

Article

Annual Variability of Total and Leachable Heavy Metal Content in Street Sweeping Waste from a Medium Sized City

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Abstract

Street sweeping waste (SSW) represents a heterogeneous urban material rich in road-deposited particles and associated contaminants, including heavy metals. Although SSW is generated systematically in all cities and constitutes a relevant indicator of diffuse urban pollution, research addressing its chemical composition, especially its temporal dynamics, remains limited. This study investigates the annual variability of total and leachable concentrations of heavy metals (Zn, Cu, Pb, Ni, Cr, and Cd) in SSW collected monthly over a one-year period in a medium-sized city. Total metal content was determined using aqua regia digestion, while leachability was assessed through standardized extraction tests. Statistical evaluation included correlation analysis, variability indices and assessment of metal mobility. Results confirm that both total and leachable metal concentrations exhibit distinct seasonal patterns, strongly influenced by traffic intensity, winter maintenance practices, and fluctuations in particle size distribution. Several metals demonstrated a high mobility factor, highlighting the potential environmental risk associated with their transport to urban soils and stormwater systems. The findings emphasize the necessity of incorporating temporal dynamics into SSW management strategies and demonstrate the importance of monitoring mobile metal fractions rather than relying solely on total concentrations. Due to the scarcity of annual-scale studies on SSW contamination, this research contributes novel insights into the environmental behavior of heavy metals in urban settings.

Keywords: heavy metals; leachability; street sweeping waste <10 mm; seasonal variability; metal mobility

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1. Introduction

Street sweeping waste is widely recognized as a highly heterogeneous urban sediment that accumulates solid-bound contaminants, including heavy metals, hydrocarbons, nutrients and a range of other anthropogenic pollutants. Because sweeping removes the material deposited directly on road surfaces, this waste stream reflects both local traffic-related emissions and the diffuse background of urban pollution, making it a sensitive indicator of roadside environmental quality. Its composition is strongly influenced by land use, traffic intensity, sweeping frequency, seasonal conditions, and the proportion of fine particles retained in the collected material [1].

Urban surfaces act as reservoirs of heavy metals. Intensively developed areas are subject to continuous anthropogenic pressure, resulting in the accumulation of contaminants on impermeable surfaces such as roads, parking lots and pavements. Road-deposited sediments (RDS) are considered important carriers of heavy metals including Pb, Zn, Cu, Cd, Ni and Cr originating primarily from traffic emissions, tire and brake wear, fuel combustion, and atmospheric deposition. According to road sediments in urban areas contain high concentrations of heavy metals, especially in industrial zones [2]. The highest metal loads occur in the 0.45–75 μm fraction, which is not effectively removed by conventional sweeping, underscoring the need to eliminate fine particles in order to protect water quality. Household dust and street sediments may also reflect ongoing atmospheric emissions, particularly for elements associated with metallurgical activity such as Fe, Co, Cr, Mn and Ni [3].

Numerous studies demonstrate that the finest grain-size fractions (<63 μm) contain elevated heavy metal concentrations due to their large specific surface area and high sorption capacity [4], highlighting the critical role of particle-size distribution in contamination assessment and environmental risk evaluation [5]. Despite its environmental relevance, street sweeping waste (SSW) remains a poorly characterized waste stream. Mechanical sweeping is widely used as a pollution-control measure in urban areas, yet the resulting material is strongly heterogeneous, containing mineral particles, organic matter, microplastics [6,7], and various anthropogenic contaminants. SSW has been investigated far less extensively than other environmental media such as sewage sludge or municipal waste. Existing studies have largely focused on operational cleaning efficiency rather than on the detailed characterization of the collected material [8].

Street sweeping waste consists of particles derived from tire wear, local soil, degraded pavement, and larger debris such as leaves, branches and miscellaneous litter [9]. It can be readily resuspended by wind or vehicle movement, becoming a significant source of fugitive particulate emissions, including PM (Particulate Matter) and total suspended particulates [10]. Street dust also contains toxic heavy metals as well as organic and inorganic pollutants, predominantly within particles <100 μm , which are easily mobilized and contribute to stormwater contamination [11], posing risks to ecosystems and human health. Coarser sediments are capable of storing and releasing substantial quantities of heavy metals during rainfall events, and their removal may therefore provide additional environmental benefits [12]. Studies indicate that metal leaching from RDS increases under lower pH conditions, and that Zn, Cu, Pb and Ni frequently associate with Fe, Al and Mn oxides. Coarser fractions may also release particle-bound metals, particularly during precipitation events [13,14].

Street sweeping is generally ineffective in reducing pollutant loads in stormwater runoff, whereas runoff itself is highly effective at mobilizing sediments, particularly fine fractions. Although metal concentrations are typically highest in particles <0.075 mm, the bulk of pollutant mass is associated with larger particles [15]. Research by Generowicz et al. has shown that sweeping reduces PM₁₀ and PM_{2.5} emissions [8,16–19], but may increase chloride loads in stormwater [20,21].

Heavy metal concentrations consistently show strong correlations with particle size, increasing toward the finest fractions [3]. Traffic intensity also affects metal loads in SSW, though the relationship is not always linear. A monitoring study from Delaware reported higher Cr and Zn concentrations on high-traffic roads, but the material remained highly variable [21,22]. The character of urban dust further varies with climatic conditions, geology, traffic structure, local infrastructure and winter deicing practices [23–25]. In terrestrial environments, the chemical composition of woody plants changes in response to heavy metal exposure [26], while aquatic communities may be affected by chemical and biochemical interactions with contaminants transported through road runoff [27–30].

From an environmental perspective, both total metal content and metal mobility are essential metrics. Although total concentrations may fall below regulatory thresholds for soils, suggesting that the material does not automatically qualify as hazardous waste, the presence of mobile metal fractions warrants integrated risk assessment [31–38].

Although most previous studies have investigated heavy metals in street sweeping waste (SSW) collected from large metropolitan areas, considerably less attention has been paid to medium-sized industrial cities. These urban areas differ substantially in terms of traffic intensity, industrial structure, land use, and stormwater management, resulting in potentially different patterns of heavy metal accumulation and mobility. Consequently, findings obtained in large metropolitan areas cannot be directly extrapolated to medium-sized cities. Moreover, medium-sized municipalities often have more limited environmental monitoring resources despite representing a substantial proportion of urban areas. Therefore, studies conducted in medium-sized industrial cities are essential for improving environmental risk assessment and supporting sustainable stormwater and street sweeping waste management.

Despite the growing number of studies on heavy metals in SSW, important scientific questions remain unanswered. Previous investigations have mainly focused on total heavy metal concentrations or short-term sampling campaigns, providing only limited information on seasonal variability and contaminant mobility. However, total metal concentrations alone do not reflect the potential release of contaminants into the environment, whereas leachable fractions provide information on their environmental availability and potential migration to urban runoff and receiving waters. Therefore, the simultaneous determination of total and leachable heavy metal concentrations enables a more comprehensive assessment of contamination levels and environmental risk. To the best of our knowledge, no previous study has comprehensively evaluated the annual variability of both total and leachable heavy metal concentrations in street sweeping waste collected from a medium-sized industrial city.

