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POLLUTION LEVELS OF POTENTIALLY TOXIC ELEMENTS IN ROAD DUST COLLECTED FROM PUBLIC TRANSPORT STOPS IN BIAŁYSTOK (POLAND)

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ABSTRACT: The aim of the study was to determine the content of Zn, Cu, Cr, Ni, Pb, Cd and Fe in dust from bus stops in Białystok and their degree of contamination. Road dust samples were collected from 28 bus stops located on expressways, near low-rise buildings, shopping centres, and in green areas. Geochemical background levels were exceeded by three (Zn) to nine (Cu) times. In the case of Ni and Cr, the exceedance was six to eight times. Sources of heavy metals in dust were identified. Correlation, FA, and CA results showed homology between elements associated with car tyre abrasion, brake wear and corrosion of vehicles and road infrastructure. The impact of heavy metals on the health of residents was determined. The hazard quotient (HQ) showed that ingestion was the dominant route of exposure for people exposed to dust particles, followed by skin contact and inhalation. According to the health risk assessment, the overall non-carcinogenic risk at the bus stops examined in Białystok was low.

KEYWORDS: heavy metals, road dust, geochemical background, bus stop

Introduction

Road dust is a serious source of environmental pollution, and its quantity and composition accurately reflect the accumulation of hazardous substances in a given environment, while also significantly affecting human health (Raj & Maiti, 2020; Zheng et al., 2020; Wang et al., 2020). They are particularly important as carriers of various organic and inorganic compounds, including toxic substances, much more so than other environmental compartments such as soil (Krajewska & Nie-sio-będzka, 2008; Trujillo-González et al., 2016). Dust particles can easily become suspended in the air or washed away by precipitation, feeding surface runoff and water bodies, making them an excellent medium for transporting toxic substances (Wang et al., 2014; Zhang et al., 2015). Road dust studies have been conducted in Białystok before (Leśniewska et al. 2004; Skorbiłowicz & Skorbiłowicz, 2019; Skorbiłowicz et al., 2020; Skorbiłowicz et al., 2021), but not near bus stops, which is a novelty of this work.

An overview of the literature

When determining the heavy metal content in road dust, important factors include traffic intensity, vehicle type, condition, speed and fuel type, atmospheric conditions and the surrounding environment, e.g. land use, location of forested areas, and presence of commercial areas (Duong & Lee, 2011; Li et al., 2018). Heavy metals, including Zn, Cu, Pb, Ni, Cd, and Cr, are of great ecological importance due to their non-biodegradability and high toxicity (Pan et al., 2017). They are estimated to cause far-reaching health consequences in humans due to direct, practically daily exposure (Elom et al., 2014). In humans, they can be easily absorbed through the digestive tract, skin and respiratory system, reaching even the lungs and alveoli (Wei et al., 2015; Li et al., 2018). Above a certain limit, they are capable of causing chronic toxicity, and the associated risk depends on their solubility in the digestive tract and routes of absorption (Ali et al., 2017). The high content of heavy metals in dust at bus stops poses a potential threat to commuters and pedestrians. Heavy metals carried by surface dust at bus stops in cities can enter the human body and pose a health risk through skin contact, inhalation and ingestion. It is important to investigate the characteristics of metallic elements in surface dust at bus stops in cities and analyse the sources of metallic elements in order to understand the quality of the urban ecological environment (Wang et al. 2020).

In view of the above, it was decided to answer the following questions: (1) Is it possible to identify heavy metals associated with vehicle activity that cause potential road dust pollution along bus stops? (2) What is the degree of heavy metal contamination of street dust from bus stops based on geochemical coefficients (I_{geo} , EF and CF), (3) Is it possible to identify the sources of heavy metals in street dust using statistical multidimensional analyses (FA) and (CA) and correlation analyses? (4) What is the potential impact of heavy metals on the health of adults and children through various exposure pathways (ingestion, inhalation and dermal contact).

Research methods

The city of Białystok covers an area of 102.13 km², which accounts for approximately 0.5% of the area of the Podlaskie Voivodeship. The area is located in a temperate, transitional climate with increased continental influences. The average annual precipitation for the period 1991–2020 is 610.2 mm. Major road and rail routes intersect in Białystok. The main industrial sectors in Białystok are heating, manufacturing, trade, and municipal waste disposal. In Białystok, road dust samples were collected from 28 bus stops located throughout the city (Figure 1). The bus stops were located in various areas: green areas (5 points), shopping centres (4 points), expressways (12 points) and low-rise buildings (7 points). All samples were collected in the same way. Sampling took place during dry weather in August 2021. The material was collected from places where dust accumulation was highest. At each point, three road dust samples were collected at random from an area of approximately

1 m² and then mixed together. This resulted in one sample from each bus stop. Road dust was collected by sweeping approximately 500 g of material with a clean brush and plastic scoop, and then transferred to self-sealing polyethene bags (Idris et al., 2020; Kabir et al., 2021). The described method of road dust sampling was used in the studies by Zgłobicki et al. (2019), Xu et al. (2020) and Wang et al. (2020).

