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ECOLOGICAL RISK ASSESSMENT OF HEAVY METALS IN SOILS FROM THE LINEAR EMISSION OF RAILWAY TRANSPORT IN WROCŁAW, POLAND

The purpose of this investigation was to assess anthropogenic soil contamination by heavy metals (HMs) from rail transport-related activities in Wrocław. The concentrations of copper, zinc, lead, chromium, nickel, and cadmium were analysed in the surface soil layer along the railway tracks and perpendicularly, at increasing distance from the rail line. Pollution indices were used to assess the level of enrichment by single elements, the degree of total HM contamination, and the ecological risk associated with their presence in soils. The results indicated moderate enrichment with Cu, Zn, and Pb, while Cr and Ni occurred at geochemical background levels. The highest degree of accumulation and ecological risk was found for Cd, indicating its strong anthropogenic origin. Multi-elemental indices classified the overall level of soil contamination as low, although locally elevated metal concentrations were observed. A considerable proportion of samples exhibited high ecological risk. The phytotoxicity tests using *Lepidium sativum* L. and *Avena sativa* L. confirmed a slight inhibition of plant growth.

1. INTRODUCTION

The toxicity of heavy metals (HMs) to microflora, microfauna, and higher plants and animals [1, 2] raises interest in the environmental impact of rail transport, particularly regarding the potential threat posed by HMs to soils adjacent to railway tracks [3–6]. In Poland, rail transport plays a significant role in passenger mobility and mass freight transport. Poland's accession to the European Union in 2004 contributed to the modernization and improvement of the country's rail network. Currently, Poland has a well-developed railway infrastructure, with an average density of 6.2 km/100 km^2, which is higher than the average for all EU countries, 4.8 km/100 km^2 [7]. In 2021, the total

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length of railway lines in Poland exceeded 19 300 km and has remained at a similar level. The Lower Silesian Voivodeship accounts for one of the largest shares of the length of the country's rail network. Railway density in Lower Silesia, measured as a line length, is 8.90 km per 100 km^2, which represents a 9.19% share of lines operated in 2021 [8]. Among all carriers in Poland, rail transport recorded the largest increase in passenger transport in 2024, rising by 8.8% compared to the preceding year. The total volume of freight transported decreased slightly by 3.9% relative to 2023. In the structure of freight transport, the largest share (23.3% in total) consisted of metal ores and other mining products, peat, uranium, and thorium. Rail freight accounted for 64.7% of domestic transport, most frequently covering distances of 150–299 km [9].

The negative environmental impact of rail transport is primarily associated with noise emission, air and soil pollution, and landscape alterations. Operation of railway networks generates pollutants, including heavy metals, along rail lines due to the abrasion of steel components, storage and transport of goods and solid or liquid fuels, leaks of operational substances (oils, lubricants), leaching from treated railway sleepers, and the use of herbicides [10, 11]. The presence of pollutants associated with rail transport in soils results from the operation of rolling stock with outdated technology and low efficiency, which leads to higher consumption of fuels and lubricants, and increased exhaust emissions from engines running on solid and liquid fuels. Dust generated by the wear of brake linings and the abrasion of wheels, surface layer of traction wires, track, and turnout components (rails, switches, and crossings) constitutes a significant source of pollution, primarily alongside railway lines [12, 13]. The extent of dust containing HMs decreases with distance from railway tracks, although this decline is not linear [14, 15]. Significantly larger amounts of dust are generated at railway junctions due to variable traffic characteristics and frequent starting and braking maneuvers, as well as at switches, level crossings, and traffic signals. Naturally, the magnitude of linear emission is influenced by the terrain and surrounding development. There is also a risk of soil contamination due to the uncontrolled release of goods during loading and unloading operations. Additional hazards may arise from wastewater generated during the cleaning of wagons and locomotives, which contains soot, mineral dust, and chemicals present in cleaning agents. Moreover, sources of metal emissions can include railway accidents, repair and maintenance work along the rail lines, periodic inspections, emergency repairs, and routine maintenance of rolling stock (wagons and locomotives) on railway sidings.

The study assessed the impact of railway infrastructure on the concentrations of six heavy metals in the surface layer of soils along the tracks, and their spatial extent perpendicular to the outer tracks at the railway lines and sidings of the Wrocław Brochów (SW part of the city) and the Wrocław Sołtysowice (NE part) railway stations. Using contamination indicators, soil enrichment by single elements and the total contribution of heavy metals were determined, and the environmental risk associated with the toxic effects of HMs on soil biocenosis was assessed.