To address this research gap, the present study investigated representative street sweeping waste samples collected during consecutive municipal street sweeping cycles over a one-year monitoring period. The study determined (i) total heavy metal concentrations, (ii) leachable heavy metal fractions, and (iii) the relationships between heavy metal mobility, pH, and seasonal variability. The findings provide new insights into the environmental behaviour of heavy metals in street sweeping waste and support more reliable environmental risk assessment and sustainable urban waste management.

2. Materials and Methods

2.1. Study Area and Sampling Procedure

The analysis of street sweeping waste (SSW) was conducted in Stalowa Wola, a medium-sized industrial city located in south-eastern Poland, with approximately 55,000 inhabitants. According to the Municipal Environmental Protection Programme, the city's economy is dominated by metallurgical and aluminium-processing industries, while road traffic represents an additional source of diffuse heavy metal emissions associated with

brake wear, tyre abrasion, vehicle corrosion, and road surface deterioration [39]. The investigated road network includes residential, commercial, and industrial areas, including residential streets, collector roads, major urban roads, and roads located in the vicinity of industrial facilities, ensuring that the collected material is representative of the overall urban environment rather than individual local hotspots. The region is characterized by a temperate climate with distinct seasonal variability. According to the Institute of Meteorology and Water Management (IMGW-PIB) [39], the region receives approximately 660 mm to 700 mm of annual precipitation, with rainfall distributed throughout the year and seasonal snow cover occurring during winter. Winter road maintenance involves the application of sand or a sand NaCl mixture, whereas spring street sweeping removes sediments accumulated during the winter period. Climate characteristics were compiled using data provided by the Institute of Meteorology and Water Management (IMGW-PIB) [40].

Street cleaning operations are carried out regularly from late winter to late autumn (March–November). The total length of road sections subjected to sweeping is approximately 140 km, and the sidewalk area is about 450,000 m². The annual amount of collected SSW varies between 300 and 1200 tonnes, depending on winter conditions. The frequency and duration of street sweeping operations are governed by weather conditions and municipal maintenance schedules. Because cleaning the entire municipal road network requires approximately one to two months, complete street sweeping cycles, rather than individual calendar months, were adopted as the sampling units.

Sampling was conducted throughout one annual monitoring period and reflected consecutive municipal street sweeping cycles. Following the winter maintenance period, the first city-wide sweeping cycle was carried out during March–April. Subsequent sweeping cycles were performed during May–June, July–August, September–October, and November, depending on operational requirements and prevailing weather conditions. Consequently, each analytical sample represented one complete municipal street sweeping cycle rather than an individual monthly collection.

During each sweeping cycle, approximately 100 incremental subsamples were systematically collected from residential, commercial, and industrial streets, including road edges, curbs, and gutters, to ensure representative spatial coverage of the municipal road network. The incremental subsamples were thoroughly homogenized to obtain one composite sample for laboratory analyses. This approach minimized the influence of local spatial variability and ensured that each analytical sample reflected the characteristics of street sweeping waste generated across the entire city. Analysis of individual monthly collections would not have provided representative information for the whole study area, as only selected sectors of the city are cleaned during a given month. Therefore, composite samples were considered the most appropriate analytical units for evaluating seasonal changes in heavy metal occurrence and leachability.

The sampling approach was consistent with previous methodologies applied to this material type; however, in the present study, the collected material was specifically used for the determination of both total and leachable heavy metal concentrations. The complete sampling strategy, preparation of composite samples, and analytical workflow are presented schematically in Figure 1.

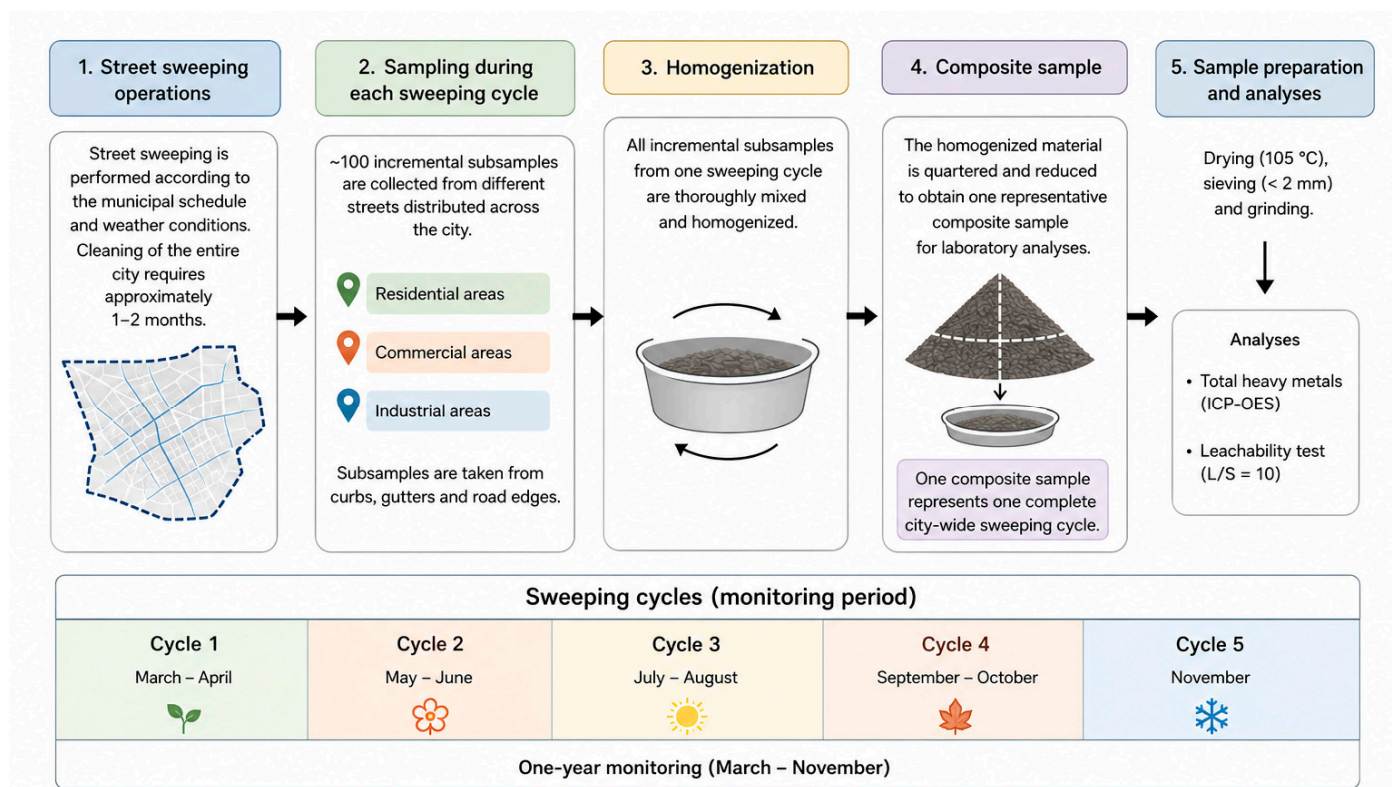


Figure 1. Schematic overview of the street sweeping cycles, representative sampling strategy, composite sample preparation, and analytical workflow adopted for the annual monitoring of street sweeping waste (SSW).