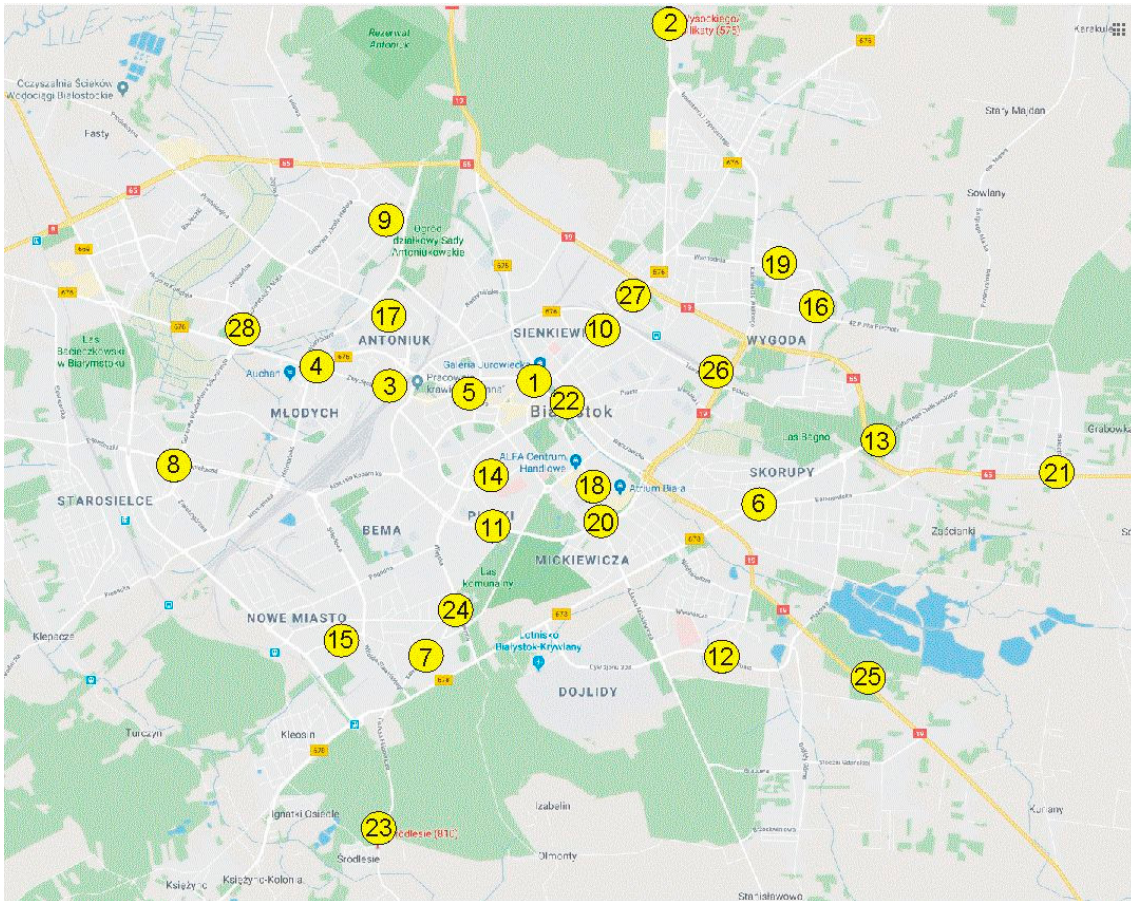


Figure 1. Location of 28 road dust sampling points in Białystok. List of points for each zone: green spaces 2, 9, 23, 24, 25; shopping centres 1, 4, 7, 8; expressways 3, 5, 6, 10, 11, 13, 20, 21, 22, 26, 27, 28; low-rise 12, 14, 15, 16, 17, 18, 19

Source: author's work based on Targeo map of Poland.

Dry dust samples were digested with nitric acid (HNO₃) with the addition of 30% hydrogen peroxide (H₂O₂) as a catalyst in a microwave mineraliser (Bourliva et al., 2017). The dust samples were digested in a Milestone ETHOS EASY system with a SK-15 high-pressure rotor. The solutions obtained were analysed for Zn, Cu, Cr, Ni, Pb, Cd and Fe using a Thermo Scientific ICE 3000 flame atomic absorption spectrometer (FAAS). The Fe content was examined as an additional test in road dust samples to calculate the EF enrichment factor. A similar procedure was used in the studies by Shahab et al. (2020), Guo and Zhang (2021) and Malakootian et al. (2021). The accuracy of the method was verified using reference material (certificate no. 0217-CM-700I-04, 7003). The research precision, expressed as relative standard deviation (RSD), ranged from 3% to 5%. Local background values for soils (LGB) proposed by Lis and Pasieczna (2012) and the geochemical background (GCB) of Taylor and McLennan (1985), as the average content of elements present in the upper part of the continental crust, were used to assess road dust pollution (Skorbiłowicz et al. 2023).

Statistical analysis

Statistical analyses began with calculations including the arithmetic mean, median, maximum, minimum, standard deviation and coefficient of variation. The Shapiro-Wilk test was used to assess the normality of the data (Skorbiłowicz et al. 2023). The data were transformed using the Box-Cox

transformation to make their distribution as close as possible to a normal distribution. Pearson's correlation coefficients were used to explain the interrelationships between metals. Before performing the FA statistical analysis, the data were checked using the KMO (Kaiser-Meyer-Olkin) index. A KMO value in the range of 0.61 to 0.85 was obtained, while Bartlett's test was statistically significant, which allowed FA analysis to be performed. The sources of metals in road dust were identified based on the results of statistical factor analysis (FA) performed using Varimax normalised rotation (Herngren et al., 2005; Settle et al., 2007). Metals of different origins but with similar geochemical characteristics were classified using Ward's statistical cluster analysis (CA) (Christoforidis & Stamatidis, 2009). Statistical analyses were performed using a licensed version of Statistica ver. 13.3.

Road dust pollution indicators

Geoaccumulation index (I_{geo})

The geoaccumulation index (I_{geo}) introduced by Müller (1969) is used to assess road dust contamination with heavy metals.

$$I_{geo} = \log_2 \left(\frac{C_n}{1.5 \cdot B_n} \right), \quad (1)$$

where:

C_n – is the metal content in road dust,

B_n – is the background content according to Lis and Pasieczna (2012),

1.5 – is a coefficient that takes into account natural background variability.