2. MATERIALS AND METHODS

Research area and collection points. The study area included two locations with railway lines and transfer points in Wrocław, in the Sołtysowice and Brochów districts. The first study site is in the northeastern part of the city, within the Sołtysowice district, and serves two railway lines: Kalaty–Wrocław Mikołajów and Jelcz Miłoszyce –Wrocław Osobowice. These lines are a part of the urban and suburban railway network of Wrocław County. Four collection points (*A*–*D*) were established along the rail line. Soil sampling was carried out perpendicular to the outer track at distances of 1, 10, 20, and 30 m, respectively (Fig. 1). In total, 16 samples were obtained.

Fig. 1. Collection points [mapy.geoportal.gov.pl]

The studied section of the railway line is used for both passenger and freight traffic. In 2024, the daily passenger exchange at Wrocław Sołtysowice station (*C*) was below 1000 persons [16]. Throughout sections *A*–*C*, two railway lines run in parallel (single- and double-track), whereas at point *D*, only a single-track line is present. Train traffic is variable due to the speed limit of 30 km/h, braking and starting maneuvers at the active railway station, as well as deceleration and acceleration on the curve of the single-track line (*D*), and at level crossings with light signals (*A* and *C*). Near points A and B, there are single- and multi-family residential buildings, while points C and D are surrounded by shops and vacant lots. The tracks are laid on impregnated wooden sleepers (*A* and *B*) or concrete sleepers (*C* and *D*). At the railway siding *B*, trains stop for loading and unloading operations and for joining or leaving regular traffic. There are no industrial facilities near the rail line; however, approximately 250 m away lies a very busy Bolesław Krzywousty Street, which forms part of the RING 3 bypass in Wrocław. Traffic measurements recorded in 2024 were highest at the Krzywousty Bridges, nearest to point *D*. At the NE entrance to the Krzywousty Bridges, heading toward the city centre, 31 566 vehicles passed over 16 hours. Traffic in the opposite direction, at the SW entrance from the city centre, amounted to 30 869 vehicles over the same period. In total, 62 435 vehicles were recorded between 5 a.m. and 9 p.m. At Wrocław Sołtysowice station (*B*), 10 716 vehicles passed over 16 hours. On the section of Sołtysowicka Street near the collection point *A*, 11 809 vehicles were observed during the same period [17].

The second study site is a freight railway junction located in the southweastern part of Wrocław, in the Brochów district. It belongs to one of the two largest freight stations in Poland. Adjacent to the freight station is a passenger station serving the railway lines Wrocław Główny–Opole and Wrocław Główny–Jelcz Laskowice. This station operates as part of the suburban and intercity railway network. The daily passenger exchange at Wrocław Brochów station is below 1500 persons [16].

Along a 4 km section, nine collection points (*A–I*) were established. At each location, soil samples were taken perpendicular to the railway line at distances of 1, 5, 10, and 20 m from the outer track (Fig. 1). In total, 36 samples were obtained.

The study area is characterized by a great variety of rail lines, laid on both concrete and wooden sleepers. The Brochów railway junction features numerous signalized points, turnouts, and level crossings with concrete panels. The railway infrastructure in Brochów is mostly surrounded by vacant land or allotment gardens. Along the tracks flow the small Brochówka River (a left-bank tributary of the upper River Oława) and the Katarzynka River. Key locations in the studied section include the railway station close to point *C*, and the maintenance halls for railway rolling stock and infrastructure near point *D*. In the immediate vicinity, there are single- and multi-family residential buildings, allotment gardens, green areas, and vacant land. Approximately 80 m from the railway line runs Mościcki Street. Traffic measurements from 2024 indicate that on the RING 3 section with the railway viaduct connecting Mościcki Street and Wiaduktowa Street (between points *A* and *B*), 15 681 vehicles passed over hours. Outside the RING 3 area, the number of vehicles increased to 31 301 between 5 a.m. and 9 p.m. However, beyond measurement point *I*, at the intersection of Mościcki Street and Pięćdziesięciu Bohaterów Street, the daily traffic was significantly lower, amounting to 2825 vehicles over 24 hours [17].

The operation of railway rolling stock and maintenance activities on the siding, including inspections, routine and emergency repairs, cleaning of wagons, locomotives (standard-gauge, electric, and diesel), and tank cars, can release heavy metals (HMs) into the environment. The presence of viaducts and noise barriers may additionally transport pollutants with air masses to greater distances from the source [18].

From an area of about 1 m^2 (including the corners and the center), five soil subsamples were collected from a depth of up to 20 cm. The subsamples were combined, thoroughly mixed, and cleared of larger particles, then air-dried, ground, and sieved. The total weight of the representative sample was approximately 100 g.

