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CAN SECONDARY DUSTING IN RECREATIONAL AREAS EXPOSE CHILDREN TO HEAVY METALS? A CASE STUDY OF NOWA RUDA IN LOWER SILESIA

This study shows the problem of the presence of toxic trace elements in the surface layer of the substrate in public playgrounds and sports facility areas. The aim was to estimate the level of non-dietary exposure of children to zinc, copper, lead, chromium, and nickel as a result of secondary dusting of the soil and sand during the use of recreational areas in Nowa Ruda in Lower Silesia, Poland. The analysis of metal concentrations showed a heterogeneous distribution in the examined samples. The highest concentrations of metals were observed in playgrounds, sports fields, and sandboxes, respectively. No exceedances of the allowable values of the elements in soils were recorded, according to Polish legal regulations. Soil pollution indices indicate deterioration of surface layer quality in recreational areas in comparison to the local geochemical background for Polish soils. The results of the exposure assessment indicate a low risk of adverse health effects in children. Currently, the potential ecological risk index is also low. It is important to monitor the metal content in recreational areas and to protect the surface layer from secondary dusting in order to minimize the negative impact of environmental hazards on children's health.

1. INTRODUCTION

The increase in heavy metal levels in urban areas is caused by the dynamic development of society, reflected in higher production and consumption of goods. During the heating season in Nowa Ruda, both the daily and annual mean concentrations for PM10 are exceeded. The daily limit is 50 μg/m^3 with a maximum of 35 exceedances allowed per year, while the annual mean limit is 40 μg/m^3. In January 2024, the daily mean PM10 concentration reached 158 μg/m^3, and in the same month the following year, it was 175 μg/m^3 [1]. Annual dust emissions, including dust containing heavy metals, from the

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heating plant in Nowa Ruda amount to 56.49 Mg/year, while those from the local boiler room total 8.94 Mg/year. Air quality monitoring at the station on Piłsudskiego Street in Nowa Ruda recorded the annual mean PM10 concentration of 44.6 $\mu g/m^3$. During the heating season, the concentration of PM10 was 75.4 $\mu g/m^3$, compared to 17.1 $\mu g/m^3$ outside the heating season [2].

The causes of dust and gas emissions in Nowa Ruda include road transport; individual solid fuel heating in single-family houses; local boiler plants using fossil fuels, fuel oil, or biomass; and the recently terminated mining of hard coal and fire-resistant shale, which left behind spoil heaps. Abrasion of vehicle components, including tires, brake discs, and pads; corrosion of chassis and bodywork; oil, grease, and fuel leaks; and road surface abrasion all contribute to the release of heavy metals [3]. Poor-quality solid fuels and unauthorized waste burned in home furnaces might also enrich dust, slag, and bottom ash with trace elements. Additionally, dust originating from accumulated mining spoil heaps in Nowa Ruda constitutes another source of metals in the local environment.

It is important to ensure that the natural levels of trace elements in the environment are not exceeded, because their toxic effects are linked to their ability to accumulate in the body [4]. Children using playgrounds and outdoor sports facilities in urban areas represent a particularly high-risk group [5–11]. The reasons for the greater exposure of young organisms include the lack of fully developed systems in the children's bodies, such as the immune, nervous, and digestive systems; increased mobility; higher consumption of food and drink per unit of body weight; and greater lung ventilation compared to adults. Children's stomachs have a higher pH than adults', and some enzymes are not yet active, which may result in easier absorption of toxins. Due to their short stature, children are more susceptible to ingesting trace elements along with particles of polluted dust emitted from road transport or recirculating in the air during active play. Inhaled particles containing toxic metals can be absorbed into the bloodstream both through the respiratory tract via the lungs and through the digestive tract after swallowing the contaminant with saliva in the mouth. When children put dirty hands or toys in their mouths, toxins are absorbed through the mucous membranes of the esophagus, stomach, and intestines. Skin contact with contaminated soil or dust is another route of entry to the body for metals, this time through epidermal structures such as hair follicles, sebaceous glands, or sweat glands.

The accumulation of heavy metals in the body primarily disrupts protein synthesis, DNA structure, and ATP production, leading to diseases, including cancer. The most commonly affected organs are the liver and kidneys, which are responsible for detoxification and metal elimination. Accumulation of trace elements in bones, brain, and muscles is also often observed. This might result in immediate acute poisoning or chronic conditions that remain latent for long periods, ultimately triggering mutagenic changes. In children, heavy metal accumulation can cause skin lesions (allergies), damage to the lungs, nervous system, cardiovascular system, immune system, digestive system, and musculoskeletal system, as well as neurological and mental disorders [12–15].

This study assumes that long-term mining operations and emissions from the developed communication network and traditional solid fuel heating systems may have contributed to environmental pollution in recreational areas in Nowa Ruda. Therefore, an attempt was made to estimate the health risk associated with non-dietary exposure of children to Cu, Zn, Ni, Cr, and Pb, which might result from secondary dusting during play on playgrounds, sports fields, and sandboxes.

2. MATERIALS AND METHODS

Sampling. All collection points were located in open areas without access restrictions for users, within the administrative boundaries of the city of Nowa Ruda (the districts of Drogosław, Centrum, and Słupiec). They differed in size, structure, and location (city park, housing estate, square, school). The research material consisted of soil and sand samples collected to a depth of 25 cm on 6 playgrounds, 5 sandboxes, and 4 sports fields (Fig. 1) [16]. Each sample was composed of five subsamples. Sampling was carried out at each edge of the sports field, near playground equipment (swings, ladders, slides, carousels), and at both the edges and the central point of the sandbox. In total, 15 samples were collected for analysis in October 2024. The total mass of each sample after mixing was approximately 100 g.