Enrichment factor (EF)

The contribution of anthropogenic sources of metals to road dust is estimated based on the enrichment factor (EF) (Mohammadi et al., 2018). Fe was selected as the reference element for the calculations due to its stability in soil and road dust. EF is calculated using the Taylor formula (1964):

$$EF = \frac{(C_n/C_{ref})_{Sample}}{(B_n/B_{ref})_{Background}}, \quad (2)$$

where:

C_n – is the metal content in road dust,

C_{ref} – is the Fe content in road dust,

B_n – content of the target component according to Lis and Pasieczna (2012),

B_n and B_{ref} are contents of metal and Fe in background soils, respectively, according to Lis and Pasieczna (2012).

Contamination factor (CF)

The contamination factor takes into account the content of metals from the soil surface and the pre-industrial reference level or environmental background values, as reported by Lis and Pasieczna (2012), among others. The CF value can be calculated using the formula provided by Hakanson (1980):

$$CF = \frac{C_n}{B_n}, \quad (3)$$

where C_n is the measured content of the tested metal in road dust, B_n denotes the geochemical background content according to Lis and Pasieczna (2012).

Health risk assessment model

The health risk assessment model was developed by the US Environmental Protection Agency (USEPA, 2004). In the model, the population was divided into two categories: adults and children, due to their behavioural and physiological differences (USEPA, 2002). Humans are exposed to road dust particles through ingestion (e.g. intentional, as in geophagy, or unintentional by children and for adults), inhalation (e.g. oral and nasal respiratory exposure to atmospheric dust or aerosols) and skin

adsorption (Tan et al., 2018; Mostafa et al., 2024). The average daily dose (ADD, [mg·kg⁻¹·d⁻¹]) for each of the three exposure routes was calculated using the following equations proposed by the USEPA (1996, 2011).

$$ADI_{ing} = \frac{C \cdot IngR \cdot EF \cdot ED \cdot CF}{BW \cdot AT}, \quad (4)$$

$$ADI_{inhal} = \frac{C \cdot InhR \cdot EF \cdot ED}{PEF \cdot BW \cdot AT}, \quad (5)$$

$$ADI_{dermal} = \frac{C \cdot SA \cdot AF \cdot ABS \cdot EF \cdot ED \cdot CF}{BW \cdot AT}, \quad (6)$$

where:

C – average metal concentration in road dust (mg·kg⁻¹),

IngR – value of daily accidental dust intake (mg·d⁻¹),

InhR – daily lung ventilation (m³·d⁻¹),

EF – contact frequency (d·year⁻¹),

ED – duration of contact (year),

BW – average body weight (kg),

AT – averaging period (d),

PEF – particle emission factor (m³·kg⁻¹),

SL – coefficient of dust adherence to the skin (mg·cm⁻² × d),

SA – skin surface exposed to dust (cm²),

ABS – percutaneous absorption coefficient, unnamed quantity.

The United States Environmental Protection Agency (USEPA) has proposed a hazard quotient (HQ) to describe the non-carcinogenic risk for each individual exposure pathway to a metallic element (USEPA, 2011), which was calculated as the ratio of the average daily dose (ADD) [mg·kg⁻¹·d⁻¹] resulting from the individual exposure pathway and the corresponding reference dose (RfD) [mg·kg⁻¹·d⁻¹] (Mostafa et al., 2024).

$$HQ = \frac{ADI}{RfD}. \quad (7)$$

The RfD values were obtained from the USEPA Integrated Risk Information System (IRIS) database as an estimate of the daily exposure of the human population that does not cause adverse effects in the human body over a lifetime (USEPA, 2011). HQ values below 1 indicate an acceptable risk, while values above 1 indicate the possibility of adverse effects. The hazard index (HI) was used to estimate the cumulative non-carcinogenic risk across all exposure pathways (Mostafa et al., 2024):

$$HI = HQ_{ing} + HQ_{inh} + HQ_{dermal} \quad (USEPA, 1989). \quad (8)$$

At $HI \leq 1$, there is no significant risk of non-carcinogenic effects. However, if $HI > 1$, there is a high chance of non-carcinogenic effects occurring, and this probability increases with increasing HI values according to (USEPA, 2011; Kumar & Khan, 2021; Faisal et al., 2022).

Results of the research

Table 1. Basic statistics of road dust test results in Białystok [$\text{mg}\cdot\text{kg}^{-1}$]

| | Mean | LGB | GCB | Min | Max | SD | CV [%] |
|----|---------|-------|-------|---------|---------|---------|--------|
| Zn | 262.33 | 88 | 71 | 171.73 | 322.70 | 34.01 | 12.96 |
| Pb | 33.60 | 35 | 17 | 21.22 | 53.71 | 8.85 | 26.34 |
| Ni | 35.20 | 6 | 44 | 17.78 | 129.70 | 20.91 | 59.42 |
| Cu | 189.87 | 10 | 25 | 70.22 | 783.23 | 135.88 | 71.56 |
| Cr | 43.16 | 6 | 85 | 5.69 | 90.91 | 20.89 | 48.39 |
| Cd | 0.39 | 0,800 | 0,089 | 0.01 | 1.49 | 0.30 | 78.27 |
| Fe | 4391.00 | 6700 | 35000 | 2402.65 | 6887.75 | 1017.98 | 23.18 |

LGB – local geochemical background (Lis and Pasieczna, 2012), GCB – global geochemical background
Source: (Taylor and McLennan, 1985).