Sample preparation and computing. Soil suspensions in a 1:2.5 (w:v) ratio were prepared to determine electrical conductivity and exchangeable acidity. In the first series, soil portions of approximately 10 g were mixed with 25 cm^3 of distilled water. In the second series, the samples were mixed with 25 cm^3 of a neutral potassium chloride solution at a concentration of 1 mol/dm^3. Soil samples of approximately 0.2 g were treated with 8 cm^3 of 65% nitric acid. Digestion was performed using a microwave mineralizer. The total content of heavy metals in the filtrates was determined by flame or graphite furnace atomic absorption spectroscopy using an iCE3500 Thermo Solaar spectrometer. Spectroscopic measurements were performed in triplicate for each solution. The results were verified based on standard deviation. Solutions of the certified reference materials were used for method validation and calibration curves. The quality of the procedure was controlled using a blank reagent sample containing only nitric acid.

The phytotoxicity of soil samples collected along railway tracks was assessed based on the inhibition of seed germination and plant organ growth. Garden cress (*Lepidium sativum L.*) and oat (*Avena sativa L.*) were used as test species. Garden soil served as the control sample. The experiment was conducted under controlled temperature and moisture conditions. Cress seeds (10 pieces each) were placed on test plates with a soil extract prepared at a 1:10 (w/v) ratio, and oat seeds (10 pieces) were sown in pots containing the studied soil. The experiment was conducted in three replicates. Observations were carried out over a period of 7 days. Based on the measured lengths of cress roots and oat roots, the percentage of growth inhibition was calculated.

The ecological exposure assessment considered the maximum permissible metal concentrations in soils on transport areas, including railway areas (group IV), as specified by Polish law in the Regulation of the Minister of the Environment of 1st September 2016, which are, in mg/kg: 2000 (Zn), 1000 (Cr), 600 (Pb and Cu), 500 (Ni), and 15 (Cd) [19]. For family allotment garden areas (group II), the acceptable metal concentrations in soils along railway routes are, in mg/kg: 500 (Zn), 300 (Cr), 250 (Pb), 150 (Ni and Cu), and 3 (Cd). The adopted reference environment was the elemental composition of the upper continental crust with concentrations in mg/kg: 92 (Cr), 67 (Zn), 47 (Ni), 28 (Cu), 17 (Pb), and 0.09 (Cd) [20]. The assumed single-elemental (I_{geo}) and multi-elemental (PLI, PI_{avg}, $PI_{Nemerow}$, RI, and $MERMQ$) environmental pollution indices have been discussed in detail by Hołtra and Zamorska-Wojdyła [21].

3. RESULTS AND DISCUSSION

3.1. ORIGIN AND DISTRIBUTION OF HMs IN SOILS

Wrocław Sołtysowice railway line. The characteristics of train traffic between points *A–D* significantly influenced the observed variability in HM concentrations in soils (Fig. 2). On the *A–C* section, there are higher train traffic intensity, frequent braking and acceleration maneuvers, and the presence of traffic lights at crossings, which correspond with the highest recorded metal levels, particularly of Pb, Zn, and Cu. These contaminants are typical of mechanical wear of brakes, traction components, and contact wires. At point *B*, located near a railway siding where trains stop for loading and unloading, local maxima of Pb and Cu concentrations are observed.

