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Unveiling Heavy Metal Links: Correlating Dust and Topsoil Contamination in Vilnius Schools

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Abstract: This study conducts a comprehensive analysis of the presence of heavy metals, specifically zinc (Zn), lead (Pb), copper (Cu), chromium (Cr), and arsenic (As), in dust samples collected from 24 schools in Vilnius during the year 2022. It compares these findings with topsoil data from prior investigations spanning from 2011 to 2023, obtained from the areas near the schools as well as multiple spots across Vilnius. The study reveals significant variations in the levels of heavy metals, providing a comprehensive understanding of the complex relationship between urban sources of pollution, environmental processes, and the correlation between soil and indoor dust pollution. An important aspect of this work is the application of principal component analysis (PCA) and hierarchical clustering on the datasets from 2017 and 2020, which unveiled separate clusters from both dust and soil samples. Three major clusters were identified, highlighting the dynamic character of heavy metal distribution in these environments. Pearson's correlation analysis provided additional evidence, demonstrating significant relationships between specific heavy metals in both dust and soil samples, emphasizing the interlinked nature of these environments. Zinc (Zn) and Lead (Pb) were determined to be the most commonly found heavy metals in the dust samples, which could potentially pose a health hazard in educational environments. This study distinguishes itself by examining indoor dust in educational facilities and topsoil in Vilnius, providing crucial insights into the relationship between these two environmental matrices. Recognizing the geographical limitations of this study, further research could be expanded to other cities to validate and compare these findings.

Keywords: heavy metal; toxic metals; environmental pollution; topsoil; soil and dust; Vilnius; dust; dust pollution

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1. Introduction

Soil is a complex and dynamic substrate consisting of a porous matrix that allows the interactions of air, water, and biota. Alterations in soil processes have a significant impact on ecosystem functioning, as the complex balance between inorganic and organic substances within the soil gives rise to a range of environmental issues. In order to maintain the quality and functionality of soil, it is essential that all soil types are maintained in a sustainable condition. The presence of heavy metals has a detrimental impact on these aspects [1].

Particulate matter, or dust, is the general term for fine solid particles smaller than 100 µm. Due to its high airborne dispersal capability, it has significant contamination potential [2–4]. One major source of pollution in metropolitan areas is street dust. Mold spores, dander, pollen, organic matters, and inorganic substances are among the many components found in this complex mixture of particles. Among these inorganic substances, certain heavy metals occur naturally in the environment as part of the geochemical background, contributing to the overall composition of urban dust [5]. Wind may carry these particles into the air, where they can become a significant cause of air pollution. Cities' roadways and roofs are among the surfaces where they may settle [5–8].

Recent studies on dust sourcing have uncovered various environmental pollutants, primarily in outdoor environments. This encompasses research on the concentration and composition of elements in dust [9], the impact of dust and aerosol particle size on the transportation of contaminants from outdoor to indoor environments [10], and the movement of polluted soil and airborne particles into indoor dust [11]. However, these studies predominantly focus on emissions from industries and vehicles, with limited consideration given to indoor dust pollutants found in schools. Furthermore, the 2011 Grimsvotn eruption in Iceland brought attention to the impact of natural phenomena, such as volcanic eruptions, on environmental pollution. This eruption notably affected atmospheric aerosol concentrations in Vilnius, Lithuania, which is nearly 3000 km away from Iceland [12]. This occurrence emphasizes the importance of taking into account both human-caused and naturally occurring sources when evaluating indoor dust pollution.

The sources of indoor air pollutants in school classrooms have been determined to be associated with occupancy and accumulated dust [13]. Indoor surroundings, especially in educational institutions, are vulnerable to contamination caused by dust. A study was conducted to determine the levels and characteristics of toxic metals, such as chromium, lead, zinc, arsenic, mercury, and copper, in dust samples [14]. Furthermore, a study conducted to measure the health impacts of dust particles in Vilnius and Kaunas emphasized the potential health hazards linked to exposure to these pollutants [15]. Although there is an increasing amount of research on environmental pollution, there is still a lack of thorough examination of heavy metal pollution in indoor dust, specifically in educational environments. This gap is crucial due to the potential health hazards that children and adolescents may face in schools. Prior research has primarily concentrated on outdoor environmental pollution, neglecting the complex dynamics of indoor pollution sources, particularly in urban educational settings.