2.2. Analytical Procedures

2.2.1. Total Heavy Metal Content

Total heavy metal content was determined in accordance with [41]. The analysed elements (Zn, Cu, Cr, Ni, Pb, Cd, Ba, Mo and As) were selected because they are among the heavy metals most frequently associated with road traffic emissions, industrial activities, and urban runoff, and are commonly included in environmental risk assessment, waste characterization, and landfill acceptance criteria. Samples were digested using microwave-assisted dissolution in a mixture of concentrated HCl and HNO₃ (3:1 v/v), following [42]. Results are expressed in mg/kg.

2.2.2. Metal Leachability

The leachable fraction of heavy metals was quantified in eluates obtained by batch leaching with deionized water at a liquid-to-solid ratio of 10:1, according to [43].

2.2.3. Instrumentation

Both total metal concentrations and leachate concentrations were measured using an Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES, Plasma 400, Perkin-Elmer Corp., Norwalk, CT, USA, 1990), capable of detecting elements at 10⁻⁸–10⁻⁹ (1–10 ppb), meeting the sensitivity requirements for environmental analyses and aqueous eluates.

2.3. Assessment of Heavy Metal Leachability and Mobility

To evaluate the environmental mobility of heavy metals in the analysed street sweeping waste (SSW) and their potential for release into the aqueous phase, two complementary indicators were applied: the Leachability Ratio (LR) and the dimensionless Mobility

Index (MI). Although both parameters are derived from the same analytical data, they serve different interpretative purposes. The Leachability Ratio expresses the percentage of the total metal content released during the standardized leaching test, whereas the dimensionless Mobility Index facilitates comparison of the relative mobility of individual metals independently of percentage notation and enables their classification into qualitative mobility categories.

The Leachability Ratio was calculated as follows:

$$LR = (L/T) \times 100$$

where

L—concentration of the metal in the leachate (mg/kg),

T—total concentration of the metal in the solid material (mg/kg).

The dimensionless Mobility Index was calculated as:

$$MI = L/T$$

To facilitate the interpretation of heavy metal mobility, MI values were classified into four qualitative categories based on the proportion of the total metal content released during the standardized batch leaching test. The adopted threshold values were introduced as a practical classification framework for comparing the relative mobility of the analysed metals. They are intended solely for environmental interpretation and do not represent regulatory or legislative limits [41–43].

Based on the adopted classification, MI values were interpreted as follows [44–46]:

MI < 0.001—trace mobility;

0.001 ≤ MI < 0.010—low mobility;

0.010 ≤ MI < 0.050—moderate mobility;

MI ≥ 0.050—elevated mobility.

Figure 1 illustrates the entire research methodology.

2.4. Statistical Analysis

2.4.1. Coefficient of Variation (CV)

The coefficient of variation was calculated using the standard formula:

$$CV(\%) = (SD/X) \times 100$$

where:

SD—standard deviation of the dataset,

X—mean value of the dataset.

The CV was used to assess the degree of variability in total metal content and leachability across the annual sampling cycle. Values below 20% were interpreted as low variability, 20–50% as moderate, and above 50% as high variability, which is consistent with commonly applied environmental data classification.

Correlation Analysis: Pearson correlation coefficients (*r*) were calculated to determine the relationships between total metal concentrations, leachable fractions, and pH. Because the monitoring programme comprised five consecutive municipal street sweeping cycles covering one annual period, the statistical analysis was performed using five composite samples (*n* = 5). Although *n* = 5 represents a limited sample size for classical hypothesis testing, each analytical observation was derived from a composite sample prepared from approximately 100 systematically collected incremental subsamples, thereby reducing the influence of local spatial variability. Accordingly, the correlation analysis was designed to identify temporal associations among seasonal datasets rather than to test statistical hypotheses or establish universally generalizable quantitative relationships.

Therefore, the calculated Pearson correlation coefficients should be interpreted as descriptive indicators of seasonal patterns and relationships within the investigated monitoring period.

2.4.2. Correlation Between Total (T) and Leachable (L) Metal Concentrations

Pearson correlation coefficients were calculated using the following formula:

$$r = \text{cov}(X,Y)/(\text{SD}_x \times \text{SD}_y)$$

where

- $\text{cov}(X,Y)$ —covariance between variables X and Y,
- SD_x —standard deviation of variable X,
- SD_y —standard deviation of variable Y.

Correlation strength was interpreted as follows:

- $|r| \geq 0.7$ —strong correlation,
- $0.3 \leq |r| < 0.7$ —moderate correlation,
- $|r| < 0.3$ —weak correlation.

This analysis enabled assessment of whether higher total metal content translated into increased leachability, thereby indicating potential environmental mobility.

It should be noted that the objective of the statistical analysis was not hypothesis testing but rather the identification of temporal trends and relationships between total and leachable metal fractions. Although the number of analytical observations was limited ($n = 5$ composite samples), each sample represented a highly integrated dataset obtained from approximately 100 incremental subsamples. Therefore, the statistical results should be interpreted as indicative of seasonal patterns rather than as evidence of universal quantitative relationships.

Although the leachable metal concentrations were generally low, the statistical analyses were not intended to demonstrate high contaminant levels but rather to characterize seasonal variability and the environmental behaviour of heavy metals in representative street sweeping waste. The coefficient of variation (CV) was applied to assess temporal variability, Pearson correlation analysis was used to explore relationships between total metal concentrations, leachable fractions and pH, whereas the Leachability Ratio (LR) and Mobility Index (MI) provided complementary measures describing the proportion and relative tendency of metals to be released from the solid phase. Together, these indices enabled a comprehensive evaluation of heavy metal behaviour during the annual monitoring period.