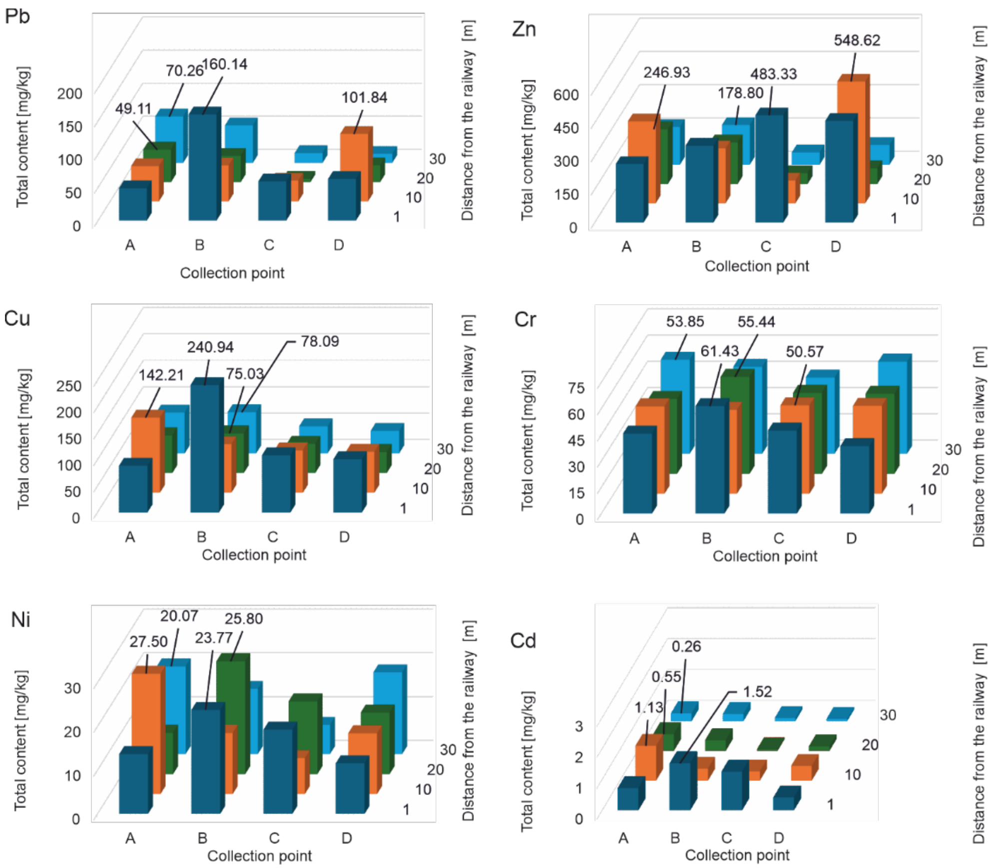

Fig. 2. Spatial distribution of HMs in soils, Wrocław Sołtysowice

This may indicate the accumulation of pollutants originating from fugitive emissions (metallic dust, lubricants, and rust particles) resulting from frequent maneuvering. Point *D*, located along a single-track section, shows a decrease in Pb (except *D*10), Cu, and Cd concentrations compared to the preceding points, suggesting a lower impact of traffic-related emissions. At points *C* and *D*, the use of concrete railway sleepers may reduce secondary emissions compared to wooden sleepers used at points *A* and *B*. Nickel and chromium show an increasing trend with distance from the railway tracks. Such a correlation may be related to the local geochemical background or to the deposition of dust particles containing pollutants emitted from the nearby arterial road (e.g., Krzywousty Street) and transported over long distances by air masses. This suggests that part of the contamination at this location may have a mixed railway-road origin.

Copper and zinc exhibit highly variable concentrations at the collection points (Fig. 2), with the highest recorded values at *B*1 (241 mg Cu/kg) and *D*10 (549 mg Zn/kg). Lead levels reach a maximum of 160 mg/kg at *B*1, followed by 102 mg/kg at *D*10. Elevated concentrations of HMs are observed locally despite greater distances from the tracks, indicating a complex deposition mechanism. Lead particles might be transported and deposited as a result of air turbulence and the movement of dust along the railway corridor. Fluctuations in chromium and nickel concentrations are somewhat more moderate. Local soil enrichment in chromium reaches 51–61 mg/kg. Nickel levels rise from 19 to 28 mg/kg, mainly at points located farther from the railway corridor, suggesting its higher mobility and a possible partial origin from road traffic emissions, specifically from Krzywousty Street. Cadmium reaches a level of 1.5 mg/kg, with its accumulation being highest in the zone of direct dust deposition, closest to the railway line at 1 m from the tracks (*A*–*C*). With increasing distance from the railway infrastructure, cadmium concentrations decrease, reaching their lowest values at 30 m.

Wrocław Brochów railway line. The variations in heavy metal concentrations among collection points *A*–*I* reflect the functional structure of the Wrocław Brochów railway junction (Fig. 3). Points located within the maneuvering area and near the rolling stock maintenance halls (*C*–*E* and *H*) show the highest concentrations of most metals. The presence of concrete crossings, various types of railway sleepers, and intensive vehicle traffic along the tracks in the vicinity of Mościcki Street further increases the local heavy metal load in the environment.

Analysis of HM distribution in soils revealed significant variability in concentrations depending on the distance from the rail tracks and the characteristics of points *A*–*I* (Fig. 3). The studied section includes segments of main railway lines, switches, sidings, and maneuvering zones, which favor local fluctuations in metal contents. The highest levels of copper (195 mg/kg at *H*1) and zinc (859 mg/kg at *D*1) were recorded closest to the tracks in the maneuvering area. Elevated concentrations of both metals at distances of 1–5 m indicate their transport-related origin from brake wear, abrasion of traction components, and rolling stock operations. At greater distances (10–20 m), copper and zinc concentrations drop significantly, often by 50–70% compared to values near the tracks. Lead shows a very high local variability, with a maximum value of 1195 mg/kg at *H*5. Such elevated concentration at this point may result not only from operational activities but also from incidental contamination. In most points, lead levels decrease with distance from the tracks. Local increases in metal concentrations are observed at *D*5 and *E*20, suggesting the influence of secondary factors such as track bed erosion or technical activities within rolling stock maintenance areas. Chromium and nickel exhibit more irregular variation patterns. In the case of chromium, both localized and distance-dependent (57–106 mg/kg at *F*1–10) enrichment in soils is noticeable. This may result from the geochemical background or the presence of mineral admixtures in the materials used for track bed construction. Nickel reaches its highest concentrations also at point *F*, with a maximum of 157 mg/kg at *F*20, which may indicate local soil enrichment. Nickel shows an increasing trend with distance from the tracks, suggesting a source other than rail transport. Cadmium is characterized by low concentrations in the studied soils, but its spatial distribution clearly reflects the impact of rail transport. The highest values were noticed at points located 1–5 m from the railway line, with a maximum of 2.6 mg Cd/kg at *B*5. At greater distances from the tracks, a systematic decrease in cadmium contents is observed.