Notable studies in this field encompass an extensive examination of the air quality and its effects on health in schools [16]. Furthermore, investigations have been conducted to identify indoor environmental pollutants in schools, such as lead, flame retardants, and phthalates [17,18]. The exclusion of this aspect is noteworthy, as indoor pollution can vary significantly in its composition and effects, especially in educational institutions located in urban areas.

The comparative analyses of indoor dust pollution in different regions worldwide demonstrate substantial disparities in the levels of heavy metal concentrations. Studies have indicated that indoor dust from various locations such as Malaysia, Iraq, Hong Kong, and Nigeria contain high concentrations of Cr, Cu, Zn, Pb, and Fe [3,4,12,19,20]. The changes observed are evidence of the extensive and varied character of indoor dust pollution, which highlights the need for a more comprehensive comprehension of its origins and effects on human health.

During the period from 1995 to 2006, significant factors that contributed to changes in pollution levels in the soil of Vilnius were Ag, Sn, Cu, Zn, Mo, and Pb. Contamination levels diminished around former industrial sites, but they escalated in different public spaces. During the period from 2006 to 2011 in Vilnius, notable changes in the amounts of Mo, Ba, Sn, Cu, Pb, Zn, and Ni elements were recorded, according to Vilnius Municipality [21]. Pollution intensified near the bus stations, railway, marketplaces, hospitals, schools, and lastly where industrial production continued. Studies conducted in Lithuania have identified significant soil contamination problems, namely in urban areas and alongside major roadways. Grigalavičiene et al. [22] and Jankaitė et al. [23] discovered heightened concentrations of Pb, Cu, and other harmful metals in surface soil samples close to the Vilnius-Klaipėda highway and other roadways, attributing this phenomenon to increased car movement. Lead concentrations at 5 to 10 m from the highway were 1.4 times higher than the maximum limit of 32 mg/kg [24] and 2.1 times higher than the local background of

17.6 ± 0.8 mg/kg in the forest soil at a distance of 5 to 20 m [25]. In 2021, there were approximately 450.89 cars per 1000 people in the population, given that there were 365,577 cars and a population of 810,797 in Vilnius [26].

Taraškevičius et al. [27,28] conducted more research and found varying degrees of Zn, Pb, and Cu pollution in different areas of Vilnius. Industrial locations had elevated levels of pollution, whereas the level of contamination in residential zones fluctuated correlated with the degree of urbanization. Soils are more vulnerable to environmental influences at the surface, but this vulnerability lessens as you go deeper. The soil in the vicinity of a preschool in Vilnius showed a high concentration of metals within the first 0.5 m, which gradually decreased with depth as a result of the sandy composition of the area's soil. As shown in these studies, metalworking drill plants have had a historical impact on the pollution levels in the region. In addition, Kumpienė et al. [29] documented the presence of metal pollution in preschool playgrounds in Vilnius, specifically in older, elevated regions with a history of industrial activity. The Vilnius Aplinka [30] investigation also revealed significant pollution in older industrial districts and landfills, primarily with lead (Pb) and zinc (Zn). The soil contamination is worsened by activities such as construction and deforestation, which disrupt the soil and contribute to the pollution caused by dust. These previous studies have mostly focused on outdoor environmental pollution, disregarding the intricate dynamics of indoor pollution sources, specifically in metropolitan educational environments. The soil pollution issues that Lithuania has had since the 1980s, primarily due to industrial activity and transportation, provide relevant background information in this context. Industries, particularly those in the automotive and railway sectors, have played a key role in the accumulation of hazardous metals like lead, copper, and zinc in metropolitan areas [31].

Despite the global concern and extensive research in various regions, studies focusing specifically on heavy metal pollution in indoor dust in educational environments in Lithuania and Eastern Europe are notably scarce. This discrepancy is substantial, considering the proven health hazards linked to high levels of heavy metals found in indoor dust, as established by research conducted in nations such as the United Kingdom [32], Nigeria [33], and China [34,35]. Moreover, the increased vulnerability of children to these contaminants, as documented in educational environments [33,36], emphasizes the need for further research in this field. The objective of this research is to conduct a pioneering investigation in Vilnius to determine a potential relationship between the level of heavy metals in the uppermost layer of soil and the accumulation of these metals in indoor dust within educational environments. This study aims to enhance comprehension of the environmental routes of heavy metals in schools, thereby filling a significant void in both global and regional environmental health studies.