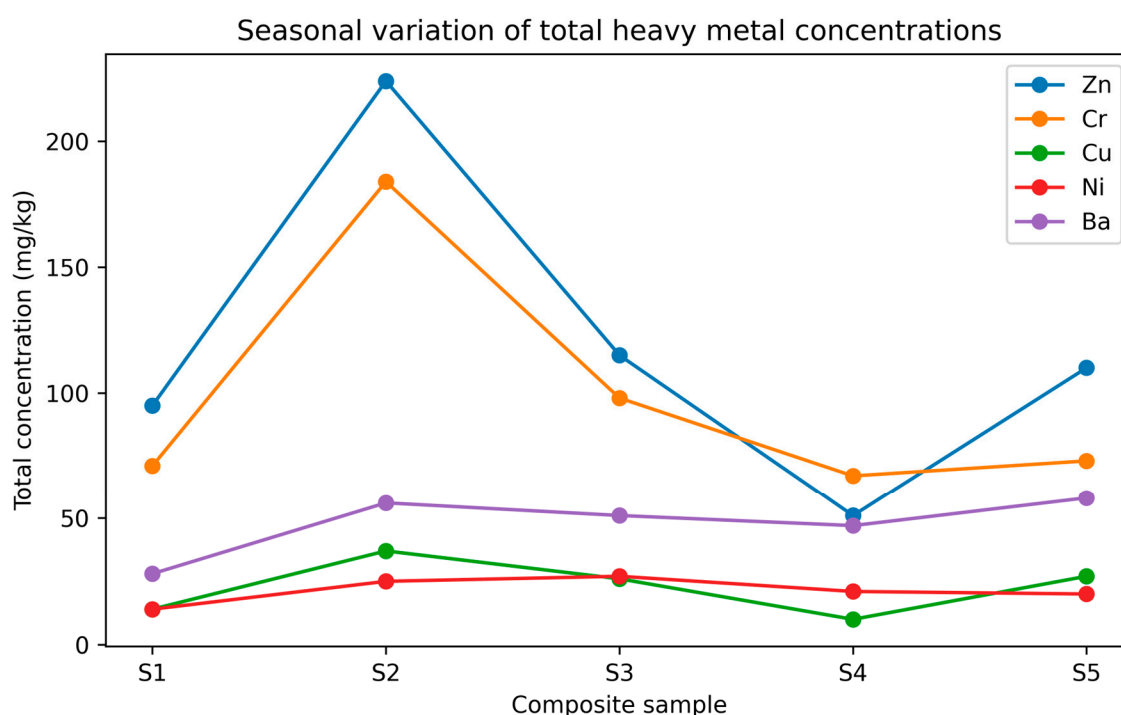
3. Results

This section presents the key findings of the study, including the seasonal variability of total and leachable heavy metal concentrations in <10 mm street sweeping waste, their mobility, and the associated environmental implications. The results are interpreted with respect to meteorological conditions, winter road maintenance practices, and the physico-chemical heterogeneity of the material. The analysis also highlights metals that pose the highest leaching potential and identifies periods of the year with increased environmental risk. Table 1 and Figure 2 present the total heavy metal concentrations determined in the analysed street sweeping waste during the annual monitoring period.

Table 1. Total heavy metal concentrations in street sweeping waste (mg kg⁻¹ d.m.).

Parameter	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Annual Mean	SD
Cr	71	184	98	67	73	98.6	48.9
Zn	95	224	115	51	110	119.0	63.8
Pb	19	26	18	15	14	18.4	4.6
Cd	1.9	6.0	2.8	2.5	3.8	3.4	1.6
Ni	14	25	27	21	20	21.4	5.2
Mo	11	19	21	24	23	19.6	5.3
Cu	14	37	26	10	27	22.8	10.9
Ba	28	56	51	47	58	48.0	12.1
As	<5	<5	<5	7	6	ND *	—
Hg	<1	<1	<1	<1	<1	ND *	—
Se	<5	<5	<5	<5	<5	ND *	—
Sb	<1	<1	<1	<1	<1	ND *	—

Note: * ND—not determined because concentrations were below the analytical limit of quantification (LOQ).

**Figure 2.** Seasonal variation in the dominant heavy metal concentrations in representative street sweeping waste samples.

Mean values and standard deviations were calculated only for elements quantified in all representative composite samples. For elements reported below the analytical limit of quantification (LOQ), descriptive values are presented without statistical calculations. Among the analysed elements, Zn and Cr exhibited the highest total concentrations, ranging from 51 to 224 mg/kg and from 67 to 184 mg/kg, respectively. Both metals reached their maximum concentrations during the second municipal street sweeping cycle (May–June). Elevated concentrations were also observed for Ba (28–58 mg/kg), Ni (14–27 mg/kg) and Cu (10–37 mg/kg), whereas Cd occurred at substantially lower levels (1.9–6.0 mg/kg). Arsenic was detected only during the final two municipal street sweeping cycles, while Hg, Se and Sb remained below the analytical limit of quantification throughout the monitoring period.

Although no consistent seasonal trend common to all analysed metals was observed, several elements, including Zn, Cr and Cu, exhibited their highest concentrations during the second municipal street sweeping cycle (May–June), whereas generally lower concentrations were recorded during the subsequent sweeping cycles. At the same time, the overall ranking of the dominant heavy metals remained relatively stable throughout the monitoring period, with Zn and Cr consistently representing the major constituents of the analysed street sweeping waste. These results demonstrate temporal variability in the chemical composition of street sweeping waste over the annual monitoring period while confirming that the dominant heavy metal composition remained generally consistent among representative municipal street sweeping cycles.

The leaching tests showed that all analysed metals occurred at concentrations substantially lower than their corresponding total contents (Table 2). Copper exhibited the highest leachable concentrations (0.14–0.45 mg/kg), followed by Ba (0.09–0.48 mg/kg) and Zn (0.12–0.42 mg/kg). Chromium, nickel and molybdenum were detected at lower concentrations, whereas Pb, Cd, As, Hg, Se and Sb remained below the analytical limit of quantification in most representative composite samples. All measured concentrations were below the permissible leaching limits specified for waste acceptance at landfills.

Table 2. Leachability of heavy metals from street cleaning waste.

Parameter	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Permissible Leaching Limits for Waste *
	mg/kg					
Cr	0.12	0.11	0.25	0.35	0.23	0.5
Zn	0.12	0.42	0.30	0.27	0.19	4
Pb	<0.10	<0.10	<0.10	<0.10	<0.10	0.5
Cd	<0.02	<0.02	<0.02	<0.02	<0.02	0.04
Ni	0.15	<0.10	0.19	0.24	0.33	0.4
Mo	0.14	<0.10	0.24	<0.10	<0.10	0.5
Cu	0.33	0.2	0.40	0.14	0.45	2
Ba	0.17	0.48	0.25	0.12	0.09	20
As	<0.5	<0.5	<0.5	<0.5	<0.5	0.5
Hg	<0.01	<0.01	<0.01	<0.01	<0.01	0.01
Se	<0.1	<0.1	<0.1	<0.1	<0.1	0.1
Sb	<0.06	<0.06	<0.06	<0.06	<0.06	0.06
pH	9.18	8.12	8.52	8.54	9.23	
Conductivity, mS/cm	2.051	0.281	0.234	0.143	0.124	

Note: * [47] Regulation of the Minister of Economy of 16 July 2015 on the acceptance of waste for landfilling

Compared with total metal concentrations, the leachable fractions showed relatively limited variation throughout the annual monitoring period. Although the leachable concentrations were generally of the same order of magnitude, small differences among representative municipal street sweeping cycles were observed for several metals, particularly Cu, Zn, Ba and Ni. The aqueous extracts exhibited alkaline pH values ranging from 8.12 to 9.23. Electrical conductivity showed the greatest variability among the measured physicochemical parameters, decreasing from 2.051 mS/cm during the first municipal street sweeping cycle to 0.124 mS/cm in the final cycle. Overall, only a minor proportion of the total heavy metal pool was released during the standardized batch leaching test, indicating effective retention of most analysed metals within the solid matrix.

3.1. Leachability Ratio (LR) Values and Environmental Implications

The calculated Leachability Ratio (LR) values demonstrated specific environmental dynamics of the heavy metals present in the street sweeping waste. The specific values are shown in Table 3.

Table 3. Assessment of the environmental mobility of heavy metals in street sweeping waste based on the calculated Leachability Ratio (LR, %).

Metal	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Mean LR $\pm$ SD
Cr	0.2	0.1	0.3	0.5	0.3	0.3 $\pm$ 0.2
Zn	0.1	0.2	0.3	0.5	0.2	0.3 $\pm$ 0.2
Pb	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.
Cd	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.
Ni	1.1	n.c.	0.7	1.1	1.7	1.2 $\pm$ 0.4
Mo	1.3	n.c.	1.1	n.c.	n.c.	1.2 $\pm$ 0.1
Cu	2.4	0.5	1.5	1.4	1.7	1.5 $\pm$ 0.7
Ba	0.6	0.9	0.5	0.3	0.2	0.5 $\pm$ 0.3
As	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.
Hg	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.
Se	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.
Sb	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.