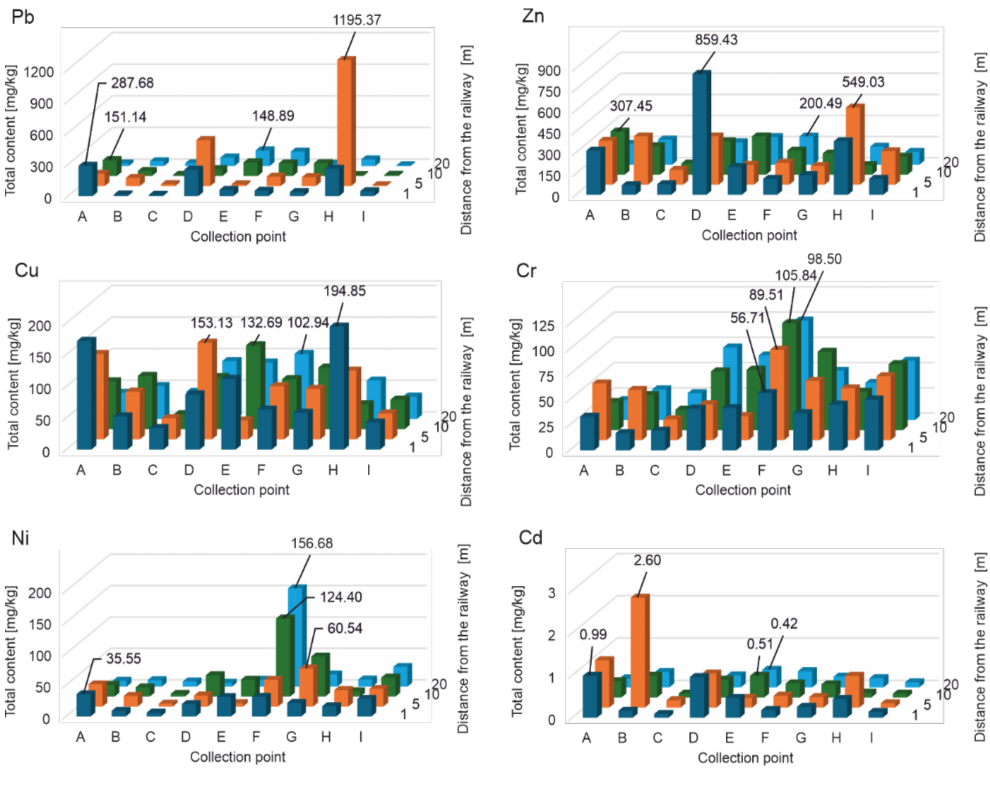

Fig. 3. Spatial distribution of HMs in soils, Wrocław Brochów

The obtained HM concentrations in soils were compared with their permissible levels established for both transport-related areas, including railway sites (group IV), and residential allotment gardens (group II), located at greater distances (over 10–20 m) from the railway infrastructure. Only lead levels were nearly twice the allowable limit at point *H*5 in Wrocław Brochów. The remaining HM levels in the analysed soils fall within acceptable limits according to the Polish standard.

3.2. SOIL CONTAMINATION, ECOLOGICAL RISK, AND PHYTOTOXICITY ASSESSMENT

Analysis of the I_{geo} index showed that soils from Wrocław Sołtysowice are characterized by low to moderate heavy metal contamination (Fig. 4). The highest enrichment was observed for Cd, Zn, Pb, and Cu, whereas Cr and Ni occurred at natural background levels. The results indicate that the primary sources of contamination are operational activities of the railway infrastructure and road traffic in the vicinity of the tracks.

In the Wrocław Brochów area, the studied soils are mostly unpolluted or slightly contaminated with heavy metals, although localized enrichment in Pb, Zn, and Cd was observed (Fig. 4). The highest contamination level was found for Cd, confirming its strong bioaccumulative potential. The results indicate that the dominant source of pollution is linear emission related to rail transport. Compared with Wrocław Brochów, soils from Wrocław Sołtysowice exhibit a lower overall pollution level. However, the presence of Cd in higher I_{geo} classes highlights the need for continued monitoring of this element in soils surrounding railway infrastructure.