2. Materials and Methods

2.1. Description of the Area of Study

Lithuania's capital and largest city, Vilnius, is located about 312 km inland from the Baltic Sea. With a population of about 550,000, it occupies an area of 401 square kilometers. Vilnius is located 112 m above sea level and is coordinated 54.687157 degrees north and 25.279652 degrees east. The city has a moderate climate, with July receiving 80 mm of precipitation on average and February receiving 30 mm. Vilnius experiences an annual average humidity of roughly 78 percent. Though it fluctuates throughout the year, the city's major wind directions are from the south and west.

2.2. Sample Collection

This work utilizes pre-existing datasets from previous research [28,37–39] instead of collecting new field samples for the evaluation of topsoil samples. The selection of this approach was based on the thorough and wide nature of the available data, which sufficiently encompasses the geographic and chronological aspects relevant to our investigation. By leveraging these existing datasets, we enhanced our research by incorporating a broader historical context and cross-validating our dust sample results with previous soil data.

In this study, we adopted a specialized dust sampling method, drawing from established techniques in existing literature. Similar to the approaches described in [19,40–42], we utilized brush techniques to collect dust samples from often neglected areas in educational institutions. This method, comparable to those in the referenced studies, ensures the collection of representative dust samples, providing an accurate reflection of indoor dust accumulation over time. Additional researchers gathered dust samples from various locations, including classroom floors, windowsills, playgrounds, balconies, doorsteps, stairs, entryways, fans, air conditioner filters, bookshelves, wall corners, desks, and chairs [3,4].

In 2022, our research team gathered dust samples from 24 educational institutions selected according to particular criteria (Figure 1), including their geographical location within Vilnius and their closeness to recognized pollution sources such as highways and frequent transit routes. We deliberately selected schools constructed from 1930 to 2012 in order to encompass a wide variety of building ages and histories. Most of these establishments have been renovated at various times, potentially affecting the composition of indoor dust. The selection criteria were formulated to encompass a thorough portrayal of dust accumulation throughout Vilnius, considering different architectural periods and maintenance approaches. The samples were collected with brush techniques from often neglected areas by cleaners, such as the area behind radiators; the upper parts of bookcases, corners, and windowsills; and hard-to-reach sections of gymnasiums. Our focus was on the gradual accumulation of dust over a long period of time in sample places. Each sample consisted of approximately 10 g of dust. At each site, we obtained a single sample from identical places to guarantee consistency and confidence in our results. We stored the dust samples in sterilized, airtight containers at room temperature in a contamination-free lab environment. Afterward, each sample was separated into capsules (max. 6 capsules) for examination in the lab.

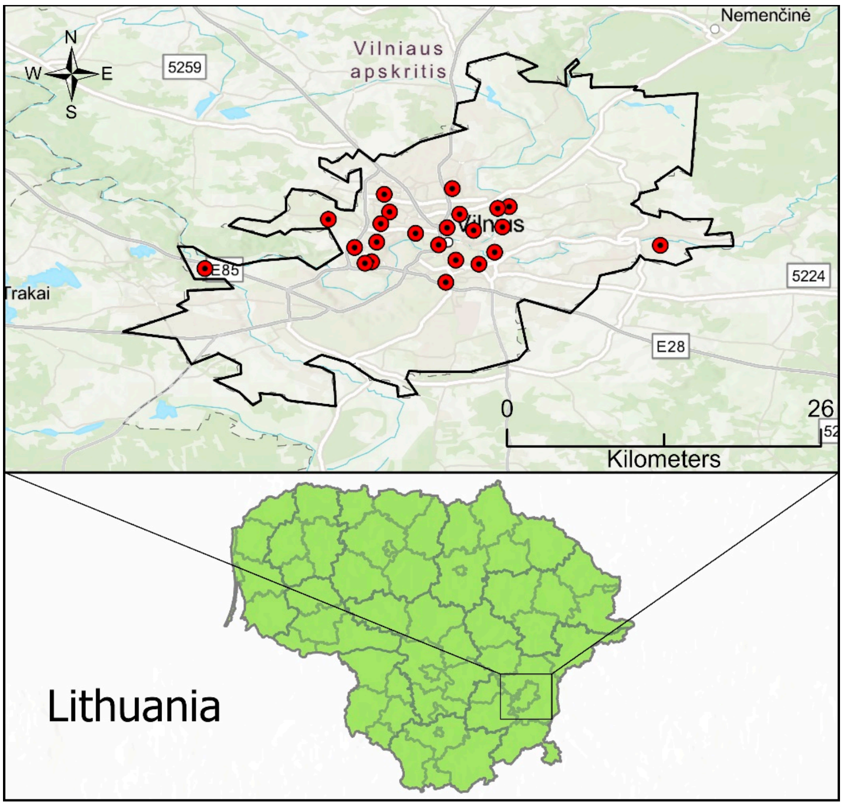

Figure 1. Locations of sampled schools of dust.