Notes: n.c. —not calculated because either the total concentration or the leachable concentration was below the analytical limit of quantification (LOQ). Mean values were calculated only from quantified results.

The calculated Leachability Ratio (LR) values provided additional information on the relative release potential of heavy metals from the solid phase during the standardized leaching test. The calculated values are presented in Table 3. The highest LR values were observed for Cu (0.5–2.4%) and Ni (0.7–1.7%), indicating a relatively greater tendency of these metals to be transferred from the solid phase to the aqueous phase. Intermediate LR values were obtained for Mo and Ba, whereas Cr and Zn exhibited consistently low leachability (<0.5%). For Pb, Cd, As, Hg, Se and Sb, LR values were not calculated because one or both analytical results were below the analytical limit of quantification (LOQ). Overall, the results indicate limited heavy metal release under the alkaline conditions of the standardized leaching test, suggesting that most metals remained associated with the solid matrix. These findings provided the basis for the subsequent evaluation of heavy metal mobility using the dimensionless Mobility Index (MI).

3.2. Statistical Analysis

To facilitate interpretation of the annual monitoring results, complementary statistical indices describing variability, correlations and metal mobility were calculated.

Pearson correlation coefficients are presented to illustrate seasonal associations observed during the annual monitoring period based on five representative composite samples.

Correlation coefficients describe associations between leachable metal concentrations and pH during the annual monitoring period and are presented for descriptive interpretation of seasonal patterns.

Statistical analysis revealed high variability in heavy metal concentrations within street sweeping waste, as confirmed by the coefficients of variation presented in Table 4. The highest heterogeneity was observed for Zn, Cr, Cu, and Cd ($CV > 0.47$), indicating an uneven distribution of contaminants associated with varying traffic intensity, industrial influence, and seasonal accumulation processes. Within the leachable fraction, Ba and Zn

exhibited the greatest variability (CV = 1.33 and 0.47, respectively), suggesting a strong influence of the physicochemical properties of the material on metal leaching processes.

Table 4. Coefficients of Variation (CV) for Total (T) and Leachable (L) Heavy Metal Concentrations in Street Sweeping Waste.

Metal	CV (T)	Interpretation (T)	CV (L)	Interpretation (L)
Zn	0.54	High variability	0.47	High variability
Cr	0.50	High variability	0.42	High variability
Cu	0.48	High variability	0.35	Moderate variability
Cd	0.47	High variability	<LOQ	Not evaluated
Mo	0.26	Moderate variability	0.55	High variability
Ba	0.25	Moderate variability	1.33	Very high variability
Pb	0.26	Moderate variability	<LOQ	Not evaluated
Ni	0.24	Moderate variability	0.58	High variability
As	0.11	Low variability (sporadic occurrence)	—	—

Correlation analysis (Table 5) indicated a relatively strong positive association between total and leachable Zn concentrations ($r = 0.69$), whereas the remaining metals exhibited weak or moderate relationships. Owing to the limited number of representative composite samples ($n = 5$), the calculated correlation coefficients should be interpreted as indicators of seasonal trends rather than evidence of statistically robust quantitative relationships. Nevertheless, the observed patterns provide valuable insight into seasonal changes in heavy metal behaviour in representative street sweeping waste collected during consecutive municipal street sweeping cycles.

Table 5. Pearson Correlation Coefficients Between Total (T) and Leachable (L) Metal Concentrations.

Metal	$r(T,L)$	Strength of Relationship
Zn	0.69	Strong positive correlation
Cr	−0.56	Moderate negative correlation
Cu	0.23	Weak positive correlation
Ni	−0.20	Weak negative correlation
Ba	0.26	Weak positive correlation
Mo	−0.29	Weak negative correlation
Pb, Cd	—	Not calculated due to insufficient variability in L

The correlation analysis suggested that pH was an important factor influencing the mobility of Zn ($r = -0.95$) and Ba ($r = -0.78$). In contrast, positive correlations were observed for Cu and Ni, which may be related to interactions with organic matter and metal complexation processes (Table 6).

Table 6. Pearson Correlation Coefficients Between Leachable Metal Concentrations (L) and pH.

Metal	$r(L-pH)$	Interpretation
Zn	−0.95	Strong pH dependence (lower pH → higher mobility)
Ba	−0.78	Strong pH dependence
Cr	−0.02	No significant relationship
Ni	+0.65	Moderate positive relationship
Cu	+0.64	Moderate positive relationship (likely associated with organic complexation)
Mo	+0.02	No significant relationship

The Mobility Index (MI) analysis indicated that among the analyzed metals, Cu was the most mobile (MI up to 0.033), whereas Cr and Pb exhibited the lowest mobility (MI < 0.005). These findings indicate that Cu, Zn and, to a lesser extent, Ba exhibited the greatest potential for release under the conditions of the applied leaching test, whereas Cr and Pb remained largely associated with the solid phase (Figure 3).

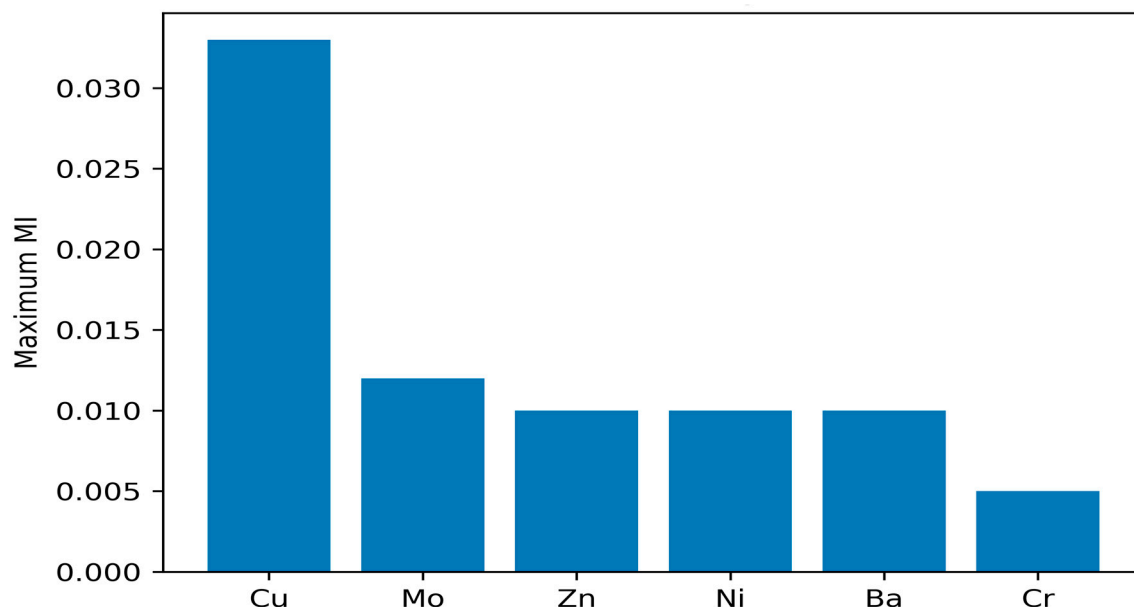


Figure 3. Maximum Mobility Index (MI) values of the analysed heavy metals.