Analytical procedure and statistical computing. Each sample was thoroughly mixed, dried, and sieved. Subsequently, approximately 0.2 g of material was weighed and subjected to mineralization with 8 cm^3 of spectrally pure nitric acid in a closed system using a microwave mineralizer (START D, Milestone). The process parameters were 2 min at 140 °C (first stage) and 15 min at 200 °C under a maximum pressure of 20 MPa and microwave power of 800 W. The content of elements (Zn, Cu, Pb, Cr, and Ni) in the obtained filtrates was determined using an atomic absorption spectrometer ASA (Thermo Solaar iCE 3500, Thermo Scientific) [17]. Measurements were repeated three times, and the device performance was controlled using blank samples. The detection limits were determined three times the standard deviation of the blanks. The accuracy of the measurements was controlled using the standard addition method. Solutions of the Certified Reference Materials (CRMs) for metals (Sigma-Aldrich) were used for the calibration curves, the validation of analytical methods, and the standard addition method. The Atomic Absorption Spectrometry (AAS) results were verified based on the standard deviation, the coefficient of variation (within 10%), and the confidence interval (by *p*-value of 0.05 for Student's *t*-test). Chemical analyses were performed in the Laboratory of Environmental Research in the Faculty of Environmental Engineering at the Wrocław University of Science and Technology.

Two series of substrate samples, 10 g of dry material each, were independently weighed. Pure water was added to one series, while a potassium chloride solution to the other, maintaining a 1:2.5 (*m*:*v*) stoichiometric ratio. After 24 hours, the pH in neutral salt solutions and the salinity in aqueous solutions were determined.

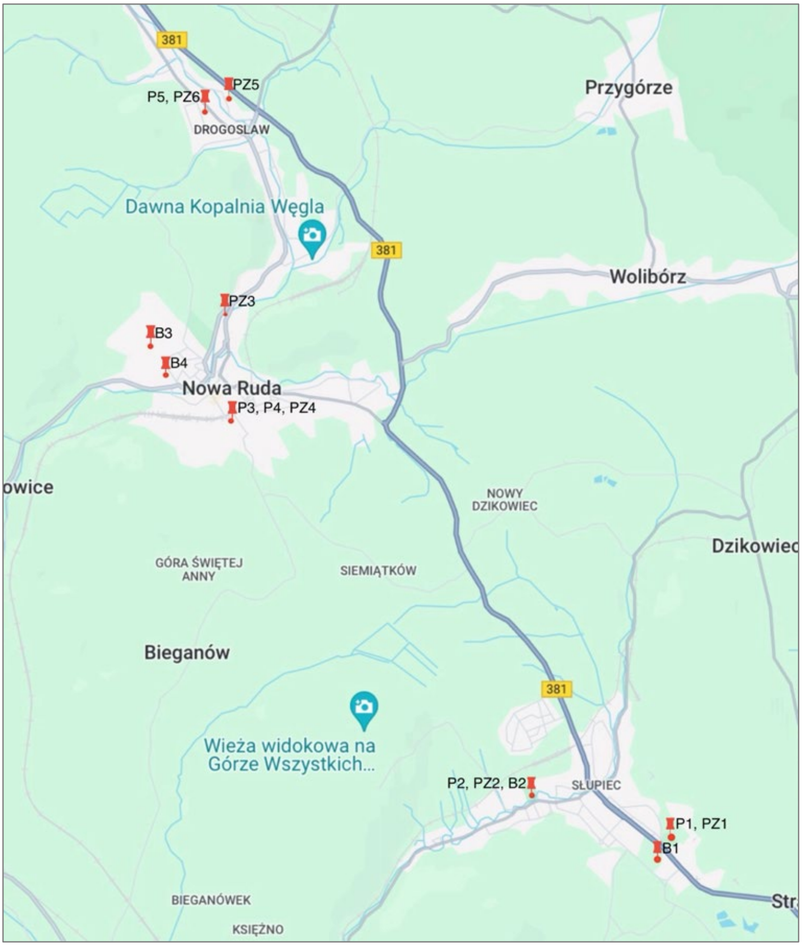

Fig. 1. Location of collection points in Nowa Ruda:
PZ1–PZ6 – playgrounds (soil), B1–B4 – sports fields (soil), P1–P5 sandboxes (sand)

Basic statistics: minimum (Min), maximum (Max), first quartile (Q1), median (Med), and third quartile (Q3) were performed using Microsoft Excel and Statistica software package. Spearman's correlation coefficients were calculated, and relationships between the concentrations within metal–metal pairs were rated according to a four-grade scale: > 0.8 indicates very strong correlation, 0.8–0.6 strong, 0.4–0.6 moderate, and < 0.4 weak.

Ecological and health risk indices. The quality of the surface layer can be determined based on critical metal levels and in accordance with the estimated indices of ecological and human health risk. The exposure assessment considered the maximum permissible metal concentrations for soils in recreational areas specified by Polish law in the Regulation of the Minister of the Environment of 1st September 2016, which are, in mg/kg: 500 (Zn), 200 (Cu, Pb, and Cr), and 150 (Ni) [16]. The adopted reference environment was the average metal concentrations in the surface layer of soils in Poland (local background) with concentrations in mg/kg: 88 (Zn), 10 (Cu), 35 (Pb), and 6 (Cr, Ni) [18].

Geoaccumulation index (I_{geo}) is a single-element indicator used to assess the level of soil contamination by a selected metal [19]. The I_{geo} is calculated according to the formula:

$$I_{geo} = \log_2 \frac{C_n}{1.5B_n} \tag{1}$$

where C_n represents the metal concentration in the sample, mg/kg, B_n is the background concentration of metal, mg/kg, and the factor 1.5 is used to compensate for B_n fluctuations due to lithogenic effects.

The seven-grade classification of I_{geo} is based on the assessment of soil contamination levels: $I_{geo} \leq 0$ represents practically uncontaminated, $0 < I_{geo} < 1$ from uncontaminated to moderately contaminated, $1 < I_{geo} < 2$ moderately contaminated, $2 < I_{geo} < 3$ from moderately to heavily contaminated, $3 < I_{geo} < 4$ heavily contaminated, $4 < I_{geo} < 5$ from heavily to extremely contaminated, and $I_{geo} > 5$ extremely contaminated.