The dust samples were examined using a Niton XL2 XRF Analyzer spectroscopy from Thermo Fisher Scientific (United States of America) [43]. Before analysis, the samples were prepared by separating them into smaller pieces and placing them onto a sample holder. The sample had to be free of any impurities that could disrupt the analysis. XRF spectroscopy provides benefits such as the accurate identification of elements and avoids the requirement for pre-treating the samples [44].

2.3. Statistical Analysis Methods

Statistical analysis and data calculations were conducted using the Python **3.12.1** programming language. The geographic mapping software, ArcGIS Pro 3.0, was used to create mapping.

2.4. Descriptive Analysis

Descriptive statistical analysis was used in this work to clarify the features and distribution of different environmental pollutants in Vilnius surface soil samples and dust samples from schools. The information included lead (Pb), zinc (Zn), copper (Cu), arsenic (As), and chromium (Cr) concentrations measured over a number of years. In order to give a thorough perspective of the data, the analysis involved calculating fundamental statistical metrics like mean, median, standard deviation, and range. This method made it possible to fully comprehend the central tendencies and variability of the dataset, providing a solid basis for additional inferential statistical studies, including Pearson's correlation, to investigate the links between dust and soil pollutant levels over time.

2.5. Pearson's Correlation Analysis

In our study, Pearson's correlation analysis is a crucial statistical method for determining the strength and direction of a linear relationship between two variables. We can precisely and statistically carefully examine and quantify the links between the important variables in our study thanks to this rigorous methodology. We utilized Python programming to employ Pearson's correlation in the construction of tables. This correlation analysis involved the integration of our own dataset with data from previous research conducted in the Vilnius region.

2.6. Principal Component Analysis

Principal component analyses (PCA) are widely used in data reduction and latent factor identification. This method aims to discover a small number of latent factors, known as principal components (PCs), that effectively reflect the relationships among observable variables. Principal component analysis (PCA) is a statistical technique that enables the transformation of a collection of correlated variables into a reduced set of orthogonal factors. This process aids in the comprehension of intricate multidimensional systems by revealing the correlations among the initial variables [45].

2.7. Hierarchical Clustering Analysis

Hierarchical clustering analysis (HCA) is a method utilized in the field of data analysis. Prior to performing the cluster analysis, it was necessary to standardize the results using z-scores. Subsequently, the Euclidean distances were computed among the heavy metal values. The linkage criterion employed in the hierarchical clustering analysis was Ward's approach, as described by Zheng et al. [46]. The objective is to ascertain clusters of data points that exhibit shared characteristics or properties. In the context of HCA, many metrics of similarity or dissimilarity can be employed to ascertain the proximity or divergence of data points. According to Radhi et al. [4], a positive coefficient signifies a positive linear relationship, whereas a negative coefficient signifies a negative linear relationship.

3. Results and Discussion

The availability of diverse dust samples collected from schools (Figure 2), particularly the notable differences in the quantity of Zn, warrants an investigation into the potential factors contributing to these discrepancies. The varying levels may be attributed to factors such as shifts in previous industrial operations in the vicinity of Vilnius, changing transportation patterns, and past instances of pollution. The distinctive dispersion pattern of Zn, which differs from that of other elements, indicates the presence of different sources of pollution, potentially associated with specific local industrial operations or high traffic volume near the schools.