Descriptive statistics of heavy metal content in road dust in the city of Białystok are presented in Table 1. The average contents of Zn, Cu, Cr, Ni, Pb and Cd were as follows: 262.33, 189.87, 43.16, 35.20, 33.60, 0.39 $\text{mg}\cdot\text{kg}^{-1}$, showing a downward trend $\text{Zn}>\text{Cu}>\text{Cr}>\text{Ni}>\text{Pb}>\text{Cd}$. The coefficients of variation (CV) for all heavy metals were as follows: $\text{Cd}>\text{Cu}>\text{Ni}>\text{Cr}>\text{Pb}>\text{Zn}$. The study shows elevated average concentrations (approx. three times higher) of Zn (262.33 $\text{mg}\cdot\text{kg}^{-1}$) and Cu (approx. nine times higher) (189.87 $\text{mg}\cdot\text{kg}^{-1}$) in relation to LGB – local geochemical background and GCB – global geochemical background. This indicates the anthropogenic origin of Zn and Cu in the dust samples collected from bus stops. Zn and Cu are the most commonly released heavy metals from road transport, accounting for at least 90% of all metals in road runoff (Bhattacharya et al., 2013). Cu comes mainly from brake wear and fuel combustion exhaust gases (Duong & Lee, 2011). This element is used as a high-temperature lubricant to control heat transfer in brake linings (Atiemo et al., 2012). The presence of zinc in road dust is due to tyre and brake wear, exhaust emissions from diesel engines and corrosion of galvanised protective fences and handrails (Świetlik et al., 2015). Compared to the local background level determined by Lis and Pasieczna (2012), elevated average concentrations of Ni (six times) (35.2 $\text{mg}\cdot\text{kg}^{-1}$) and Cr (eight times) (46.16 $\text{mg}\cdot\text{kg}^{-1}$) were also observed. In contrast, the average Pb (about twice) (33.6 $\text{mg}\cdot\text{kg}^{-1}$) and Cd (about five times) (0.39 $\text{mg}\cdot\text{kg}^{-1}$) contents exceed the geochemical background values proposed by Taylor and McLennan (1985). Elevated Pb content is observed due to the use of leaded petrol (banned in Europe and some non-European countries) and is often associated with traffic jams, which promote the accumulation of Pb on the road surface (Jadoon et al., 2018). In addition, Pb is present in trace amounts in brake linings (Atiemo et al., 2012). Studies have shown high variability in relation to Cu (71.56%) and Cd (78.27%). Copper (Cu) is used in tyre production to increase adhesion between the steel components of the wheels and the rubber of the tyres, and in the production of brakes to reduce heat exchange (Huang et al. 2009; Kadhem et al., 2018). The variability in the occurrence of other metals was significantly lower (from 12.36% to 59.42%). High variability of Cu and Cd indicates their diversity in the environment, which is probably largely related to their anthropogenic origin. The origin of other metals may be mixed in various proportions (Al-Khashman, 2004; Lin et al., 2017; Tian et al., 2015). The sampling points at bus stops were divided into four different zones, including green areas, shopping malls, fast traffic zones and low-density development zones. The average heavy metal levels in each zone were as follows: green areas $\text{Zn}>\text{Cu}>\text{Cr}>\text{Pb}>\text{Ni}>\text{Cd}$, shopping malls $\text{Zn}>\text{Cu}>\text{Cr}>\text{Ni}>\text{Pb}>\text{Cd}$, fast traffic zone $\text{Zn}>\text{Cu}>\text{Cr}>\text{Ni}>\text{Pb}>\text{Cd}$ and low-rise buildings $\text{Zn}>\text{Cu}>\text{Cr}>\text{Pb}>\text{Ni}>\text{Cd}$.

Table 2. Average metal content in dust from bus stops in different areas [$\text{mg}\cdot\text{kg}^{-1}$]

| | Zn | Pb | Ni | Cu | Cr | Cd |
|------------------|--------|-------|-------|--------|-------|------|
| green spaces | 243.42 | 30.43 | 25.49 | 129.06 | 30.65 | 0.35 |
| shopping centres | 246.40 | 30.46 | 37.38 | 226.61 | 59.51 | 0.40 |
| expressways | 275.33 | 37.07 | 41.02 | 233.86 | 47.76 | 0.40 |
| low-rise | 262.67 | 31.71 | 30.90 | 136.92 | 34.88 | 0.39 |

The highest average contents of Zn ($275.33 \text{ mg}\cdot\text{kg}^{-1}$), Pb ($37.07 \text{ mg}\cdot\text{kg}^{-1}$), Ni ($41.02 \text{ mg}\cdot\text{kg}^{-1}$), Cu ($233.86 \text{ mg}\cdot\text{kg}^{-1}$) and Cd ($0.40 \text{ mg}\cdot\text{kg}^{-1}$) were recorded in road dust from bus stops located in areas with high traffic intensity (Table 2). A fast-traffic zone is a zone with high traffic intensity (approx. 1,000 vehicles per hour) where vehicle movement is slowed down with periodic speed restrictions. The locations of these bus stops are associated with high vehicle density (Lin et al., 2017; Tian et al., 2015). In contrast, lower metal concentrations were found in other areas (green areas, shopping centres and low-rise buildings), which is associated with lower traffic intensity, lower vehicle density and generally lower human activity (Al-Khashman, 2004). The presence of metals in various proportions is associated with the abrasion of tyres on the road surface,

Table 3. Pearson correlations at a significance level of <0.05

| | Zn | Pb | Ni | Cu | Cr | Cd |
|----|-------|-------|-------|-------|-------|------|
| Zn | 1.00 | | | | | |
| Pb | 0.41 | 1.00 | | | | |
| Ni | 0.46 | 0.19 | 1.00 | | | |
| Cu | 0.49 | 0.16 | 0.95 | 1.00 | | |
| Cr | 0.30 | 0.36 | 0.64 | 0.67 | 1.00 | |
| Cd | -0.36 | -0.51 | -0.03 | -0.05 | -0.26 | 1.00 |

As a result of the analyses, a correlation matrix was obtained at a significance level of 0.05 (Table 3). The correlation coefficients for Zn-Pb, Zn-Ni and Zn-Cu were 0.41, 0.46 and 0.49, respectively, and their values fluctuated around the average level. Stronger correlations were observed in the case of: Ni-Cu and Ni-Cr, amounting to 0.95 and 0.64, and Cr-Cu, amounting to 0.67. Correlations between metals indicate their common sources of origin.

