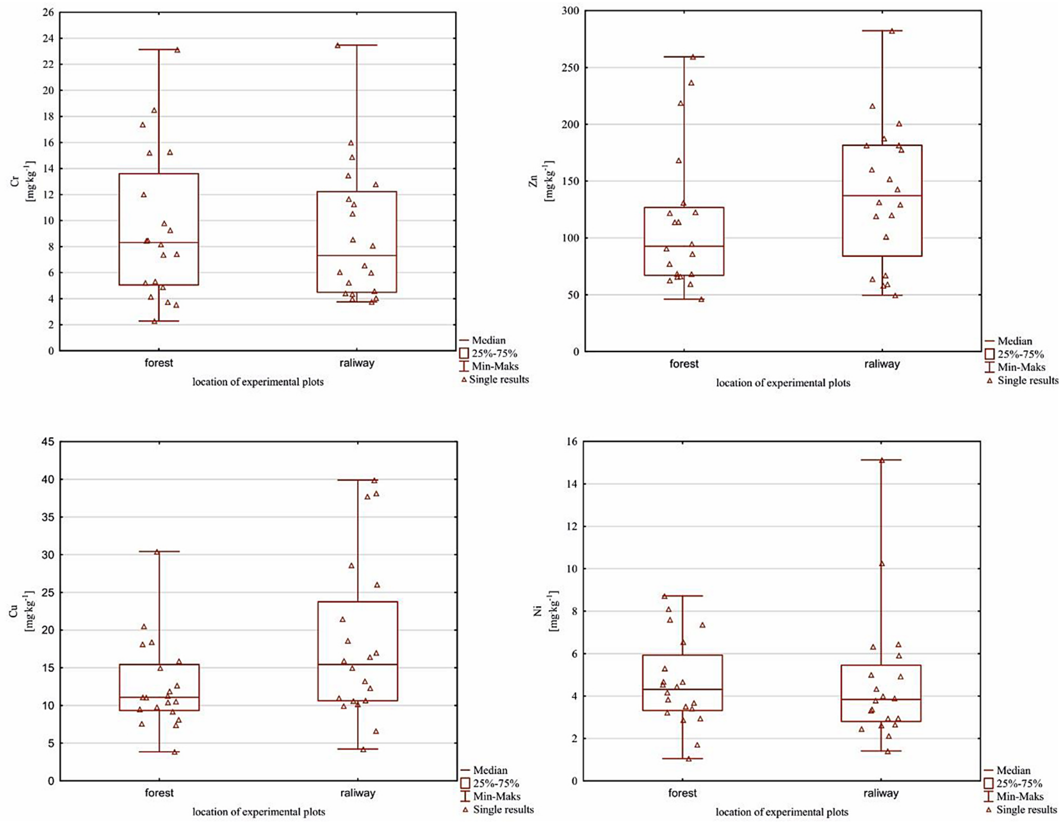

Figure 4. Distributions of total forms of the studied heavy metals (Cr, Zn, Cu, Ni, Pb) determined in the soils located in the vicinity of the forest and the railway line

anthropogenic accumulation of Cu in soils near the railway is associated with elements of the electric traction system and copper wiring (Safadoust et al., 2025).Taking into account the framework guidelines for agriculture by Kabata-Pendias et. al (1995), presented at the Table 1, an elevated (levels I and II) copper content was found in some soils, without correlation with their location (forest edge or railway line). Simultaneously, according to the Regulation of the Minister of the Environment of 1 September 2016 on the method of assessing soil contamination (Journal of Laws 2016, item 1395), for allotment garden soils (soil group category II, subgroup II–1), all analyzed soils exhibited copper levels within permissible limits, not indicating an exceedance of the allowable content of this element, set at 100 mg·kg^{-1}.