Nemerow pollution index (PI_{Nem}) is a multi-element indicator used to assess the contamination of soils by multiple selected elements simultaneously. The PI_{Nem} is calculated based on the single-factor index PI for toxic metals [19]:

$$PI_{Nem} = \left(\frac{\left(\frac{\sum_{i=1}^{n} PI_i}{n} \right)^2 + PI_{max}^2}{2} \right)^{1/2}, \quad PI = \frac{C_n}{B_n} \tag{2}$$

and C_n is the concentration of metal n, B_n is the background concentration of metal n, both in mg/kg.

The PI_{Nem} is classified according to a five-grade scale: $PI_{Nem} \leq 0.7$ means excellent, $0.7 < PI_{Nem} \leq 1.0$ clean, $1 < PI_{Nem} \leq 2.0$ slightly polluted, $2.0 < PI_{Nem} \leq 3.0$ moderately polluted, and $PI_{Nem} > 3.0$ heavily polluted.

Potential ecological risk (RI) is a comprehensive index based on the ecological risk factors (E_{ri}) for selected toxic metals [19].

$$RI = \sum_{i=1}^{n} E_{ri}, \quad E_r = T_r PI \tag{3}$$

and T_r is the biological toxic-response factor for a metal, with the following values: 1 for Zn, 2 for Ni, Cr, and 5 for Cu and Pb.

The *RI* index is classified into five grades: < 90 presents low potential ecological risk, 90–180 moderate, 180–360 strong, 360–720 very strong, and > 720 highly strong.

Average daily potential dose (ADD) of metal that could be absorbed by preschool children (from 2 to 6 years of age) and school-age adolescents (from 7 to 16 years of age) from non-food sources was calculated, assuming that they spend an average of 4 hours per day on playgrounds and sports fields for 6 months each year [20]:

- Ingestion

$$ADD_{\text{ing}} = C_n \frac{EF \times ED \times IngR}{BW \times AT} \tag{4}$$

- Inhalation

$$ADD_{\text{inh}} = C_n \frac{EF \times ED \times InhR}{BW \times AT \times PEF} \times 10^6 \tag{5}$$

- Dermal contact

$$ADD_{\text{derm}} = C_n \frac{SL \times SA \times ABS \times EF \times ED}{BW \times AT} \tag{6}$$

The following parameters were used to calculate the *ADD* in ng/(kg·day):

C_n – average concentration, mg/kg, of the toxic metal *n* in the sample,

EF – exposure frequency: 6 months × 30 days × 4 hours/24 hours = 30 days/year,

ED – child exposure duration: assumed to be 5 years for playgrounds (children aged 2–6 years inclusive); and 10 years for sports fields (adolescents aged 7–16 years inclusive),

IngR – ingestion rate of the sample containing the metal, determined at 100 mg/day,

BW – body weight of children aged 2–6 years: 16.85 kg; and adolescents aged 7–16 years: 40.85 kg,

AT – average time spent on playgrounds: 5 years × 30 days = 150 days; on sports fields: 10 years × 30 days = 300 days,

InhR – child's daily lung ventilation rate: 7.6 m^3/day,

PEF – particle emission factor for a child: 1.39·109 m^3/kg,

SL – child's skin adherence coefficient: 0.2 mg/(cm^2·day),

SA – child's exposed skin area: 2800 cm^2,

ABS – percutaneous absorption coefficient for a child: 0.001.

Hazard quotient (HQ) describes the risk to human health caused by contact with toxic metals according to the formula [21]:

$$HQ = \frac{ADD}{RfD} \tag{7}$$

where *ADD* is the daily potential dose of metal, and *RfD* is the reference dose of metal absorbed through a single route of exposure. According to the *Integrated Information Risk System* (IRIS), the values of *RfD*, ng/(kg·day, are as follows [22, 23]:

$RfD_{\rm ing}$ – 3×10^5 (Zn), 4×10^4 (Cu), 3.5×10^3 (Pb), 3×10^3 (Cr), and 2×10^4 (Ni),
$RfD_{\rm inh}$ – 3×10^5 (Zn), 4×10^4 (Cu), 3.5×10^3 (Pb), 2.86×10^1 (Cr), and 2×10^4 (Ni),
$RfD_{\rm derm}$ – 6×10^4 (Zn), 1.2×10^4 (Cu), 5.25×10^2 (Pb), 6×10^1 (Cr), and 5.4×10^2 (Ni).

Hazard index (*HI*) is used to express the cumulative effect of a single metal that enters a child's body through all routes of exposure simultaneously:

$$HI = \sum\left(HQ_{\rm ing} + HQ_{\rm inh} + HQ_{\rm derm}\right) \tag{8}$$

The values of all hazard indices < 1 mean that the risk of negative health effects in the child is negligible, and ≥ 1 indicate probable risk of negative health effects in the exposed population.

3. RESULTS

3.1. METAL CONTENT

No exceedances of the maximum permissible metal concentrations are recorded in the tested samples from the surface layer of soils and sands in Nowa Ruda, in accordance with the applicable Polish standard (Table 1) [16]. Higher metal contents are found in soils from playgrounds than in sports fields, and the lowest concentrations are found in sandboxes (Fig. 2).

Measurements of exchangeable acidity in 1 M KCl show that more than half of the tested substrates (6 soil and 2 sand samples) are in the pH range of 5.16–6.41, while the remaining samples (4 soils and 3 sands) are neutral. In 53% of the locations, there is potential for leaching of metal ions by rainwater and meltwater, which may lead to exposure of biocenosis and intake of elements by plants. Measurements of electrical conductivity indicate that 20% of the samples are moderately saline (38–47 mS/m), while the remaining substrates are low-salinity.