Contamination coefficients calculated on the basis of metal content are useful in estimating relative levels of contamination and anthropogenic influences. The most commonly used indicators are: 1) geoaccumulation index (I_{geo}), 2) enrichment factor (EF) and 3) contamination factor (CF) (Murray et al., 2004).

I_{geo}

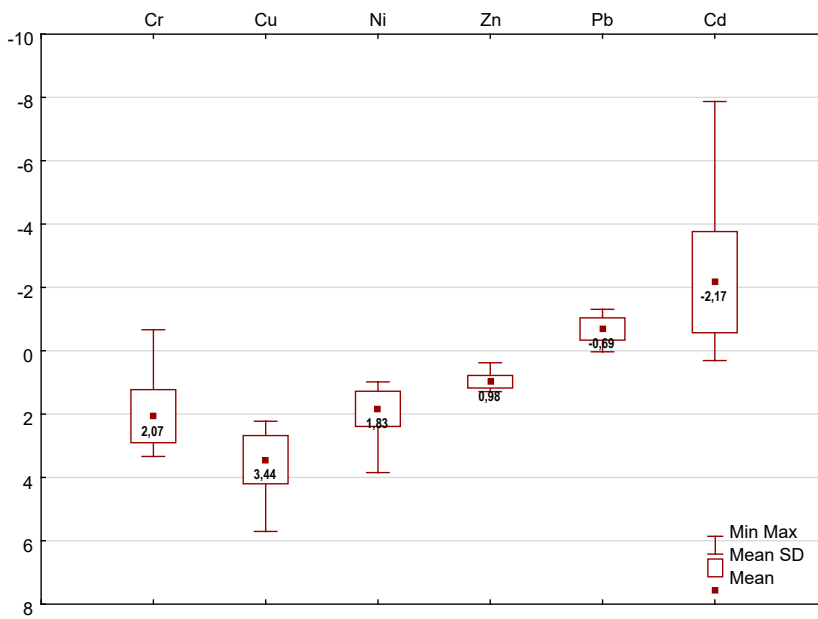


Figure 2. Pollution level of road dust near bus stops in Białystok according to I_{geo}

The mean I_{geo} values were as follows: Cd<Pb<Zn<Ni<Cr<Cu (Figure 2). Taking into account the average calculated I_{geo} values for Cd (-2.17) and Pb (-0.69), the tested dusts can be classified as uncontaminated. The average I_{geo} value for Zn (0.98) classifies the dust in Białystok as uncontaminated or moderately contaminated. A moderately contaminated level was recorded for Ni (1.83), falling within the range (1 < I_{geo} < 2). The highest dust pollution levels, ranging from 2 < I_{geo} < 3, were obtained for Cr (2.07) – moderately or heavily polluted dust, and from 3 < I_{geo} < 4 for Cu (3.44) – heavily polluted dust.

EF

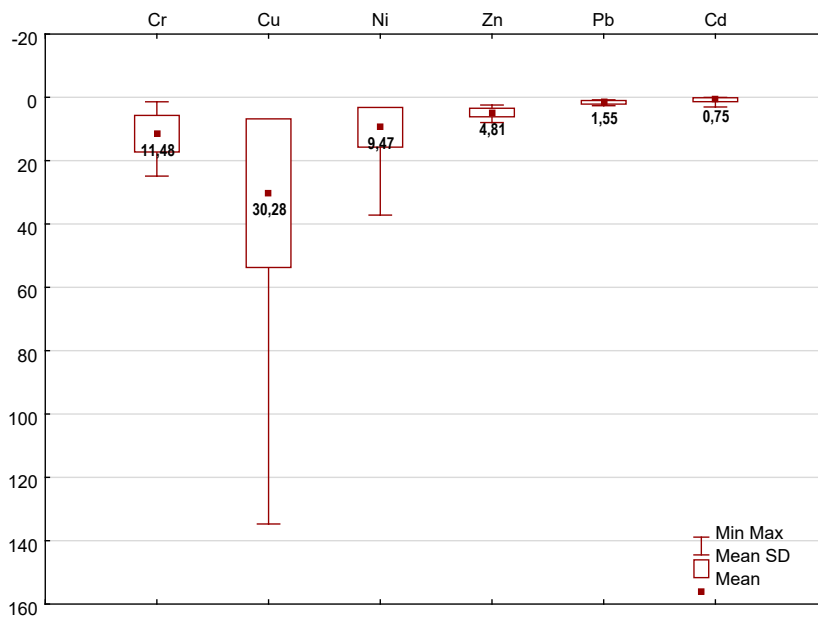


Figure 3. Enrichment factor (EF) values in road dust near bus stops in Białystok

Wu et al. (2015) believe that the enrichment factor (EF) is an effective tool for assessing anthropogenic contributions. Minimal enrichment in Cd can be attributed to road dust from bus stops in Białystok based on the average EF value (0.75) (Figure 3). However, the average EF value for Pb ranges from 2 to 5, which indicates moderate enrichment of the tested dust with this element. Significant enrichment was observed for Ni (9.47) and Cr (11.48), where EF values ranged from 5 to 20, which may suggest an anthropogenic origin of Ni and Cr in road dust in Białystok. Based on the calculated EF value (30.28), very high enrichment of Cu was found in the tested dust from bus stops. Practically 100% of the Cu in this case may be related to traffic and the associated processes of brake pad and disc wear. Every vehicle entering a bus stop area stops, which results in braking and the emission of large amounts of Cu into the environment. Zn, on the other hand, which is known for its high mobility and bioavailability in the environment (Boussen et al., 2013), can be enriched in road dust due to emissions associated with the use of Zn as an additive to engine oil and as a vulcanising agent in tyre production (Mostafa et al., 2024). The erosion of galvanised materials (e.g. road signs and metal vehicle parts) also causes Zn to enter the environment (Choi et al., 2020; Fan et al., 2021).