Pb concentrations ranged widely, from 16.4 to 532 mg·kg^{-1}. In reference soils, Pb values were low (median of 31.2 mg·kg^{-1}) and within a narrow range. In contrast, the distribution of Pb in soils near the railway line was much broader, with maximum values exceeding 532 mg·kg^{-1} – possibly indicating localized contamination. This enrichment may result from the historical use of lubricants, lead components, or fossil fuel combustion (Wong et al., 2006; Alloway, 2013). Considering the framework guidelines for agriculture by Kabata-Pendias et. al (1995), an elevated (levels I and II) as well as high (levels III and IV) lead content was identified in some soils (Table 1). The highest concentrations of lead were found in soils from plots 6, 8, 12, and 16, which are directly adjacent to the railway line. This clearly indicates the source of contamination and indicates these plots as a buffer zone for neighboring soils of other plots located parallel to the railway line. At the same time, in accordance with the Regulation of the Minister of the Environment of 1 September 2016 on the method of assessing soil contamination (Journal of Laws 2016, item 1395), the soils from these specific plots (6, 8, 12, 16) exceeded the permissible content of lead, which is set at 100 mg·kg^{-1}.

In the studied soils, Cr concentrations ranged from 2.29 to 23.4 mg·kg^{-1}. In soils located near the forest, these values varied widely, with a few outliers and a median of 8.31 mg·kg^{-1}. A similar distribution was observed in soils near the railway tracks; however, values in this group were lower and clustered near the lower end of the range