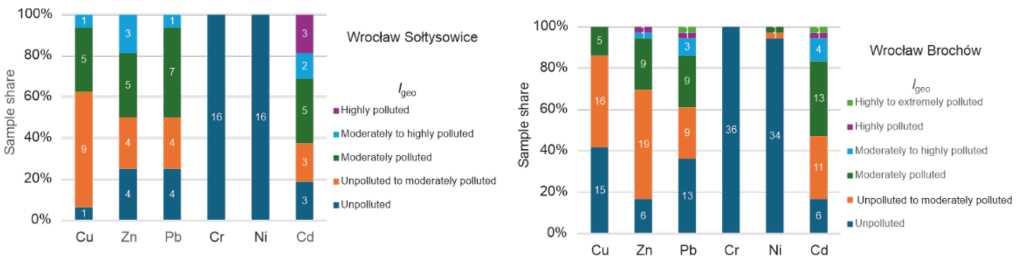

Fig. 4. Soil pollution according to the single-elemental index

The *PLI* indices for Wrocław Sołtysowice and Wrocław Brochów show a moderate decrease in soil environmental quality within the railway-adjacent zone, resulting from long-term, dispersed anthropogenic impacts (Figs. 5 and 6). These values are consistent with the I_{geo} distribution (Fig. 4).

The distribution of PI_{avg} values indicates low to moderate contamination in more than 60% of the analysed soils (Figs. 5 and 6). The remaining 37% of samples from Wrocław Sołtysowice and 36% from Wrocław Brochów were classified as strongly and very strongly polluted. This suggests that, although the overall level of soil contamination is relatively low, there are areas with locally elevated metal concentrations. The applied index effectively averages environmental conditions, thereby reducing the influence of point-source anomalies.

The $PI_{Nemerow}$ indices confirm the heterogeneous nature of soil contamination, with 63% of samples from Wrocław Sołtysowice and 56% from Wrocław Brochów falling into the heavy pollution class (Figs. 5 and 6). Such a high proportion of the heavy pollution class suggests the presence of local enrichment points, particularly for cadmium, which reached values close to the highly polluted category in the I_{geo} analysis (Fig. 4).

anomalies. As an index sensitive to extreme values, the PI_{Nemerow} highlights the spatial heterogeneity of contamination in soils along railway tracks.

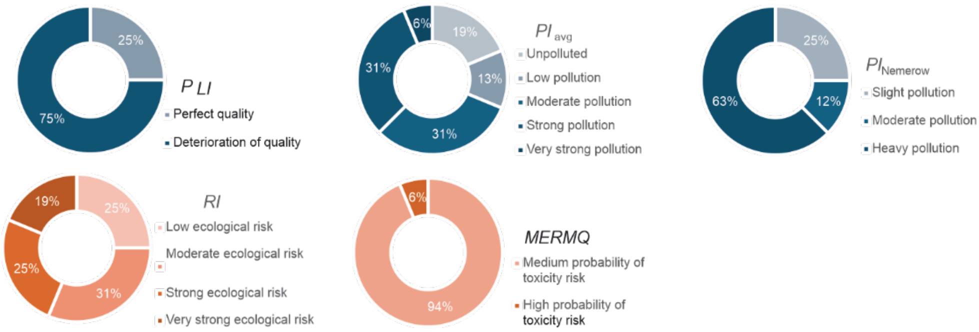

Fig. 5. Soil pollution according to the multi-elemental indices, Wrocław Sołtysowice

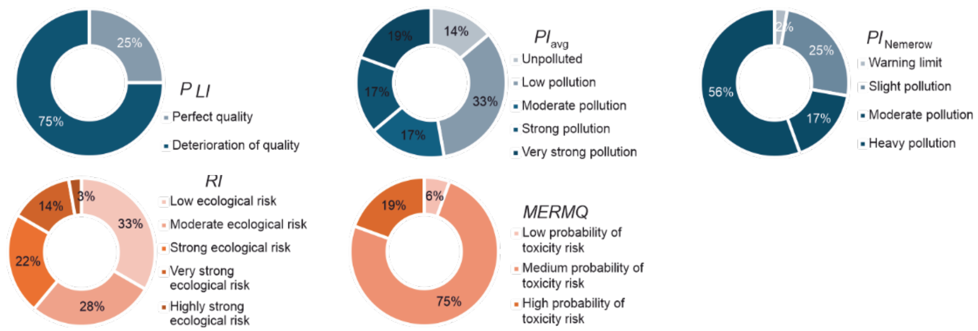

Fig. 6. Soil pollution according to the multi-elemental indices, Wrocław Brochów

The analysis of the *RI* index showed that 44% of samples from Wrocław Sołtysowice and 39% from Wrocław Brochów exhibit strong or very strong ecological risk (Figs. 5 and 6). The proportion of samples with high ecological risk is therefore considerable. The main element responsible for the increase in *RI* values is cadmium, which has the highest toxicity coefficient compared to the other metals. This indicates that even with a moderate level of overall soil contamination, the potential ecological impact of Cd may be significant. However, the low salinity of all analysed samples (below 25 mS/m) and their neutral ($pH > 6.5$ in 28% of soils) or alkaline ($pH > 7.2$ in 69%) character reduces the potential ecological risk.