CF

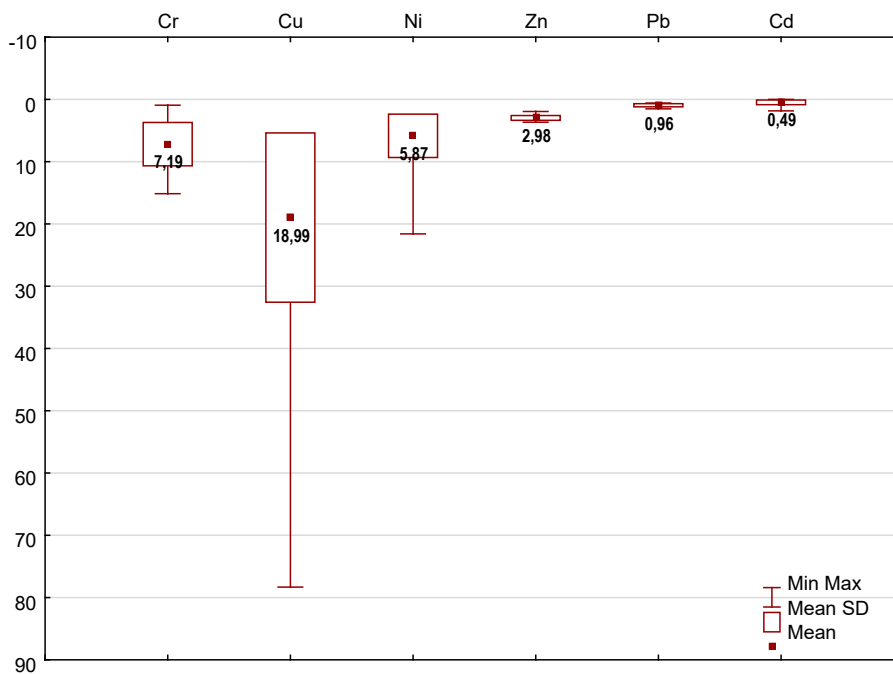


Figure 4. Pollution factor (CF) values in road dust near bus stops in Białystok

The contamination factor (CF) results showed low contamination levels ($CF < 1$) for Pb and Cd (Figure 4). Moderate contamination levels were found (CF) ranging from 1 to 3 for Zn. High contamination levels were found for Ni (5.87), where CF ranged from 3 to 6. Very high contamination levels were found for Cr (7.19) and Cu (18.99) with $CF > 6$. Tyre, brake and engine wear, heavy equipment workshops, petrol stations and motor oils are significant anthropogenic sources of Cu and Cr in road dust according to Kadhem et al. (2018); Kabir et al. (2021) and Mostafa et al., (2024).

Table 4. Results of statistical analysis of multiple factors with Varimax rotation. Factor loadings >0.7 were considered significant

| | Factor 1 | Factor 2 |
|---------------|----------|----------|
| Zn | 0.49 | 0.55 |
| Pb | 0.15 | 0.83 |
| Ni | 0.96 | 0.03 |
| Cu | 0.97 | 0.04 |
| Cr | 0.75 | 0.29 |
| Cd | 0.02 | -0.87 |
| % of variance | 51 | 25 |

A statistical factor analysis (FA) was performed (Table 4). The FA analysis yielded two factors: F1 and F2. The eigenvalues of the factors exceeded 1. The factors obtained (F1 and F2) explain a total of approximately 76% of the total variance. Factor 1 explained 51% of the variance and was correlated with Ni, Cu and Cr, indicating the dominant sources of these metals. The sources of Ni, Cu and Cr in dust from bus stops in urban conditions are emissions related to road traffic, such as tyre and brake wear as a result of braking and abrasion, as well as diesel engine exhaust gases (Idris et al. 2020). Studies have shown that the main source of Cr in road dust is the ageing of car tyres and the corrosion of old cars (car body chrome plating) (Ekoa Bessa et al., 2022; Jose & Srimuruganandam, 2020). Cr comes mainly from chromium plating processes (Bhattacharya et al., 2013), erosion or abrasion, including metal plating and car bodies, but tyres may also contain trace amounts (Carrero et al., 2013). In addition, it may come from stainless steel components, yellow road signs and yellow road markings (Murakami et al., 2007). The second component correlated with Pb and Cd explains only 25% of the total variance. The presence of Pb in road dust is associated with historical pollution and blowing of contaminated particles from roadside soil. (Jiang et al., 2019). Cd is found in lubricating oil and tyres (Meng et al., 2018). It is also present in petrol, diesel fuel, lubricating oils and has been used as a tyre hardener (Murphy & Hutchinson, 2015; Meng et al., 2018). It has also been used as a component of copper-based brake pads, in the manufacture of radiators and car paints. Furthermore, asphalt concrete pavement contains significant amounts of cadmium (Murphy & Hutchinson, 2015).