According to the coefficient of variation, very strong spatial variability above 100% is observed for zinc and chromium in sandboxes, while strong variability equal to or above 45% is noted for lead and zinc in playgrounds and also for lead in sports fields (Table 1). The large variation in metal contamination of the tested samples has also resulted in high values of standard deviations. Kurtosis values below zero indicate a dispersion of the results that significantly differ from the average value. Only in four cases is the set of results concentrated around the average value. Almost half of the skewness values are positive, indicating that the average values are higher than the median values. The remaining skewness results show the opposite trend. Both kurtosis and skewness values differ significantly from zero, indicating an asymmetric distribution of the results for the concentrations of the studied metals.

Table 1

Basic statistics for metals in the surface layer

Area	Metal	Avg. [mg/kg]	Std. dev. [mg/kg]	Coef. var. [%]	Skewness	Kurtosis
Playgrounds	Zn	100.94	45.24	45	0.55	–1.77
	Cu	30.92	12.49	40	0.43	–2.20
	Pb	34.38	19.91	58	0.83	–1.81
	Cr	32.82	10.32	31	0.13	0.36
	Ni	21.87	6.46	30	–0.46	–1.39
Sports fields	Zn	66.14	22.49	34	–0.35	–0.08
	Cu	20.77	3.06	15	–0.34	0.47
	Pb	24.62	13.66	55	–0.70	–0.17
	Cr	33.49	12.94	39	–0.17	–3.35
	Ni	19.74	3.90	20	0.92	1.14
Sandboxes	Zn	0.86	1.07	125	2.24	5.00
	Cu	3.49	0.77	22	–0.71	–1.17
	Pb	7.78	2.50	32	–0.14	–1.38
	Cr	7.23	7.37	102	0.66	–1.00
	Ni	12.92	5.38	42	–0.64	–0.15

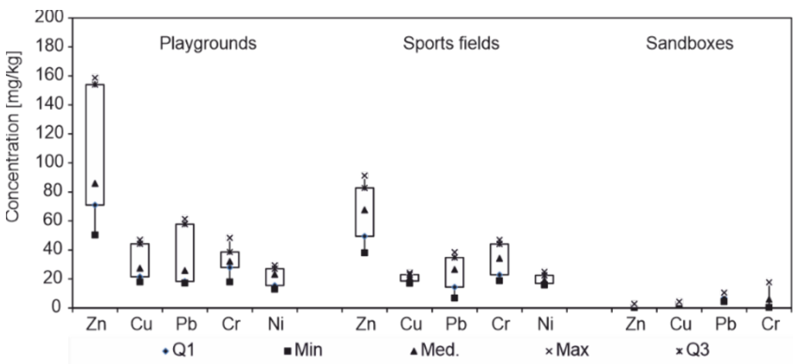

Fig. 2. The content of metals in the surface layer of recreational areas

In the surface layer of tested substrates in Nowa Ruda, 30% of metal–metal pair correlations are positive in both playgrounds and sports fields, and only one in sandboxes (Table 2). Two very strong (above 0.8), three strong (above 0.6), and one moderate (above 0.4) correlations are recorded for Zn–Cu, Zn–Pb, Cu–Pb, and Cu–Ni pairs. Also, moderately significant dependencies occurred for negative values of the correlation coefficient between Cr–Zn for sports fields and Ni–Zn/Pb for sandboxes. The other relationships were statistically insignificant.

Table 2

Analysis of Spearman's correlations (significant at $p < 0.05$)

Area		Cu	Pb	Cr	Ni
Playgrounds	Zn	0.86	0.91	0.13	0.27
	Cu	–	0.74	0.02	0.25
	Pb	–	–	–0.01	0.20
	Cr	–	–	–	0.24
Sports fields	Zn	0.43	0.74	–0.55	–0.19
	Cu	–	0.17	–0.36	0.76
	Pb	–	–	0.01	–0.36
	Cr	–	–	–	–0.17
Sandboxes	Zn	0.09	0.65	0.10	–0.53
	Cu	–	–0.07	–0.07	0.08
	Pb	–	–	0.23	–0.44
	Cr	–	–	–	0.09

3.2. RISK ASSESSMENT

Based on the obtained metal concentrations, an estimated assessment of environmental and health risks related to children's exposure to selected trace elements through a non-dietary route was performed in Nowa Ruda.

Ecological exposure. According to the geoaccumulation index (I_{geo} 1–3), the soils tested at all playgrounds are moderately polluted with chromium (Fig. 3). Additionally, moderate nickel contamination is recorded at four playgrounds (PZ1–PZ4), and at three of them (PZ2–PZ4), moderate enrichment of copper is also observed. Samples from two of these locations (PZ3, PZ4) are also slightly polluted with lead and zinc ($I_{geo} > 1$). The soils from the sports fields are moderately polluted with chromium, similarly to those from the playgrounds. At three sports fields (B2–B4), moderate nickel contamination is noted, and the location of B1 shows slight contamination with Ni. Low copper contamination is also observed in all these soil samples. In sandbox samples, low contamination with nickel or chromium is noted, except for location P4, where the sand is moderately polluted with nickel.

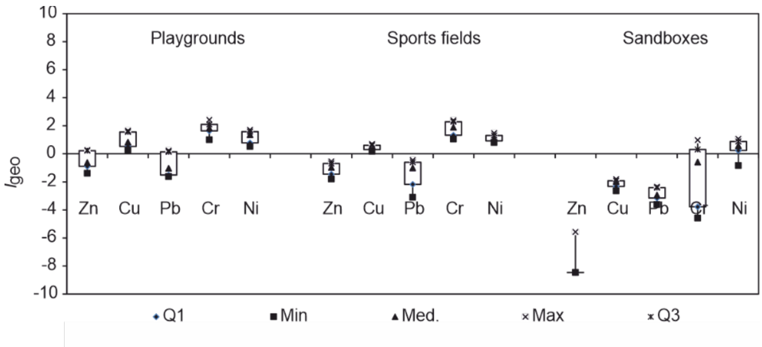

Fig. 3. Parameters characterizing the I_{geo} indices of metals in the surface layer of recreational areas

Based on the Nemerow pollution index (PI_{Nem} values not mentioned in this paper), it is concluded that the total contribution of toxic elements in the studied soils results in heavy pollution (PI_{Nem} 3–7) in both playgrounds and sports fields, except for moderately polluted locations of PZ5 and B4 (PI_{Nem} 2–3). Three sand samples from P1, P3, and P5 are slightly polluted, and the other two samples (P2, P4) from sandboxes are moderately polluted with metals (PI_{Nem} 1–3).