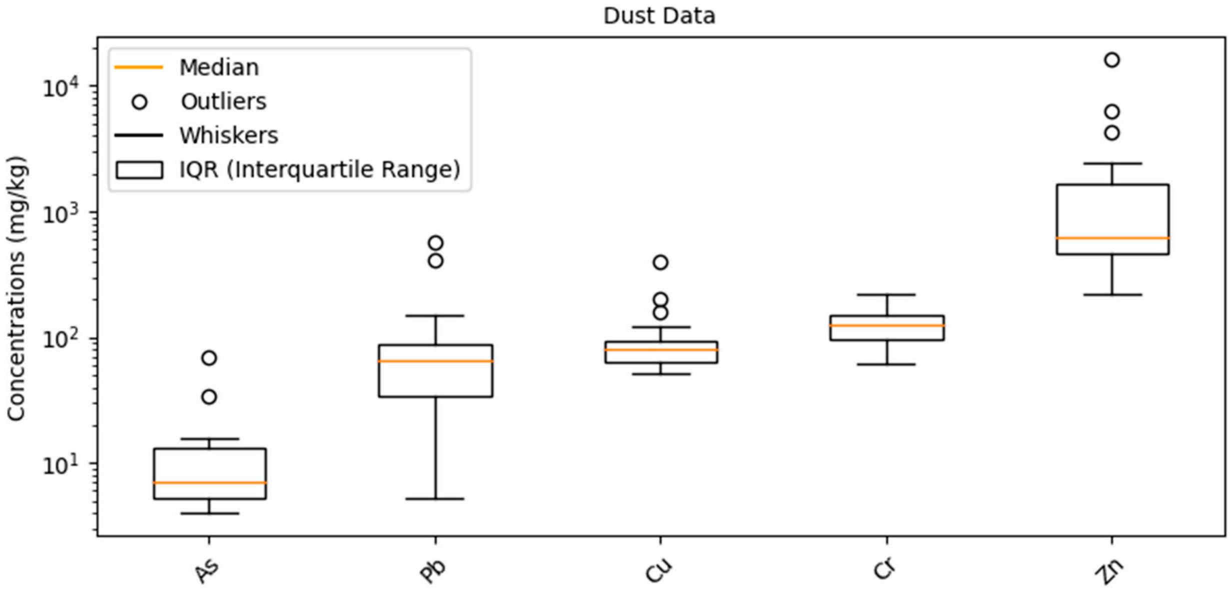

Figure 2. Descriptive analysis of dust data.

Furthermore, more distinct distribution patterns were shown by the comparative visualization of elements including As, Cu, Pb, Cr, and Zn in the dust samples. These trends might provide information about the types and origins of dust buildup in educational settings. The pronounced variations in element concentrations between the dust and soil samples emphasize how difficult it is to sample the environment and the how careful analysis and interpretation of such environmental data are required. The element concentration range and variability seen in this preliminary analysis set the stage for a more thorough comparative and correlational investigation that may clarify the connections between the compositions of soil and dust in urban environments.

Our descriptive analysis of soil datasets [28,37–39] (Figure 3) across various years in Vilnius presents a summarized overview of heavy metal concentrations in soil. Significant patterns and variations were noted: The amounts of zinc exhibited considerable fluctuation, with extreme values in specific years indicating episodes of severe contamination. The levels of lead exhibited significant variation, hence emphasizing certain cases of extreme pollution. Copper and chromium exhibited less variability; however, their highest amounts in specific years indicate the presence of pollution sources in localized areas. The levels of arsenic, while relatively smaller, exhibited a similar pattern of variation. Older studies' data indicate a consistent decrease in pollution levels over time, whereas occasional increases in metal concentrations indicate complex relationships with nearby pollution sources.

The examination of soil (Table 1) and dust data ranging from 1999 to 2023 demonstrates significant variations in the levels of element concentrations. The analysis of dust samples constantly reveals higher concentrations of metals such as Zn, Pb, Cu, Cr, and As in comparison to soil samples. As an example, the average concentration of Zn in dust is 1882.59 mg/kg, which is significantly higher than in soil. In 2018, there was a peak concentration of 219.50 mg/kg. Moreover, the concentration of Pb in dust reaches an average of 107.09 mg/kg, above the maximum limit of 57.00 mg/kg set for soil in 2019. Cu and Cr in dust also surpass soil levels, with dust Cu averaging 98.79 mg/kg and Cr at 130.22 mg/kg. Significantly higher amounts of As are found in dust at 13.23 mg/kg compared to soil, indicating that dust, rather than soil, is the main source of exposure in schools. It is worth acknowledging that the datasets from 2017 and 2020 exhibit the closest proximity to our dust samples, given they were likewise collected from nearby schools. A comprehensive analysis of soil samples in Šnipiškės Vilnius reveals pervasive pollution, particularly in close proximity to main streets and industrial areas. There is a significant correlation between residential activities, industrial operations, and soil contamination, particularly in areas near metal processors and locations with high vehicle activity [37].