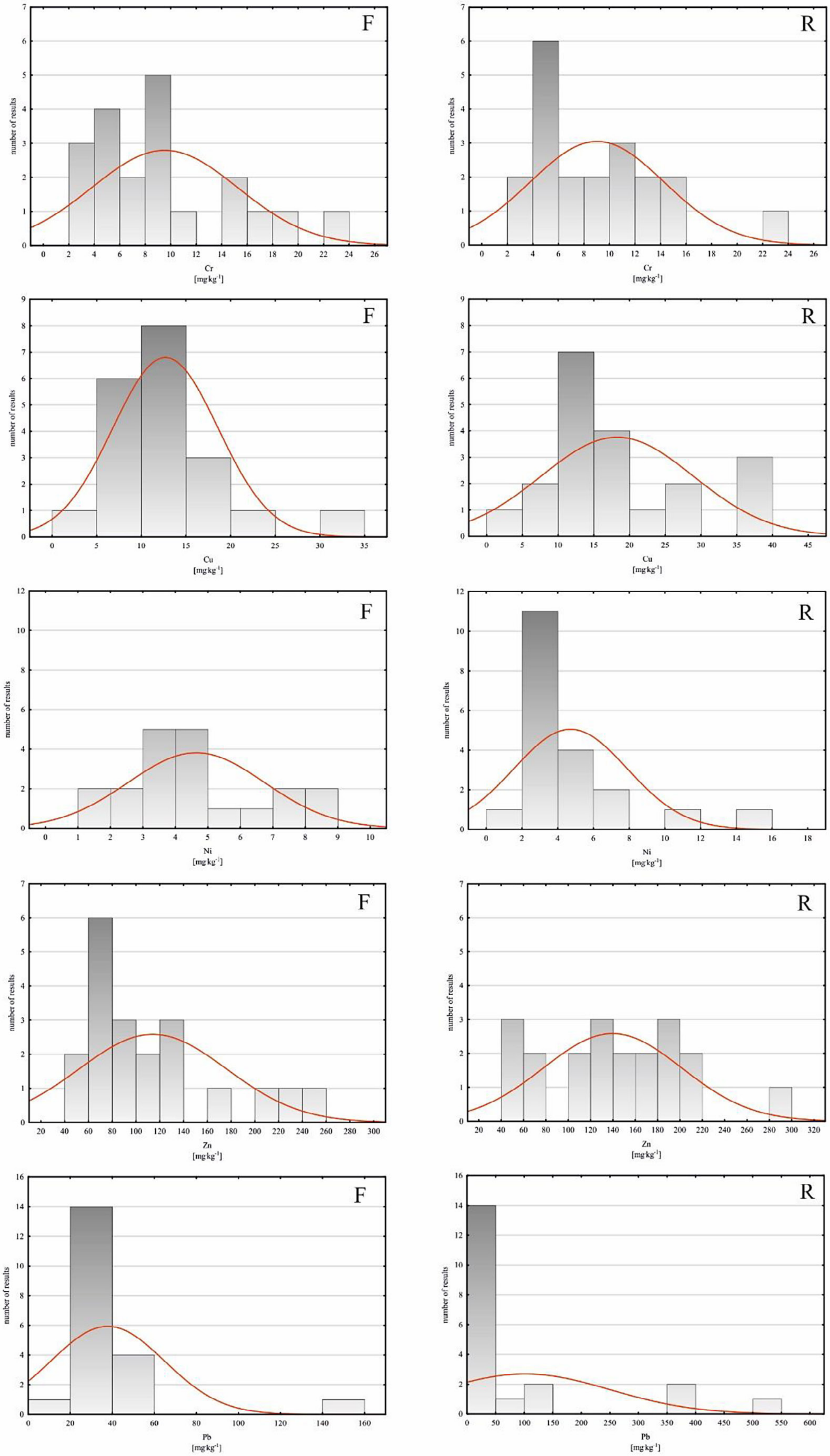

Figure 5. Distributions of total forms of Cu, Zn, Ni, Pb, and Cr determined in the soils located in the vicinity of the forest (F) and the railway line (R)

Table 1. The level of contamination according to Kabata-Pendias et al. (1995)

No of object	Collection time	Zn	Cu	Pb	Cr	Ni
Localization next to the forest line						
1	Spring	II	0	I	0	0
	Autumn	II	I	III	0	0
2	Spring	I	0	I	0	0
	Autumn	I	0	0	0	0
3	Spring	II	I	I	0	0
	Autumn	II	I	I	0	0
4	Spring	I	0	0	0	0
	Autumn	I	I	0	0	0
9	Spring	I	0	I	0	0
	Autumn	I	0	I	0	0
10	Spring	II	0	0	0	0
	Autumn	II	I	I	I	0
17	Spring	I	0	0	0	0
	Autumn	II	0	0	0	0
18	Spring	II	0	I	0	0
	Autumn	I	0	0	0	0
19	Spring	I	0	I	0	0
	Autumn	II	0	I	0	0
20	Spring	I	II	0	0	0
	Autumn	I	0	0	0	0
Average content in mg·kg^{-1}	Spring	93.23	12.69	31.79	6.23	4.30
	Autumn	134.04	12.55	43.46	12.72	4.94
Localization next to the railway line						
5	Spring	II	0	I	0	0
	Autumn	II	I	I	0	0
6	Spring	II	II	III	0	I
	Autumn	II	II	IV	I	I
7	Spring	II	0	I	0	0
	Autumn	II	I	I	0	0
8	Spring	II	I	I	0	0
	Autumn	II	I	III	0	0
11	Spring	I	0	0	0	0
	Autumn	II	0	0	0	0
12	Spring	II	0	0	0	0
	Autumn	II	I	III	0	0
14	Spring	I	0	0	0	0
	Autumn	II	0	0	0	0
16	Spring	I	I	III	0	0
	Autumn	II	0	I	0	0
18	Spring	II	0	I	0	0
	Autumn	I	0	0	0	0
20	Spring	I	II	0	0	0
	Autumn	I	0	0	0	0
Average	Spring	104.12	18.03	102.21	5.35	5.05
	Autumn	163.09	15.89	101.38	12.40	4.75
Coefficient of variation [%]	Spring	40.14%	65.05%	160.54%	60.01%	65.48%
	Autumn	46.36%	51.07%	160.65%	40.08%	49.00%

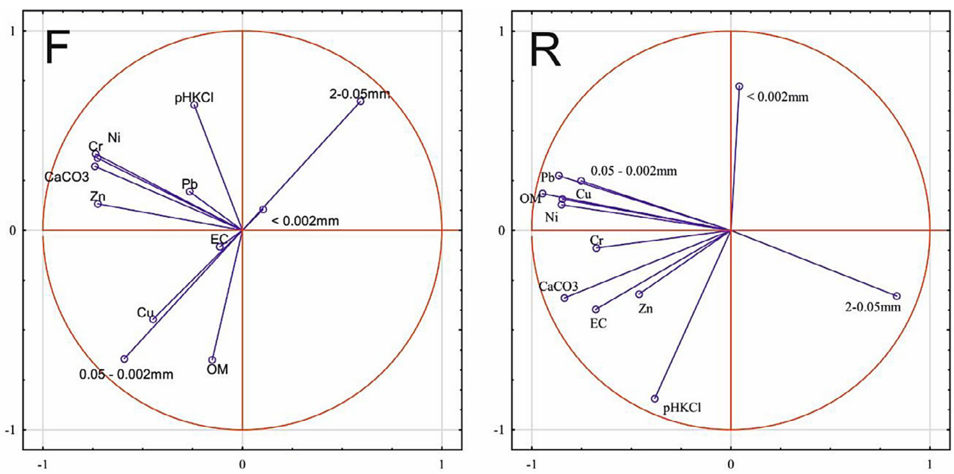

Figure 6. Principal component analysis (PCA) in the analyzed soils, including reference soils – F and those affected by emissions from the railway traction – R