The deterioration of the quality of studied substrates is also evidenced by the ecological risk factors (E_r) that exceeded established values of the biological toxic-response factors (T_r) for selected metals. Detailed data of E_r are not shown in the paper. Exceedances of T_r values for Cr, Ni, and Cu are recorded in all soil samples collected from playgrounds and sports fields. In some of these locations, T_r values for Zn (PZ2–PZ4 and B3) and Pb (PZ3, PZ4, and B3) are also exceeded. In the sand samples, the T_r exceedances are noted only for Ni (P2–P5) and Cr (P1, P2, P4). Despite the T_r factors for single metals being over the limits, the environmental risk index *RI,* integrating all elements, is below 90 and currently does not indicate the ecological risk in every tested substrate.

Health exposure. During physical activities in open urban recreational areas, children are likely to come into frequent contact with surfaces containing heavy metals, which poses a risk of exposure to toxic elements through a non-dietary route.

The estimated health risk, based on the methodology recommended by the U.S. EPA [20–23], indicated that the highest non-dietary risk for children may result from accidental metal intake through the ingestion route ADD_{ing} (Table 3). The obtained hazard quotient (*HQ*) values vary considerably and largely depend on the route by which metals enter the body: $HQ_{ing} > HQ_{derm} > HQ_{inh}$. The potential risk of negative health effects in both considered populations in Nowa Ruda, resulting from the presence of toxic elements in the tested substrates from areas designed for recreation and active leisure, is negligible (*HQ* below 1). According to the *HI* index, chromium and lead pose a significantly greater health risk to children than the other elements present in the studied substrates.

Table 3

Average daily doses and hazard indices characterizing children's health risk in Nowa Ruda exposed to heavy metals in substrate samples