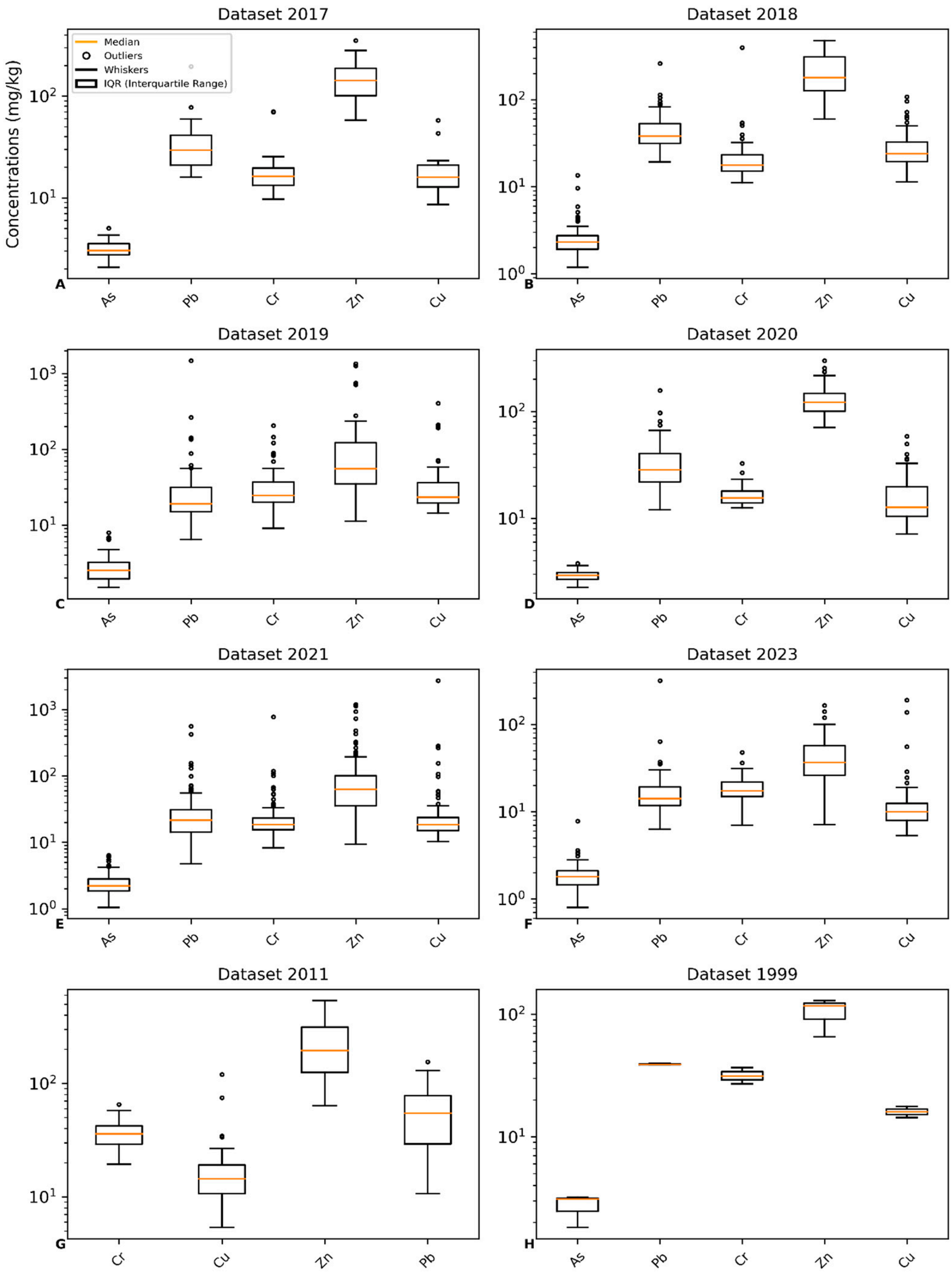

Figure 3. Descriptive analysis of soil datasets from (**A**) 2017, (**B**) 2018, (**C**) 2019, (**D**) 2020, (**E**) 2021, (**F**) 2023, (**G**) 2011 and (**H**) 1999.

Table 1. The 2017–2021 and 2023 mean concentration levels of soil studies (mg/kg) [28,37–39].