The *MERMQ* index, which defines the probability of toxic effects, showed that as many as 94% of samples from Wrocław Sołtysowice and 81% from Wrocław Brochów fall into the medium probability of toxicity risk class (Figs. 5 and 6). The remaining samples exhibit a high probability of toxicity risk. This indicates that the soils are exposed to a mixture of metals, which may adversely affect soil organisms, even though the total levels of pollutants are not extreme.

The phytotoxicity test confirmed a low impact of railway soils on seed germination and plant root growth, with an average inhibition of 12.6% for Garden cress (*Lepidium sativum* L.) and 20.5% for oat (*Avena sativa* L.). No significant differences were observed with the distance from the tracks, suggesting that phytotoxic factors may spread up to 30 m from the railway line. In 11.2% of all samples, a growth-stimulating effect was even recorded, which may result from low concentrations of microelements. Cases of locally high phytotoxicity may be associated with the presence of other contaminants and products of metal corrosion.

4. CONCLUSIONS

- The highest concentrations of Cu, Zn, Pb, and Cd are observed within 1–5 m of the railway tracks, confirming the influence of linear emission associated with train traffic and railway operation.
- The concentrations of Pb, Cd, and Cu gradually decrease with increasing distance from the railway tracks.
- Cr and Ni show fewer regular variations in concentrations, which may partly result from local soil properties and geochemical background conditions.
- The sites with the highest metal accumulation are located near maneuvering zones and railway crossings, where dust emission is most intense.
- At one point in Wrocław Brochów, the Pb concentration exceeds the permissible value for transport-related soils (group IV) according to the Polish standard.
- The soils from the Wrocław Sołtysowice study area show lower metal load compared to Wrocław Brochów, although local maxima of Cd, Pb, and Zn within the 1–5 m zone may pose a potential ecological risk.
- The highest enrichment (I_{geo}) in soils at both locations was observed for cadmium, lead, and zinc. These elements are of anthropogenic origin, associated with the operation of braking systems and wear of traction wires and metallic components of rolling stock. Chromium and nickel remained at geochemical background levels, indicating the absence of significant anthropogenic sources. Cadmium represents the element with the greatest toxic potential in the studied area.
- The *PLI* and PI_{avg} indices indicated a deterioration in soil quality at both sites.
- The $PI_{Nemerow}$ index showed the presence of areas with strong metal enrichment. Over half of the samples are classified into the heavy pollution class. This indicates local accumulations of metals within the track zone, representing potential point sources of pollution.

• The analysis of the *RI* index revealed that the soils are exposed to ecological risk. In both cases, cadmium is the main element determining the *RI* value, as its high toxicity coefficient means that even slight increases in cadmium concentration lead to an elevated risk for soil organisms.

• The *MERMQ* index showed that soils with a medium probability of toxic effects dominate. Some soils reach a high toxicity risk. These results clearly confirm the biological hazard.

• Soils near the Wrocław Brochów railway station exhibit higher values of multi-elemental indices compared to the soils along the tracks at Wrocław Sołtysowice. This indicates a greater degree of soil environmental degradation in the studied area. These differences result from more intensive use of the infrastructure, higher rail traffic density, and proximity to urban development.

REFERENCES

[1] NAGAJYOTI P.C., LEE K.D., SREEKANTH T.V.M., *Heavy metals, occurrence and toxicity for plants. A review*. Environ. Chem. Lett., 2010, 8 (3), 199–216. DOI: 10.1007/s10311-010-0297-8.

[2] JAISHANKAR M., TSETEN T., ANBALAGAN N., MATHEW B.B., BEEREGOWDA K.N., *Toxicity, mechanism and health effects of some heavy metals*. Interdiscip. Toxicol., 2014, 7 (2), 60–72. DOI: 10.2478/intox-2014-0009.

[3] POLLOCK S.Z., CLAIR C.C.S., *Railway-Associated Attractants as Potential Contaminants for Wildlife*. Environmental Management, 2020, 66, 16–29. DOI: 10.1007/s00267-020-01277-6.

[4] BRTNICKÝ M., PECINA V., JUŘIČKA D., KOWAL P., VAŠINOVÁ GALIOVÁ M., BALTAZÁR T., RADZIEMSKA M., *Can rail transport-related contamination affect railway vegetation? A case study of a busy railway corridor in Poland*, Chemosphere, 2022, 133521. DOI: 10.1016/j.chemosphere.2022.133521.