Figure 5. Ward's statistical cluster analysis – dendrogram

Table 5. Non-carcinogenic risks – daily dose (ADD [mg·kg⁻¹·d⁻¹]), hazard quotient (HQ) and hazard index (HI)

| HMs | Stat | ADI ing adults | ADI inh adults | ADI derm adults | ADI ing children | ADI inh children | ADI derm children | HQ ing adults | HQ inh adults | HQ derm adults | HQ ing children | HQ inh children | HQ derm children | HI adults | HI children |
|-----|------|----------------|----------------|-----------------|------------------|------------------|-------------------|---------------|---------------|----------------|-----------------|-----------------|------------------|-----------|-------------|
| Cr | Mean | 5,91E-05 | 4,35E-08 | 2,36E-07 | 5,52E-04 | 4,06E-07 | 1,55E-06 | 1,97E-02 | 1,52E-03 | 3,93E-03 | 1,84E-01 | 1,42E-02 | 2,58E-02 | 2,52E-02 | 2,24E-01 |
| | Min | 7,79E-06 | 5,73E-09 | 3,11E-08 | 7,27E-05 | 5,35E-08 | 2,04E-07 | 2,60E-03 | 2,00E-04 | 5,18E-04 | 2,42E-02 | 1,87E-03 | 3,39E-03 | 3,32E-03 | 2,95E-02 |
| | Max | 1,25E-04 | 9,16E-08 | 4,97E-07 | 1,16E-03 | 8,55E-07 | 3,25E-06 | 4,15E-02 | 3,20E-03 | 3,20E-03 | 8,28E-03 | 3,87E-01 | 2,99E-02 | 5,42E-02 | 5,30E-02 |
| Cu | Mean | 2,60E-04 | 1,91E-07 | 1,04E-06 | 2,43E-03 | 1,79E-06 | 6,80E-06 | 6,50E-03 | 4,76E-06 | 8,65E-05 | 6,07E-02 | 4,44E-05 | 5,66E-04 | 6,59E-03 | 6,13E-02 |
| | Min | 9,62E-05 | 7,07E-08 | 3,84E-07 | 8,98E-04 | 6,60E-07 | 2,51E-06 | 2,40E-03 | 1,76E-06 | 3,20E-05 | 2,24E-02 | 1,64E-05 | 2,09E-04 | 2,44E-03 | 2,27E-02 |
| | Max | 1,07E-03 | 7,89E-07 | 4,28E-06 | 1,00E-02 | 7,36E-06 | 2,80E-05 | 2,68E-02 | 1,96E-05 | 3,57E-04 | 2,50E-01 | 1,83E-04 | 2,34E-03 | 2,72E-02 | 2,53E-01 |
| Ni | Mean | 4,82E-05 | 3,55E-08 | 1,92E-07 | 4,50E-04 | 3,31E-07 | 1,26E-06 | 2,41E-03 | 1,72E-06 | 3,56E-05 | 2,25E-02 | 1,61E-05 | 2,33E-04 | 2,45E-03 | 2,27E-02 |
| | Min | 2,44E-05 | 1,79E-08 | 9,72E-08 | 2,27E-04 | 1,67E-07 | 6,37E-07 | 1,22E-03 | 8,69E-07 | 1,80E-05 | 1,14E-02 | 8,12E-06 | 1,18E-04 | 1,24E-03 | 1,15E-02 |
| | Max | 1,78E-04 | 1,31E-07 | 7,09E-07 | 1,66E-03 | 1,22E-06 | 4,64E-06 | 8,88E-03 | 6,34E-06 | 1,31E-04 | 8,29E-02 | 5,92E-05 | 8,60E-04 | 9,02E-03 | 8,38E-02 |
| Pb | Mean | 4,60E-05 | 3,38E-08 | 1,84E-07 | 4,30E-04 | 3,16E-07 | 1,20E-06 | 1,32E-02 | 9,61E-06 | 3,50E-04 | 1,23E-01 | 8,97E-05 | 2,29E-03 | 1,35E-02 | 1,25E-01 |
| | Min | 2,91E-05 | 2,14E-08 | 1,16E-07 | 2,71E-04 | 2,00E-07 | 7,60E-07 | 8,31E-03 | 6,07E-06 | 2,21E-04 | 7,75E-02 | 5,67E-05 | 1,45E-03 | 8,53E-03 | 7,90E-02 |
| | Max | 7,36E-05 | 5,41E-08 | 2,94E-07 | 6,87E-04 | 5,05E-07 | 1,92E-06 | 2,10E-02 | 1,54E-05 | 5,59E-04 | 1,96E-01 | 1,43E-04 | 3,66E-03 | 2,16E-02 | 2,00E-01 |
| Zn | Mean | 3,59E-04 | 2,64E-07 | 1,43E-06 | 3,35E-03 | 2,47E-06 | 9,39E-06 | 1,20E-03 | 8,81E-07 | 2,39E-05 | 1,12E-02 | 8,22E-06 | 1,57E-04 | 1,22E-03 | 1,13E-02 |
| | Min | 2,35E-04 | 1,73E-07 | 9,39E-07 | 2,20E-03 | 1,61E-06 | 6,15E-06 | 7,84E-04 | 5,77E-07 | 1,56E-05 | 7,32E-03 | 5,38E-06 | 1,02E-04 | 8,00E-04 | 7,43E-03 |
| | Max | 4,42E-04 | 3,25E-07 | 1,76E-06 | 4,13E-03 | 3,03E-06 | 1,16E-05 | 1,47E-03 | 1,08E-06 | 2,94E-05 | 1,38E-02 | 1,01E-05 | 1,93E-04 | 1,50E-03 | 1,40E-02 |
| Cd | Mean | 5,32E-07 | 3,91E-10 | 2,12E-09 | 4,97E-06 | 3,65E-09 | 1,39E-08 | 5,32E-04 | 3,91E-07 | 2,12E-04 | 4,97E-03 | 3,65E-06 | 1,39E-03 | 7,45E-04 | 6,36E-03 |
| | Min | 7,03E-09 | 5,17E-12 | 2,81E-11 | 6,56E-08 | 4,83E-11 | 1,84E-10 | 7,03E-06 | 5,17E-09 | 2,81E-06 | 6,56E-05 | 4,83E-08 | 1,84E-05 | 9,84E-06 | 8,41E-05 |
| | Max | 2,04E-06 | 1,50E-09 | 8,12E-09 | 1,90E-05 | 1,40E-08 | 5,32E-08 | 2,04E-03 | 1,50E-06 | 8,12E-04 | 1,90E-02 | 1,40E-05 | 5,32E-03 | 2,85E-03 | 2,43E-02 |