Area	Metal	Population	ADD_{ing} [ng/(kg·day)]	ADD_{derm} [ng/(kg·day)]	ADD_{inh} [ng/(kg·day)]	HQ_{ing}	HQ_{derm}	HQ_{inh}	HI
Playgrounds	Zn	Children	$5.99\cdot10^{2}$	3.35	$2.78\cdot10^{-4}$	$2.00\cdot10^{-3}$	$5.59\cdot10^{-5}$	$1.09\cdot10^{-7}$	$2.05\cdot10^{-3}$
		Adolescents	$2.47\cdot10^{2}$	1.38	$1.35\cdot10^{-2}$	$8.24\cdot10^{-4}$	$2.31\cdot10^{-5}$	$4.50\cdot10^{-8}$	$8.47\cdot10^{-4}$
		Avg.	$4.23\cdot10^{2}$	2.37	$6.89\cdot10^{-3}$	$1.41\cdot10^{-3}$	$3.95\cdot10^{-5}$	$7.71\cdot10^{-8}$	$1.45\cdot10^{-3}$
	Cu	Children	$1.83\cdot10^{1}$	1.03	$1.00\cdot10^{-2}$	$4.59\cdot10^{-3}$	$8.56\cdot10^{-5}$	$2.51\cdot10^{-7}$	$4.67\cdot10^{-3}$
		Adolescents	$7.57\cdot10^{2}$	$4.24\cdot10^{-1}$	$4.14\cdot10^{-3}$	$1.89\cdot10^{-3}$	$3.53\cdot10^{-5}$	$1.03\cdot10^{-7}$	$1.93\cdot10^{-3}$
		Avg.	$1.30\cdot10^{2}$	$7.26\cdot10^{-1}$	$7.09\cdot10^{-3}$	$3.24\cdot10^{-3}$	$6.05\cdot10^{-5}$	$1.77\cdot10^{-7}$	$3.30\cdot10^{-3}$
	Pb	Children	$2.04\cdot10^{2}$	1.14	$1.12\cdot10^{-2}$	$5.83\cdot10^{-2}$	$2.18\cdot10^{-3}$	$3.19\cdot10^{-6}$	$6.05\cdot10^{-2}$
		Adolescents	$8.42\cdot10^{1}$	$4.71\cdot10^{-1}$	$4.60\cdot10^{-3}$	$2.40\cdot10^{-2}$	$8.98\cdot10^{-4}$	$1.31\cdot10^{-6}$	$2.49\cdot10^{-2}$
		Avg.	$1.44\cdot10^{2}$	$8.07\cdot10^{-1}$	$7.88\cdot10^{-3}$	$4.12\cdot10^{-2}$	$1.54\cdot10^{-3}$	$2.25\cdot10^{-6}$	$4.27\cdot10^{-2}$
	Cr	Children	$1.95\cdot10^{2}$	1.09	$1.07\cdot10^{-2}$	$6.49\cdot10^{-2}$	$1.82\cdot10^{-2}$	$3.72\cdot10^{-4}$	$8.35\cdot10^{-2}$
		Adolescents	$8.03\cdot10^{1}$	$4.50\cdot10^{-1}$	$4.39\cdot10^{-3}$	$2.68\cdot10^{-2}$	$7.50\cdot10^{-3}$	$1.54\cdot10^{-4}$	$3.44\cdot10^{-2}$
		Avg.	$1.38\cdot10^{2}$	$7.70\cdot10^{-1}$	$7.52\cdot10^{-3}$	$4.59\cdot10^{-2}$	$1.28\cdot10^{-3}$	$2.63\cdot10^{-4}$	$5.90\cdot10^{-2}$
	Ni	Children	$1.30\cdot10^{2}$	$7.27\cdot10^{-1}$	$7.10\cdot10^{-3}$	$6.49\cdot10^{-3}$	$1.35\cdot10^{-3}$	$3.55\cdot10^{-7}$	$7.84\cdot10^{-3}$
		Adolescents	$5.35\cdot10^{1}$	$3.00\cdot10^{-1}$	$2.93\cdot10^{-3}$	$2.68\cdot10^{-3}$	$5.55\cdot10^{-4}$	$1.46\cdot10^{-7}$	$3.23\cdot10^{-3}$
		Avg.	$9.17\cdot10^{1}$	$5.13\cdot10^{-1}$	$5.01\cdot10^{-3}$	$4.58\cdot10^{-3}$	$9.51\cdot10^{-4}$	$2.51\cdot10^{-7}$	$5.53\cdot10^{-3}$
Sports fields	Zn	Children	$3.93\cdot10^{2}$	2.20	$2.15\cdot10^{-2}$	$1.31\cdot10^{-3}$	$3.66\cdot10^{-5}$	$7.15\cdot10^{-8}$	$1.35\cdot10^{-3}$
		Adolescents	$1.62\cdot10^{2}$	$9.07\cdot10^{-1}$	$8.85\cdot10^{-3}$	$5.40\cdot10^{-4}$	$1.51\cdot10^{-5}$	$2.95\cdot10^{-8}$	$5.55\cdot10^{-4}$
		Avg.	$2.77\cdot10^{2}$	1.55	$1.52\cdot10^{-2}$	$9.24\cdot10^{-4}$	$2.59\cdot10^{-5}$	$5.05\cdot10^{-8}$	$9.50\cdot10^{-4}$
	Cu	Children	$1.23\cdot10^{2}$	$6.90\cdot10^{-1}$	$6.74\cdot10^{-3}$	$3.08\cdot10^{-3}$	$5.75\cdot10^{-5}$	$1.69\cdot10^{-7}$	$3.14\cdot10^{-3}$
		Adolescents	$5.09\cdot10^{1}$	$2.85\cdot10^{-1}$	$2.78\cdot10^{-3}$	$1.27\cdot10^{-3}$	$2.37\cdot10^{-5}$	$6.95\cdot10^{-8}$	$1.30\cdot10^{-3}$
		Avg.	$8.71\cdot10^{1}$	$4.88\cdot10^{-1}$	$4.76\cdot10^{-3}$	$2.18\cdot10^{-3}$	$4.06\cdot10^{-5}$	$1.19\cdot10^{-7}$	$2.22\cdot10^{-3}$
	Pb	Children	$1.46\cdot10^{2}$	$8.18\cdot10^{-1}$	$7.99\cdot10^{-3}$	$4.17\cdot10^{-2}$	$1.56\cdot10^{-3}$	$2.28\cdot10^{-6}$	$1.79\cdot10^{-2}$
		Adolescents	$6.03\cdot10^{1}$	$3.38\cdot10^{-1}$	$3.30\cdot10^{-3}$	$1.72\cdot10^{-2}$	$6.43\cdot10^{-4}$	$9.41\cdot10^{-7}$	$1.79\cdot10^{-2}$
		Avg.	$1.03\cdot10^{2}$	$5.78\cdot10^{-1}$	$5.64\cdot10^{-3}$	$2.95\cdot10^{-2}$	$1.10\cdot10^{-3}$	$1.61\cdot10^{-6}$	$1.79\cdot10^{-2}$
	Cr	Children	$1.99\cdot10^{2}$	1.11	$1.09\cdot10^{-2}$	$6.62\cdot10^{-2}$	$1.85\cdot10^{-2}$	$3.80\cdot10^{-4}$	$8.52\cdot10^{-2}$
		Adolescents	$8.20\cdot10^{1}$	$4.59\cdot10^{-1}$	$4.48\cdot10^{-3}$	$2.73\cdot10^{-2}$	$7.65\cdot10^{-3}$	$1.57\cdot10^{-4}$	$3.51\cdot10^{-2}$
		Avg.	$1.40\cdot10^{2}$	$7.86\cdot10^{-1}$	$7.67\cdot10^{-3}$	$4.68\cdot10^{-2}$	$1.31\cdot10^{-2}$	$2.68\cdot10^{-4}$	$6.01\cdot10^{-2}$
	Ni	Children	$1.17\cdot10^{2}$	$6.56\cdot10^{-1}$	$6.41\cdot10^{-3}$	$5.86\cdot10^{-3}$	$1.21\cdot10^{-3}$	$3.20\cdot10^{-7}$	$7.07\cdot10^{-3}$
		Adolescents	$4.83\cdot10^{1}$	$2.71\cdot10^{-1}$	$2.64\cdot10^{-3}$	$2.42\cdot10^{-3}$	$5.01\cdot10^{-4}$	$1.32\cdot10^{-7}$	$2.92\cdot10^{-3}$
		Avg.	$8.27\cdot10^{1}$	$4.63\cdot10^{-1}$	$4.52\cdot10^{-3}$	$4.14\cdot10^{-3}$	$8.58\cdot10^{-4}$	$2.26\cdot10^{-7}$	$4.99\cdot10^{-3}$
Sandboxes	Zn	Children	5.08	$2.84\cdot10^{-2}$	$2.78\cdot10^{-4}$	$1.69\cdot10^{-5}$	$4.74\cdot10^{-7}$	$9.25\cdot10^{-10}$	$1.74\cdot10^{-5}$
		Adolescents	2.09	$1.17\cdot10^{-2}$	$1.14\cdot10^{-4}$	$6.98\cdot10^{-6}$	$1.95\cdot10^{-7}$	$3.82\cdot10^{-10}$	$7.18\cdot10^{-6}$
		Avg.	3.59	$2.01\cdot10^{-2}$	$1.96\cdot10^{-4}$	$1.20\cdot10^{-5}$	$3.35\cdot10^{-7}$	$6.53\cdot10^{-10}$	$1.23\cdot10^{-5}$
	Cu	Children	$2.07\cdot10^{1}$	$1.16\cdot10^{-1}$	$1.13\cdot10^{-3}$	$5.18\cdot10^{-4}$	$9.67\cdot10^{-6}$	$2.83\cdot10^{-8}$	$5.28\cdot10^{-4}$
		Adolescents	8.55	$4.79\cdot10^{-2}$	$4.67\cdot10^{-4}$	$2.14\cdot10^{-4}$	$3.99\cdot10^{-6}$	$1.17\cdot10^{-8}$	$2.18\cdot10^{-4}$
		Avg.	$1.46\cdot10^{1}$	$8.19\cdot10^{-2}$	$8.00\cdot10^{-4}$	$3.66\cdot10^{-4}$	$6.83\cdot10^{-6}$	$2.00\cdot10^{-8}$	$3.73\cdot10^{-4}$