Year	Arsenic (As)	Chromium (Cr)	Copper (Cu)	Zinc (Zn)	Lead (Pb)
1999	2.5	32.9	8.8	30.9	16
2011	-	36.22	18.40	216.82	57.97
2017	3.20	20.31	18.41	150.69	38.98
2018	2.76	26.60	29.82	219.50	48.64
2019	2.86	36.35	45.59	141.19	57.00
2020	2.93	16.61	16.65	131.25	34.90
2021	2.44	28.31	47.46	110.75	34.58
2023	1.97	18.58	16.76	44.33	21.58

In soil studies, Zn levels continuously exceed the WHO limit [47] for soil pollution in several regions, with values ranging from 103–1352 mg/kg, which is significantly beyond the target of 50 mg/kg. Pb is also found in certain areas at levels that exceed the World Health Organization's recommended limit of 85 mg/kg. Cu and Cr typically go below the desired levels of 36 mg/kg and 100 mg/kg, respectively. Nevertheless, it is crucial to acknowledge that certain regions exhibit notably elevated levels of certain metals, potentially limited to specific areas. This variability in Zn concentration could partly stem from historical agricultural practices in Lithuania. Notably, the use of commercial fertilizers, a key contributor to soil pollution, surged fourfold from 1960 to the late 1980s, likely influencing soil quality in urban areas like Vilnius [48].

One possible explanation for the observed differences can be attributed to the linked distinctions between soil and dust particles. The composition of soil extends a wider spectrum of particle sizes, ranging from bigger to finer, in contrast to dust particles which are generally characterized by their smaller size. The difference in size between these entities has a notable impact on their ability to concentrate and engage with their surroundings. The study on outdoor dust revealed a positive correlation between the presence of smaller particles and elevated pollutant levels [49]. The concentration of heavy metals and other elements indoor dust exhibits considerable variation across various particle sizes. Another investigation conducted by Beamer et al. [50] investigated the presence of increased metal concentrations in small particles (less than 63 µm) discovered in indoor dust and soil. Notably, the finest dust particles tend to contain the highest concentrations of numerous heavy metals and elements, while there is a general decline in concentration as the particle size increases [51]. Additionally, it should be acknowledged that particles of smaller sizes, specifically those less than 150 µm [52] and less than 100 µm [53], exhibit a greater specific surface area, elevated levels of organic carbon content, and enhanced cation exchange capacity. According to Gunawardana et al. [52], such characteristics increase the effectiveness of smaller particles in the process of metal adsorption when compared to bigger particles. It might be asserted that there may exist a correlation between higher concentration and this particular aspect.

In soil, increased concentrations of toxic metals, possibly resulting from the presence of metal acquisition and storage operations in the vicinity. Another possible cause could be the presence of a significant Cu content, which is likely associated with adjacent car repair operations and inadequate waste disposal practices. These particular instances illustrate how regional industrial or commercial operations can have a substantial influence on soil contamination levels [21].

3.1. Pearson's Correlations

Pearson's correlation analysis between the metals was carried out in order to gain further insight into the differences in the distribution of metal contamination across various investigations conducted in the same city. Significant relationships were found between the concentrations of the various metal species, and in some data locations, there was nevertheless no correlation found between the levels of heavy metals in urban dust and soil (Figure 4).