[5] RADZIEMSKA M., GUSIATIN Z.M., KOWAL P., BĘŚ A., MAJEWSKI G., JEZNACH-STEINHAGEN A., MAZUR Z., LINIAUSKIENE E., BRTNICKÝ M., *Environmental impact assessment of risk elements from railway transport with the use of pollution indices, a biotest and bioindicators*, Hum. Ecol. Risk Assess., 2021, 27 (2), 517–540. DOI: 10.1080/ 10807039.2020.1736984

[6] WANG Z., WATANABE I., OZAKI H., ZHANG J., *Enrichment and bioavailability of trace elements in soil in vicinity of railways in Japan*, Arch. Environ. Contam. Toxicol., 2018, 74 (1), 16–31. DOI: 10.1007 /s00244-017-0471-0.

[7] Regulation of the Minister of Infrastructure, 2020, *on the sustainable development plan for public transport in inter-voivodeship and international passenger transport, and in voivodeship passenger rail transport*. J. Laws of 4 December 2020, Item 2328 (in Polish).

[8] Office of Rail Transport. *Railway lines in Poland – basic parameters*, https://utk.gov.pl/pl/aktualnosci /19158,Linie-kolejowe-w-Polsce-podstawowe-parametry.html [access on 01.06.2025] (in Polish).

[9] Central Statistical Office. *Freight and passenger transport in 2024*. https://stat.gov.pl/obszary-tematyczne/transport-i-lacznosc/transport/przewozy-ladunkow-i-pasazerow-w-2024-r-,11,13.html [access on 01.06.2025] (in Polish).

[10] WIERZBICKA M., BEMOWSKA-KAŁABUN O., GWOREK B., *Multidimensional evaluation of soil pollution from railway tracks*, *Ecotoxicology*, 2015, 24 (4), 805–822. DOI: org/10.1007/s10646-015-1426-8.

[11] LEVENGOOD J.M., HESKE E.J., WILKINS P.M., SCOTT J.W., *Polyaromatic hydrocarbons and elements in sediments associated with a suburban railway*, Environ. Monit. Assess., 2015, 187 (8), 534. DOI: 10.1007/s10661-015-4757-2.

[12] WIŁKOMIRSKI B., SUDNIK-WÓJCIKOWSKA B., GALERA H., WIERZBICKA M., MALAWSKA M., *Railway transportation as a serious source of organic and inorganic pollution*, Water, Air, Soil Poll., 2011, 218 (1–4), 333–345. DOI: 10.1007/s11270-010-0645-0.
[13] ZHANG H., WANG Z., ZHANG Y., HU Z., *The effects of the Qinghai–Tibet railway on heavy metals enrichment in soils*, Sci. Total Environ., 2012, 439, 240–248. DOI: 10.1016/j.scitotenv.2012.09.027.
[14] ZHANG H., ZHANG Y., WANG Z., DING M., *Heavy metal enrichment in the soil along the Delhi–Ulan section of the Qinghai–Tibet railway in China*, Environ. Monit. Assess., 2013, 185 (7), 5435–5447. DOI: 10.1007/s10661-012-2957-6.
[15] LI D., LIAO Y., *Spatial characteristics of heavy metals in street dust of coal railway transportation hubs: a case study in Yuanping*, China. Int. J. Environ. Res. Publ. Health, 2018, 15 (12), 2662. DOI: 10.3390/ijerph15122662.
[16] The Office of Rail Transport. *Passenger Transport. Passenger exchange at stations*. *Station data 2024*, https://dane.utk.gov.pl/sts/przewozy-pasazerskie/wymiana-pasazerska-na-s/22403,Przewozy-pasazerskie.html#PLIKI [access on 01.09.2025] (in Polish).
[17] BIP UM Wrocław of October 2024. Public Information Bulletin of the City Hall of Wrocław. *Comprehensive Traffic Research in Wrocław and its surroundings*, KBR 2024, https://bip.um. wroc.pl/artykul/565 /70659/ kompleksowe-badania-ruchu-we-wroclawiu-i-otoczeniu-kbr-2024 [access on 01.09.2025] (in Polish).
[18] HOŁTRA A., ZAMORSKA-WOJDYŁA D., *Application of individual and integrated pollution indices of trace elements to evaluate the noise barrier impact on the soil environment in Wrocław (Poland)*, Environ. Sci. Poll. Res., 2023, 30, 26858–26873. DOI: 10.1007/s11356-022-23563-y.
[19] Polish Regulation 2016, *Regulation of the Polish Ministry of Environment from September 1st, 2016, regarding the manner of conducting the assessment of the contamination of ground*, pos. 1395.
[20] RUDNICK R.L., GAO S., *Composition of the continental crust*, Treat. Geochem., 2003, 3, 1–64. DOI: 10.1016/B0-08-043751-6/03016-4.
[21] HOŁTRA A., ZAMORSKA-WOJDYŁA D., *Single- and multi-elemental pollution indices as a useful tool for the evaluation of road dust contaminated by trace elements*, Environ. Prot. Eng., 2024, 50 (4), 127–145. DOI: 10.37190/epe240408.