4. Discussion

4.1. Seasonal Variability and Sources of Heavy Metals

The annual monitoring revealed clear seasonal variability in heavy metal concentrations, indicating that contaminant accumulation in street sweeping waste (SSW) was controlled by the combined influence of traffic-related emissions, industrial activities, winter road maintenance, and meteorological conditions. Because the investigated city represents a medium-sized industrial centre rather than a large metropolitan area, the observed contamination patterns likely reflect the interaction of diffuse traffic emissions with a relatively constant industrial background [10,11,16,17]. Zn was the dominant heavy metal throughout the monitoring period, which agrees with previous studies identifying tyre wear, corrosion of galvanized vehicle components and road infrastructure as its principal sources [11,28,30]. The elevated Zn concentrations observed after winter most likely resulted from the accumulation of fine road-deposited particles during periods of limited street cleaning and intensive application of sanding materials [8,17,22,36]. In contrast, Cu was associated mainly with brake wear and exhibited a relatively stable occurrence throughout the monitoring period, suggesting continuous emissions related to everyday traffic [11,21,30]. Lower seasonal variability of Cr and Ni indicates that these metals were influenced predominantly by relatively stable industrial emissions rather than by rapidly changing traffic conditions. Considering the metallurgical profile of the investigated city, these elements most likely originated from atmospheric deposition associated with metal-processing industries [23,25,26,42,43]. Similarly, Ba showed seasonal fluctuations consistent with its recognised association with brake lining wear, confirming the growing contribution of non-exhaust traffic emissions to urban contamination [11,28,30]. The observed seasonal trends should also be interpreted in the context of the municipal street sweeping strategy. Because each analytical sample represented one complete city-wide

sweeping cycle composed of approximately 100 systematically collected incremental sub-samples, the obtained results reflect representative contamination patterns for the entire urban area rather than local hotspots. Consequently, the first post-winter sampling period represents the cumulative accumulation of contaminants deposited during the winter season before large-scale municipal cleaning commenced [17,20,34]. Overall, the results demonstrate that seasonal variability of heavy metals in SSW is controlled by the interaction between traffic emissions, industrial activities and municipal maintenance practices, confirming the need for representative long-term monitoring in medium-sized industrial cities.

4.2. Factors Controlling Heavy Metal Mobility

Although total metal concentrations provide information on contaminant accumulation, they do not adequately reflect potential environmental risk. Metal mobility depends primarily on physicochemical speciation, adsorption–desorption processes and environmental conditions controlling contaminant release. Therefore, simultaneous assessment of total and leachable metal fractions provides a substantially more realistic evaluation of potential metal transfer to urban runoff and receiving waters [13–15,36]. Cu exhibited the highest Mobility Index despite not being the dominant metal in the solid phase. This behaviour is consistent with previous studies showing that Cu released from brake wear commonly occurs in exchangeable forms and forms soluble complexes with dissolved organic matter, enhancing its release during leaching [11,13,14]. Consequently, Cu mobility appears to be governed primarily by its geochemical speciation rather than its total concentration. Zn behaved differently, showing a strong negative relationship with pH. The increased mobility observed under more acidic conditions is consistent with proton-promoted desorption from iron and manganese oxides, which reduces metal retention and facilitates Zn release into solution [13–15]. Because Zn is mainly associated with fine tyre-derived particles, changes in pH can substantially influence its environmental availability [11,13,28]. In contrast, Cr exhibited very limited mobility despite measurable total concentrations, indicating that it remained strongly associated with stable mineral phases. Similar behaviour has been reported for Cr bound to iron oxides and aluminosilicates, where low solubility effectively restricts metal release during leaching [14,15,25]. The relatively high variability of Ba is likely related to seasonal changes in the physical properties of brake wear particles rather than to changes in emission intensity alone [11,28,30]. Overall, the results indicate that heavy metal mobility is controlled mainly by geochemical processes rather than by total concentrations alone. The combined assessment of total and leachable fractions therefore provides a more reliable basis for evaluating the environmental behaviour of street sweeping waste [13–15,36].

4.3. Environmental Implications

The results indicate that street sweeping waste represents not only a municipal waste stream but also a potential secondary source of diffuse pollution. Although most analysed metals exhibited relatively low mobility, the elevated mobility of Cu and the pronounced pH dependence of Zn demonstrate that changes in environmental conditions may significantly influence contaminant release to urban runoff [1,13–15]. The representative composite sampling strategy adopted in this study proved suitable for assessing seasonal contamination at the scale of the entire urban area. Unlike individual monthly collections, each composite sample integrated material collected from all major functional zones of the city during one complete municipal sweeping cycle, providing representative information on temporal changes in heavy metal occurrence [17,20,34]. These findings indicate that regular street sweeping should be considered not only as a cleaning activity but also as an important preventive environmental management measure limiting the transfer of

particulate-bound contaminants to urban runoff, stormwater systems, and receiving waters. Overall, the present study demonstrates that representative annual monitoring combining total and leachable heavy metal analyses provides valuable information on contaminant accumulation, mobility, and potential environmental risk. These findings contribute to the limited knowledge available for medium-sized industrial cities and support evidence-based urban stormwater management, sustainable street sweeping programmes, and informed waste management strategies.

5. Conclusions

This study provides one of the few annual assessments of both total and leachable heavy metal concentrations in street sweeping waste (SSW) collected from a medium-sized industrial city. The results demonstrated clear seasonal variability in heavy metal occurrence, reflecting the combined influence of traffic-related emissions, industrial activities, winter road maintenance, and municipal street sweeping operations. Although Zn, Cu and Cr were among the dominant metals in the solid phase, their environmental behaviour differed considerably. Zinc exhibited strong pH-dependent mobility, whereas Cu showed the highest Mobility Index, indicating greater susceptibility to release under favourable physicochemical conditions. In contrast, Cr and Pb remained largely associated with the solid phase, exhibiting very low mobility throughout the monitoring period. Importantly, the generally low Mobility Index values obtained in this study indicate that the majority of heavy metals remain strongly bound within the solid fraction of street sweeping waste and are not readily released during contact with water. Consequently, regular municipal street sweeping functions as an effective pollution prevention measure by physically removing contaminated particulate matter before heavy metals can be mobilised by rainfall and transported to stormwater systems and receiving waters. From a municipal management perspective, these findings support the implementation of systematic street sweeping programmes combined with routine environmental monitoring of both total and leachable heavy metal fractions. Such an integrated approach provides a scientific basis for optimizing street cleaning schedules, improving landfill management decisions, evaluating the potential beneficial reuse of street sweeping waste following appropriate quality assessment, and supporting sustainable urban water protection. Overall, this study demonstrates that representative annual monitoring integrating total heavy metal concentrations with leachability assessment provides a scientific basis for evidence-based municipal management, sustainable street sweeping strategies, environmental monitoring, and urban stormwater protection, particularly in medium-sized industrial cities where comparable long-term datasets remain scarce.