— suggesting a lack of significant chromium enrichment in railway soils. For this element, a natural origin is indicated, with no clear anthropogenic influence. Similarly to Cr, the distribution of Ni content in the studied samples was comparable and did not show significant differences between them. The lack of observed enrichment in this element may suggest its natural origin in the studied area, presented at the Table 1. The content of chromium and nickel in the analyzed soils, according to the Regulation of the Minister of the Environment (Journal of Laws 2016, item 1395), did not exceed the permissible limits: 150 $mg \cdot kg^{-1}$ for chromium and 100 $mg \cdot kg^{-1}$ for nickel. The average chromium content ranged from 6.23 $mg \cdot kg^{-1}$ in the spring season to 12.72 $mg \cdot kg^{-1}$ in the autumn season in soils located along the forest edge and from 5.35 $mg \cdot kg^{-1}$ in spring to 12.40 $mg \cdot kg^{-1}$ in autumn in soils along the railway line. For nickel, these values were 4.30 $mg \cdot kg^{-1}$ and 4.95 $mg \cdot kg^{-1}$ for forest-edge soils, and 5.05 $mg \cdot kg^{-1}$ and 4.75 $mg \cdot kg^{-1}$ for railway-line soils, respectively.

Based on PCA conducted for the reference soils (F) and the soils under the influence of railway traction emissions (R), significant differences were observed in the distribution of variables, which can be interpreted both in terms of their sources and the geochemical factors influencing their distribution (Figure 6).

In the case of reference soils (F), variables such as Cr, Ni, Zn, Pb, and $CaCO_3$ cluster closely together, indicating a strong correlation, which suggests a common – lithogenic – origin of these elements (Kabata-Pendias and Pendias, 1999). These metals are often associated with the mineral fraction of soil, especially in areas not affected by anthropogenic activities. The variable pH_{KCl}, representing soil acidity, is positioned independently, which may indicate that pH does not have a significant effect on the mobility of the studied metals under these conditions (Alloway, 2013). Granulometric fractions such as < 0.002 mm and 0.05–0.002 mm, as well as organic matter content (OM) and electrical conductivity (EC), play a lesser role in the PCA distribution, confirming the dominant influence of natural geochemical factors.

In soils affected by railway traction emissions, a distinctly different distribution of heavy metals is observed. Pb, Cu, Ni, and Cr are strongly correlated and aligned with the 0.05–0.002 mm fraction and OM, indicating their association with organic matter and the fine mineral fraction. This is consistent with studies showing that metals of anthropogenic origin (e.g., from transportation emissions, including railway traction) tend to accumulate in the fine soil fractions and organic matter (Wong et al., 2006; Chen et al., 2008).

The significance of variables such as EC and pH_{KCl} increases in contaminated soils – which may indicate increased ion content and changes in the soil's sorption conditions due to anthropogenic emissions (Adriano, 2001).

CONCLUSIONS

The conducted study in the area of the "Hutnik" Family Allotment Gardens in Zawadzkie revealed clear differences in the chemical composition of reference soils and soils located near the railway line. The most noticeable increases in concentrations were observed for zinc (Zn), copper (Cu), and lead (Pb) in the railway-adjacent soils. This indicates their anthropogenic origin, most likely related to transport activities, wear of mechanical components of railway infrastructure, and emissions of metallic dust.

Elevated levels of Cu, Zn, and Pb in soils in close proximity to the railway line may pose a threat to the environment, particularly concerning the bioavailability of these elements and their potential toxicity. Soils play a key role as a chemical buffer and reservoir of pollutants, and the presence of heavy metals can affect the health of plants, microorganisms, and higher organisms. Soil contamination along railway tracks thus requires continued monitoring and, if necessary, the implementation of protective measures.

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