Table 3

Average daily doses and hazard indices characterizing children's health risk in Nowa Ruda exposed to heavy metals in substrate samples

Sandboxes	Pb	Children	$4.62\cdot10^{1}$	$2.58\cdot10^{-1}$	$2.52\cdot10^{-3}$	$1.32\cdot10^{-2}$	$4.92\cdot10^{-4}$	$7.21\cdot10^{-7}$	$1.37\cdot10^{-2}$
		Adolescents	$1.90\cdot10^{1}$	$1.07\cdot10^{-1}$	$1.04\cdot10^{-3}$	$5.44\cdot10^{-3}$	$2.03\cdot10^{-4}$	$2.97\cdot10^{-7}$	$5.64\cdot10^{-3}$
		Avg.	$3.26\cdot10^{1}$	$1.83\cdot10^{-1}$	$1.78\cdot10^{-3}$	$9.31\cdot10^{-3}$	$3.48\cdot10^{-4}$	$5.09\cdot10^{-7}$	$9.66\cdot10^{-3}$
	Cr	Children	$4.29\cdot10^{1}$	$2.40\cdot10^{-1}$	$2.34\cdot10^{-3}$	$1.43\cdot10^{-2}$	$4.00\cdot10^{-3}$	$8.20\cdot10^{-5}$	$1.84\cdot10^{-2}$
		Adolescents	$1.77\cdot10^{1}$	$9.91\cdot10^{-2}$	$9.67\cdot10^{-4}$	$5.90\cdot10^{-3}$	$1.65\cdot10^{-3}$	$3.38\cdot10^{-5}$	$7.58\cdot10^{-3}$
		Avg.	$3.03\cdot10^{1}$	$1.70\cdot10^{-1}$	$1.66\cdot10^{-3}$	$1.01\cdot10^{-2}$	$2.83\cdot10^{-3}$	$5.79\cdot10^{-5}$	$1.30\cdot10^{-2}$
	Ni	Children	$7.67\cdot10^{1}$	$4.29\cdot10^{-1}$	$4.19\cdot10^{-3}$	$3.83\cdot10^{-3}$	$7.95\cdot10^{-4}$	$2.10\cdot10^{-7}$	$4.63\cdot10^{-3}$
		Adolescents	$3.16\cdot10^{1}$	$1.77\cdot10^{-1}$	$1.73\cdot10^{-3}$	$1.58\cdot10^{-3}$	$3.28\cdot10^{-4}$	$8.64\cdot10^{-8}$	$1.91\cdot10^{-3}$
		Avg.	$5.41\cdot10^{1}$	$3.03\cdot10^{-1}$	$2.96\cdot10^{-3}$	$2.71\cdot10^{-3}$	$5.61\cdot10^{-4}$	$1.48\cdot10^{-7}$	$3.27\cdot10^{-3}$

4. DISCUSSION

Substrate samples from playgrounds and play areas contain toxic metals, posing a source of non-dietary exposure to trace elements in children. Many authors point to the need to monitor locations frequently visited by preschool-and school-aged children, especially in urbanized areas with a high degree of industrialization, mainly related to processing and mining industries [5–11].

Although the substrates from recreational areas in Bydgoszcz and Warsaw [5], and Krakow [6], similarly to those in Nowa Ruda, meet the requirements of the applicable Polish standard [16] and were classified as uncontaminated, the geoaccumulation index indicates enrichment with metals due to exceedances of reference background levels for Polish soils. The I_{geo} classified soils from Bydgoszcz as uncontaminated to moderately contaminated, and soils from two locations in the city center of Warsaw as moderately contaminated with lead and zinc [5]. The surface layers of playgrounds and sports fields in Nowa Ruda are generally moderately polluted with chromium and nickel, and occasionally with copper. Similarly, sand from sandboxes in Lower Silesia is mostly slightly enriched with nickel and locally with chromium.

The problem of exceeding maximum permissible metal concentrations in surface layers remains persistent, particularly in the Silesian Voivodeship in Poland. This region has a historical association with intensive industrial activity, mining, non-ferrous metal ore processing, and metallurgy. The latest studies confirm severe environmental contamination in urban squares, playgrounds, gyms, sports fields, and primary school surroundings in three districts: Katowice–Szopienice (Med.–Max: Cd 3.8–20.3, Pb 199.9–4930.1; Zn 594.4–4743.3 mg/kg), Świętochłowice–Lipiny (Cd 3.6–24.5, Pb 139.3–850.2, Zn 510.0–4616.6 mg/kg), and Piekary Śląskie–Orzeł Biały (Cd 5.6–28.0, Pb 282.3–1594.0, Zn 1345.9–4159.1 mg/kg) [7].

In recreational areas of Księża Góra in Radzionków, excessive average concentrations of cadmium and lead were also recorded on playgrounds and sports fields, amounting to 8.9 and 13.8 mg/kg, and 476.6 and 336.2 mg/kg, respectively [8].