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References

1. Sansalone, J.J.; Buchberger, G. Partitioning and First Flush of Metals in Urban Roadway Storm Water. *J. Environ. Eng.* **1997**, *123*, 134–143. [https://doi.org/10.1061/\(ASCE\)0733-9372\(1997\)123:2\(134\)](https://doi.org/10.1061/(ASCE)0733-9372(1997)123:2(134)).
2. Hengren, L.; Goonetilleke, A.; Ayoko, G.A. Analysis of Heavy Metals in Road-Deposited Sediments. *Anal. Chim. Acta* **2006**, *571*, 270–278. <https://doi.org/10.1016/j.aca.2006.04.064>.
3. Apeagyei, E.; Bank, M.S.; Spengler, J.D. Distribution of Heavy Metals in Road Dust along an Urban–Rural Gradient in Massachusetts. *Atmos. Environ.* **2011**, *45*, 2310–2323. <https://doi.org/10.1016/j.atmosenv.2010.11.015>.
4. Maiké, W.; Nina, V.; Rainer, M. The Efficiency of Storm Water Sedimentation Tanks for Fine Particles in Urban Runoff. In *New Trends in Urban Drainage Modelling*; Springer: Cham, Switzerland, 2019. https://doi.org/10.1007/978-3-319-99867-1_147.
5. Grąz, K.; Kwaśny, J. Microplastics in Composts as a Barrier to the Development of Circular Economy. *Archit. Civ. Eng. Environ.* **2021**, *4*, 137–144. <https://doi.org/10.21307/ACEE-2021-037>.
6. Grąz, K.; Gronba-Chyła, A.; Generowicz, A.; Kwaśny, J.; Kwaśnicki, P.; Ciula, J.; Łapiński, J.; Bajdur, W. Microplastics from Plastic Waste as a Limitation of Sustainability of the Environment. *Rocz. Ochr. Sr.* **2023**, *25*, 367–373. <https://doi.org/10.54740/ros.2023.037>.
7. Grąz, K. Qualitative Studies of Selected Types of Composts. *Rocz. Ochr. Sr.* **2024**, *26*, 700–706. <https://doi.org/10.54740/ros.2024.061>.
8. Lin, S.L.; Deng, Y.; Lin, M.Y.; Huang, S.W. Do the Street Sweeping and Washing Work for Reducing the Near-ground Levels of Fine Particulate Matter and Related Pollutants? *Aerosol Air Qual. Res.* **2023**, *23*, 220338. <https://doi.org/10.4209/aaqr.220338>.
9. Zglobicki, W.; Telecka, M.; Skupiński, S. Assessment of Short-Term Changes in Street Dust Pollution with Heavy Metals in Lublin (E Poland): Levels, Sources and Risks. *Environ. Sci. Pollut. Res.* **2019**, *26*, 35049–35060. <https://doi.org/10.1007/s11356-019-06496-x>.
10. Müller, A.; Österlund, H.; Marsalek, J.; Viklander, M. The Pollution Conveyed by Urban Runoff: A Review of Sources. *Sci. Total Environ.* **2020**, *709*, 136125. <https://doi.org/10.1016/j.scitotenv.2019.136125>.
11. Piscitello, A.; Bianco, C.; Casasso, A.; Sethi, A. Non-Exhaust Traffic Emissions: Sources, Characterization, and Mitigation Measures. *Sci. Total Environ.* **2021**, *766*, 144440. <https://doi.org/10.1016/j.scitotenv.2020.144440>.
12. Aryal, R.; Beecham, S.; Sarkar, B.; Chong, M.N.; Kinsela, A.; Kandasamy, J.; Vigneswaran, S. Readily Wash-Off Road Dust and Associated Heavy Metals on Motorways. *Water Air Soil Pollut.* **2017**, *228*, 1.
13. Gunawardana, C.; Egodawatta, P.; Goonetilleke, A. Adsorption and Mobility of Metals in Build-Up on Road Surfaces. *Chemosphere* **2015**, *119*, 1391–1398. <https://doi.org/10.1016/j.chemosphere.2014.02.048>.
14. Joshi, U.M.; Vijayaraghavan, K.; Balasubramanian, R. Elemental Composition of Urban Street Dusts and Their Dissolution Characteristics in Various Aqueous Media. *Chemosphere* **2009**, *77*, 526–533. <https://doi.org/10.1016/j.chemosphere.2009.07.043>.
15. Borris, M.; Österlund, H.; Marsalek, J.; Viklander, M. Contribution of Coarse Particles from Road Surfaces to Dissolved and Particle-Bound Heavy Metal Loads in Runoff: A Laboratory Leaching Study with Synthetic Stormwater. *Sci. Total Environ.* **2016**, *573*, 212–221. <https://doi.org/10.1016/j.scitotenv.2016.08.062>.
16. Ghasemi, M.; Kamareh, T.F.; Morovati, M.; Kazembeigi, F.; Alinejad, N.; Moein, H.; Hassani, G. The Fate of Leaked Heavy Metals in the Urban Environment under Different Persistence and Precipitation Scenarios. *Sci. Rep.* **2024**, *14*, 8343. <https://doi.org/10.1038/s41598-024-59057-9>.
17. Calabrò, P.S. Impact of Mechanical Street Cleaning and Rainfall Events on the Quantity and Heavy Metals Load of Street Sediments. *Environ. Technol.* **2010**, *31*, 1255–1262. <https://doi.org/10.1080/09593331003671255>.
18. Generowicz, A.; Gronba-Chyła, A.; Kulczycka, J.; Harazin, P.; Gąska, K.; Ciula, J.; Odroń, P. Life Cycle Assessment for the Environmental Impact Assessment of a City’ Cleaning System. *J. Clean. Prod.* **2022**, *382*, 135184. <https://doi.org/10.1016/j.jclepro.2022.135184>.