Ward's method. Two groups were separated based on Euclidean similarities. The first (I) group contains Cu and Zn, and the second (II) group contains Cd (as a separate object) and Cr, Ni, and Pb. The first group identified the source of Cu and Zn as emissions resulting exclusively from the abrasion and corrosion of the vehicle components mentioned above. The second group contains metals (Cd, Cr, Ni and Pb) whose origin is not only related to the braking or corrosion of car components.

A health risk assessment was conducted based on a model developed by the United States Environmental Protection Agency (USEPA, 1996; USEPA, 2011) (Table 5). During the research and analysis of the hazard quotient (HQ), it was found that ingestion was the most dominant route for people exposed to dust particles, followed by skin contact and inhalation, similar to the study by Mostafa et al. (2024). The order in which dust particles entered the body was the same for both adults and children. Similar results were obtained by Li et al. (2017) and Wang et al. (2021). For most metals, the hazard quotient (HQ) was higher in children than in adults. Children appear to be more susceptible to dust exposure due to their natural, reflexive behaviour associated with play (Bourliva et al., 2017). The analysis of the hazard index (HI) for all metals for children and adults showed values lower than one, which means that the residents of Białystok, in particular those using urban motor transport, are not exposed to significant non-carcinogenic risks. However, attention should be paid to possible long-term effects that may be harmful to human health. Therefore, it is recommended to continuously monitor the heavy metal content in road dust at bus stops.

Conclusions

The average metal content in road dust from bus stops in Białystok was as follows: Zn>Cu>Cr>Ni>Pb>Cd (262.33, 189.87, 43.16, 35.20, 33.60, 0.39 mg·kg⁻¹), showing a downward trend. Local and reference geochemical background levels were exceeded three times for Zn and nine times for Cu. In contrast, the local background for Ni and Cr was exceeded six and eight times, respectively. The studies showed high variability in the content of Cu (71.56%) and Cd (79.27%), indicating their high diversity in the environment due to anthropogenic origin. The highest average contents of Zn (275.33 mg·kg⁻¹), Pb (37.07 mg·kg⁻¹), Ni (41.02 mg·kg⁻¹), Cu (233.86 mg·kg⁻¹) and Cd (0.40 mg·kg⁻¹) were recorded in road dust from bus stops located in areas with heavy traffic. The assessment of road dust pollution levels based on (Igeo, EF and CF) showed anthropogenic origin of Cu, Cr and Ni. The highest values of the indicators were found for Cu. This is related to tyre wear as a result of friction, braking and driving. Multivariate statistical analyses FA and CA indicated Cu, Ni and Cr as the main metals polluting dust from bus stops in Białystok, which confirms previous correlation analyses. The hazard quotient (HQ) analysis showed that ingestion was the most dominant route for people exposed to dust particles, followed by skin contact and inhalation. The order of dust particle entry into the body was the same for both adults and children. The hazard index (HI) analysis for all metals for children and adults showed that residents of Białystok, especially those using urban motor transport, are not exposed to significant non-cancer risks due to contact with contaminated road dust. The studies showed the presence of heavy metals in road dust at levels varying depending on the location of sampling. Some metals showed concentrations exceeding the geochemical background level, which may indicate anthropogenic sources of their origin, in particular related to road traffic. The study did not include seasonal analysis, so it is not possible to assess the temporal variability of metal content. Changes related to weather conditions, traffic intensity or road service activities (e.g. salting) may affect metal levels and are an important direction for future research. The analyses covered a wide range of metals, but future studies should focus on those elements that showed levels exceeding the background level. Seasonality analysis will allow the dynamics of metal accumulation to be assessed, and the study of the distance gradient from the road will allow the distance from the emission source at which elevated levels persist to be determined.

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Mirosław SKORBIŁOWICZ

POZIOM ZANIECZYSZCZENIA POTENCJALNIE TOKSYCZNYMI PIERWIASTKAMI W PYŁACH DROGOWYCH ZEBRANYCH Z PRZYSTANKÓW TRANSPORTU PUBLICZNEGO W BIAŁYMSTOKU (POLSKA)

STRESZCZENIE: Celem pracy było określenie zawartości Zn, Cu, Cr, Ni, Pb, Cd i Fe w pyłach z przystanków autobusowych Białegostoku i ich stopnia zanieczyszczenia. Identyfikowano źródła metali ciężkich w pyłach. Określono wpływ metali ciężkich na zdrowie mieszkańców. W Białymstoku pobrano próbki pyłów z 28 przystanków autobusowych. Wykryto przekroczenia tła geochemicznego od trzech (Zn) do dziewięciu (Cu) razy. W przypadku Ni i Cr przekroczenie wynosiło od sześciu do ośmiu razy. Wyniki korelacji, FA i CA wykazały homologię między pierwiastkami związaną ze ścieraniem opon samochodowych, zużywaniem się hamulców oraz korozją pojazdów i infrastruktury drogowej. Iloraz zagrożenia (HQ) wykazał, że spożycie dominowało u osób narażonych na cząstki pyłu, następnie kontakt skórny oraz wdychanie. Mieszkańcy Białegostoku nie są narażeni na ryzyko nienowotworowe.

SŁOWA KLUCZOWE: metale ciężkie, pyły drogowe, tło geochemiczne, przystanek autobusowy