Excessive levels of cadmium, lead, and zinc in soils from sports fields and playgrounds, and in sand from sandboxes have been found in many other cities in Upper Silesia. Particularly high exceedances of maximum permissible metal concentrations were recorded on sports fields in Bukowno (Cd 9.5–44.2, Pb 280.0–1412.9, Zn 1279.7 –11772.6 mg/kg), then in Siemianowice (Cd 5.5–12.5, Pb 266.3–608.8, Zn 905.5–3732.8 mg/kg), and Katowice Szopienice (Cd 9.8, Pb 479.8, Zn 1643.0 mg/kg), Bytom Stroszek (Cd 5.4, Pb 226.6, Zn 800.8 mg/kg), Sosnowiec Klimontów (Cd 2.8–5.4, Pb 369.6, Zn 573.2–615.5 mg/kg) [9]. Exceedances of elemental concentrations in playground soils from parks and housing estates in Upper Silesia reached the following values: Bukowno (Cd 6.0–36.0, Pb 243.1–789.1, Zn 853.5–3180.6 mg/kg), Siemianowice (Cd 3.8–18.8, Pb 217.5–392.4, Zn 510.7–1928.2), Bytom Stroszek (Cd 2.7–6.1, Pb 248.9–281.5, Zn 1414.6), Dąbrowa Górnicza (Cd 2.6–7.6, Pb 291.4, Zn 657.3–1659.3), Sosnowiec (Cd 7.2, Pb 277.7, Zn 937.9), Sosnowiec Klimontów (Cd 3.4, Pb 254.6, Zn 522.1), and Tarnowskie Góry (Cd 5.8, Pb 279.4–314.6, Zn 860.6–987.9) [9]. In soils from kindergartens in the Silesian region, the recorded exceedances of toxic elements were as follows: Bytom (Cd 4.8–20.7, Pb 223.4–420.4, Zn 690.4–3951.1 mg/kg), Tarnowskie Góry (Cd 2.7–7.6, Pb 210.0–445.8, Zn 583.0–1250.3), Piekary Śląskie (Cd 8.5, Pb 1042.8, Zn 772.9), Bukowno (Cd 3.5–6.8, Pb 220.9, Zn 580.3–1317.2), Radzionków (Cd 4.6–25.3, Pb 2007.6, Zn 706.1–4931.7), Zabrze (Cd 6.5, Pb 383.2, Zn 948.2), Chorzów-Stary (Cd 5.3, Zn 642.3), and Sosnowiec Klimontów (Cd 2.4–5.1, Zn 504.9) [9]. Anthropogenic excessive contamination of sandbox sand in housing estates was also observed in Sosnowiec Klimontów (Cd 3.2, Zn 522.0 mg/kg) and Bukowno (Cd 2.4) [9].

In Sosnowiec, the maximum recorded metal concentrations in soils from playgrounds reached, in mg/kg: 34.6 (Cd), 4140.5 (Pb), and 14149.2 (Zn), and on sports fields: 59.0 (Cd), 4482.2 (Pb), and 14698.1 (Zn) [10].

The normative values for at least one of the three analyzed heavy metals in soil samples from sports fields and playgrounds in the Upper Silesia region were exceeded, reaching maximum concentrations, in mg/kg: 43.0 (Cd), 1393.8 (Pb), and 4315.8 (Zn) [11].

When considering the issue of environmental safety of children, it is important to remember that the gradual accumulation of metals in surface samples from recreation areas may be associated with the development of health disorders. Estimated children's exposure in the Upper Silesia region to Cd and Pb through a non-dietary route indicates a significant risk for children who intensively use playgrounds and recreational areas [11]. In Radzionków, it has also been confirmed that industrial areas can be a risk factor for children's health due to Pb contamination in playground soils [8]. The greatest health risk was noted in the youngest age group, under 6 years of age, resulting from lead exposure in soils in Katowice-Szopienice. A similar problem may also arise in Piekary Śląskie-Brzeziny [7]. It is concerning that in the center of Warsaw, there is a potential health risk to children due to the presence of Pb and Zn [5]. In Bydgoszcz [5], as well as in Nowa Ruda, children's exposure levels are sufficiently low that they currently do not pose a significant health risk.

5. CONCLUSIONS

Substrate samples collected from recreational areas commonly used by children and adolescents in Nowa Ruda do not indicate significant contamination. The highest recorded concentrations of elements are observed in playgrounds and amount to, in mg/kg: 158.65 (Zn), 46.94 (Cu), 61.36 (Pb), 48.28 (Cr), and 29.40 (Ni). The research material from recreational areas shows considerable variability in the content of the analyzed elements. However, none of the samples exceeds the maximum permissible concentrations of the determined metals with respect to the normative limits for soils in recreational areas, as defined by the Regulation of the Minister of the Environment from 2016.

However, enrichment of substrates with toxic metals is observed in recreational areas in Nowa Ruda compared to their natural concentrations typical of the surface layer of soils in Poland. The index assessment of substrates indicates a light or moderate level of contamination with at least one metal, primarily nickel and chromium, and occasionally copper. The comprehensive index suggests a more serious degree of pollution, ranging from heavy to moderate contamination in playgrounds and sports fields, and moderate to light enrichment of sand in sandboxes. The surface layer of substrates in Nowa Ruda should be maintained in good condition, as a gradual increase in metal concentrations may pose a threat to the environment and to children's health, even though no such risk is presently observed.

Currently, children's presence in recreational areas in Nowa Ruda is not associated with health risks, as the estimated exposure assessment to toxic elements indicates a negligible probability of adverse health effects in the studied population.

To ensure a safe environment for children using playgrounds and sports fields, it is important to implement and promote monitoring of metal concentrations in substrates and to control associated health risks. It is also advisable to consider lowering permissible metal limits and adequately securing the upper soil layer to eliminate secondary dusting during activities and games, and prevent the entry of hazardous toxic elements into children's bodies. Equally important is raising parents' awareness of children's environmental safety and encouraging them to promote proper behaviors in children, such as washing hands and toys, and changing clothes after returning from play.

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