19. Generowicz, A.; Gaska, K.; Hajduga, G. Multi-Criteria Analysis of the Waste Management System in a Metropolitan Area. In Proceedings of the 10th Conference on Interdisciplinary Problems in Environmental Protection and Engineering EKO-DOK 2018, Polanica-Zdrój, Poland, 16–18 April 2018; Volume 44, p. 43.
20. Gronba-Chyla, A.; Generowicz, A.; Kwaśnicki, P.; Cycoń, D.; Kwaśny, J.; Grąz, K.; Gaska, K.; Ciula, J. Determining the Effectiveness of Street Cleaning with the Use of Decision Analysis and Research on the Reduction in Chloride in Waste. *Energies* **2022**, *15*, 3538. <https://doi.org/10.3390/en15103538>.
21. Karanasiou, A.; Amato, F.; Moreno, T.; Lumbreras, J.; Borge, R.; Linares, C.; Boldo, E.; Alastuey, A.; Querol, X. Road Dust Emission Sources and Assessment of Street Washing Effect. *Aerosol Air Qual. Res.* **2014**, *14*, 734–743. <https://doi.org/10.4209/aaqr.2013.03.0074>.
22. Calvillo, S.J.; Williams, E.S.; Brooks, B.W. Street Dust: Implications for Stormwater and Air Quality, and Environmental Management Through Street Sweeping. In *Reviews of Environmental Contamination and Toxicology*; Springer: Cham, Switzerland, 2015; Volume 233. https://doi.org/10.1007/978-3-319-10479-9_3.
23. Adewumi, A.J. Heavy Metals in Soils and Road Dust in Akure City, Southwest Nigeria: Pollution, Sources, and Ecological and Health Risks. *Expo. Health* **2022**, *14*, 375–392. <https://doi.org/10.1007/s12403-021-00456-y>.
24. Laniyan, T.A.; Popoola, O.J. Integrated Assessment of Heavy Metal Contamination in Urban Road Dust: Implications for Human Health and Ecosystem Sustainability in Abeokuta, Nigeria. *Environ. Forensics* **2025**, *26*, 204–222. <https://doi.org/10.1080/15275922.2024.2366786>.
25. Acosta, J.A.; Gabarrón, M.; Faz, A.; Martínez-Martínez, S.; Zornoza, R.; Arocena, J.M. Influence of Population Density on the Concentration and Speciation of Metals in Soil and Street Dust from Urban Areas. *Chemosphere* **2015**, *134*, 328–337.
26. Denny, M.; Baskaran, M.; Burdick, S.; Tummala, C.; Dittrich, T. Investigation of Pollutant Metals in Road Dust in a Post-Industrial City: Case Study from Detroit, Michigan. *Front. Environ. Sci.* **2022**, *10*, 974237. <https://doi.org/10.3389/fenvs.2022.974237>.
27. Nguyen, T.-T.; Le, T.-C.; Chen, S.-C.; Peng, Z.-Y.; Kuo, T.-Y.; Chang, K.-M.; Tsai, C.-J. Street Dust Properties and Effective Control of Secondary Particle Emission from Vacuum Street Sweepers Using Composite Filters. *Sep. Purif. Technol.* **2025**, *354*, 129065. <https://doi.org/10.1016/j.seppur.2024.129065>.
28. Kreider, M.L.; Panko, J.M.; McAtee, B.L.; Sweet, L.L.; Finley, B.L. Physical and Chemical Characterization of Tire-Related Particles: Comparison of Particles Generated Using Different Methodologies. *Sci. Total Environ.* **2010**, *408*, 652–659. <https://doi.org/10.1016/j.scitotenv.2009.10.016>.
29. Alves, C.A.; Vicente, E.D.; Vicente, A.M.P.; Rienda, I.C.; Tomé, M.; Querol, X.; Amato, F. Loadings, Chemical Patterns and Risks of Inhalable Road Dust Particles in an Atlantic City in the north of Portugal. *Sci. Total Environ.* **2020**, *737*, 139596. <https://doi.org/10.1016/j.scitotenv.2020.139596>.
30. Amato, F.; Favez, O.; Pandolfi, M.; Alastuey, A.; Querol, X.; Moukhtar, S.; Bruge, B.; Verlhac, S.; Orza, J.; Bonnaire, N.; et al. Traffic-Induced Particle Resuspension in Paris: Emission Factors and Source Contributions. *Atmos. Environ.* **2016**, *129*, 114–124. <https://doi.org/10.1016/j.atmosenv.2016.01.022>.
31. Kumar, G.; Vyas, S.; Sharma, S.N.; Dehalwar, K. Challenges of Environmental Health in Waste Management for Peri-Urban Areas. In *Solid Waste Management*; Springer: Cham, Switzerland, 2024. https://doi.org/10.1007/978-3-031-60684-7_9.
32. Brunelli, A.; Breda, S.; Scanferla, P.; Calgaro, L.; Marcomini, A.; Badetti, E. A Methodology to Assess a Mobile Urban Street Cleaning Activity. *Atmos. Pollut. Res.* **2023**, *14*, 101680. <https://doi.org/10.1016/j.apr.2023.101680>.
33. Tan, Z.; Lu, S.; Zhao, H.; Kai, X.; Jiexian, P.; Win, M.S.; Yu, S.; Yonemochi, S.; Wang, Q. Magnetic and Geochemical Characterization and Health Risk Assessment of Road Dust in Xuanwei and Fuyuan, China. *Environ. Geochem. Health* **2018**, *40*, 1541–1555.
34. Lloyd, L.N.; Fitch, G.M.; Singh, T.S.; Smith, J.A. Characterization of Environmental Pollutants in Sediment Collected During Street Sweeping Operations to Evaluate Its Potential for Reuse. *J. Environ. Eng.* **2019**, *145*, 04018141. [https://doi.org/10.1061/\(ASCE\)EE.1943-7870.0001493](https://doi.org/10.1061/(ASCE)EE.1943-7870.0001493).
35. Christoforidis, A.; Stamatis, N. Heavy Metal Contamination in Street Dust and Roadside Soil along the major national road in Kavala's region, Greece. *Geoderma* **2009**, *151*, 257–263. <https://doi.org/10.1016/j.geoderma.2009.04.016>.
36. Nawrot, N.; Wojciechowska, E.; Rezanian, S.; Walkusz-Miotk, J.; Pazdro, K. The Effects of Urban Vehicle Traffic on Heavy Metal Contamination in Road Sweeping Waste and Bottom Sediments of Retention Tanks. *Sci. Total Environ.* **2020**, *749*, 141511. <https://doi.org/10.1016/j.scitotenv.2020.141511>.
37. Das, S.; Wiseman, C.L.S. Examining the Effectiveness of Municipal Street Sweeping in Removing Road-Deposited Particles and Metal(loid)s of Respiratory Health Concern. *Environ. Int.* **2024**, *187*, 108697. <https://doi.org/10.1016/j.envint.2024.108697>.

38. Woźniak, A.D.; Ciula, J.; Kochanek, A.; Guzal-Dec, D. Renewable Energy as a Strategic Mechanism for Achieving the Sustainable Development Goals: A Bibliometric Review. *Energies* **2026**, *19*, 1201. <https://doi.org/10.3390/en19051201>.
39. Stalowa Wola City Council. *Update of the Environmental Protection Program for the Gmina of Stalowa Wola for the Years 2020–2023 with a Perspective to 2026 (Resolution No. XXXVIII/433/2021)*; Stalowa Wola Town Hall: Stalowa Wola, Poland, 2021.
40. Institute of Meteorology and Water Management (IMGW-PIB). *Climate Data for the Stalowa Wola Region*; IMGW-PIB: Warsaw, Poland, 2025.
41. PN-EN 11885:2009 “Water quality—Determination of 33 elements by inductively coupled plasma optical emission spectrometry”.
42. PN-EN 13657:2006 “Characterization of waste—Digestion for subsequent determination of aqua regia soluble fractions”.
43. PN-EN 12457-2:2006 “Characterization of waste—Compliance test for leaching of granular waste materials and sludges—Part 2: One-stage batch test at L/S = 10 L/kg for materials <4 mm”.
44. Mahmud, M.; Hasan, M.M. Assessment of Heavy Metal Contamination on Road Dust: A Case Study of Khulna City. *Adv. Environ. Eng. Res.* **2025**, *6*, 008. <https://doi.org/10.21926/aeer.2501008>.
45. Zhang, H.; Wang, L.; Wang, Q.; Wu, X. Source Apportionment and Health Risk Assessment of Heavy Metals in PM_{2.5} in Handan: A Typical Heavily Polluted City in North China. *Atmosphere* **2021**, *12*, 1232. <https://doi.org/10.3390/atmos12101232>.
46. Cai, K.; Li, C. Street Dust Heavy Metal Pollution Source Apportionment and Sustainable Management in A Typical City-Shijiazhuang, China. *Int. J. Environ. Res. Public Health* **2019**, *16*, 2625. <https://doi.org/10.3390/ijerph16142625>. PMID: 31340519; PMCID: PMC6678876.
47. Regulation of the Minister of Economy of 16 July 2015 on the acceptance of waste for landfilling. Dz.U. 2015 poz. 1277.

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