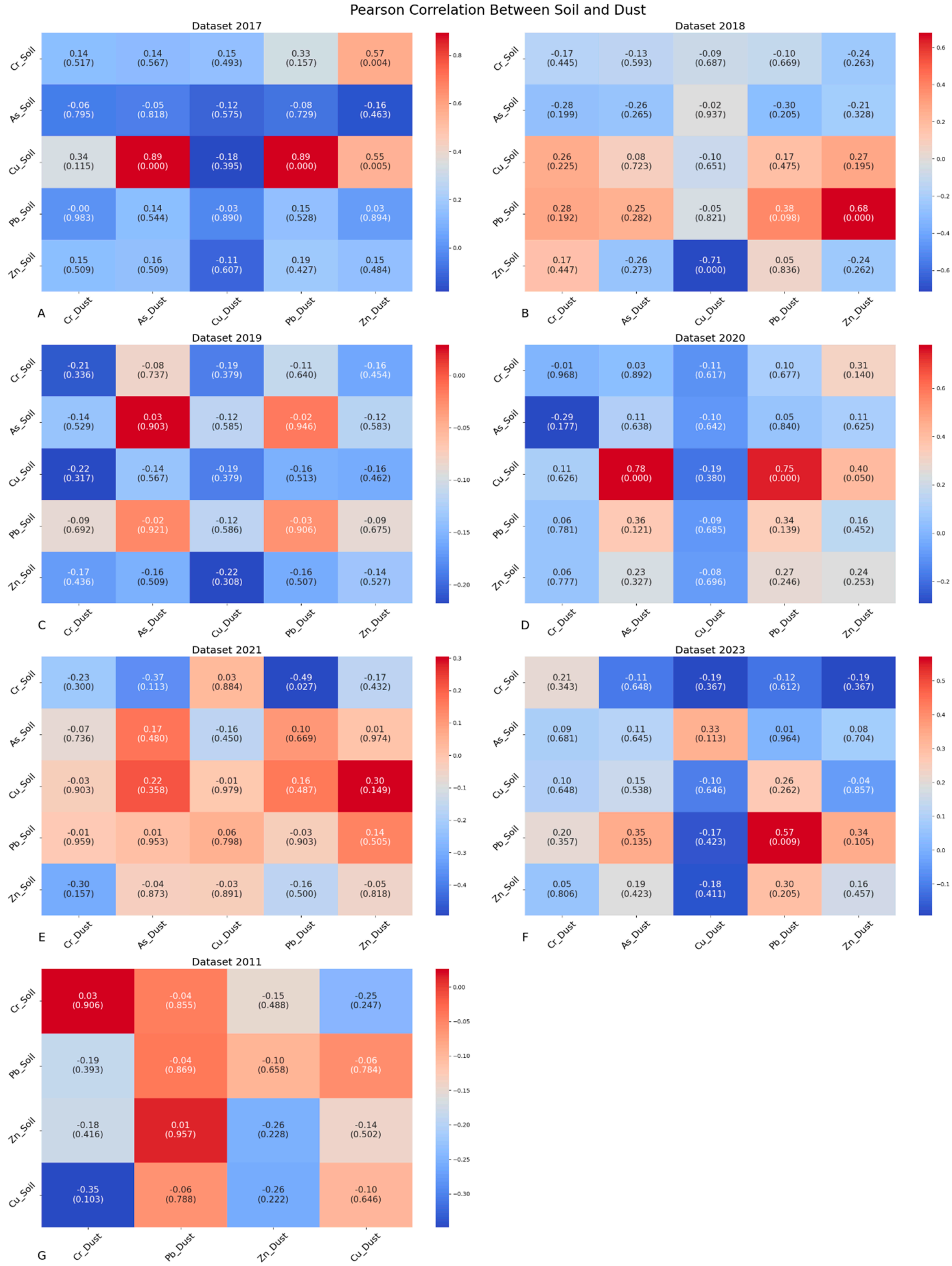

Figure 4. Pearson's correlation between dust and soil datasets from (**A**) 2017, (**B**) 2018, (**C**) 2019, (**D**) 2020, (**E**) 2021, (**F**) 2023, and (**G**) 2011.

Since all *p*-values in the 2011 dataset are higher than the 0.05 threshold, none of the connections between elements in soil and school dust, such as Pb, Cu, Cr, and Zn, are statistically significant, there was no As in this study to pair. This may be because of different environmental circumstances or other unmeasured factors impacting their distributions, but it also shows that there are weak or inconsistent correlations between these components in soil and school dust for this specific year.

Investigations over a number of years have shown intriguing relationships between elements in soil and those in school dust. In 2017, we found a substantial relationship between Pb in school dust and Cu levels in soil, as well as an association between As and Cu in the dust. Furthermore, a moderate but substantial association between Zn in school dust and Cr and Cu in soil was discovered. According to the 2018 data, there was a significant inverse association between Cu in schools' dust and Zn in soil, and a substantial correlation between Zn in school dust and Pb in soil. Surprisingly, the 2019 data showed no considerable connections. Significant relationships were found in 2020 between Cu in soil and Pb, As, and Zn, among other elements in school dust. A moderately negative connection was seen in the 2021 data between Pb in school dust and Cr in soil. In 2023 revealed a somewhat favorable association between Pb concentrations in soil and school dust. These annual correlations highlight the sophisticated relationships that exist between dust and soil pollutants in school settings.

Similar sources, such as industrial emissions, infrastructure deterioration, and transportation, are frequently the source of heavy metals found in urban soil and dust. But between soil and dust, concentrations vary greatly [54]. According to Peng et al. [55] and Mahanta et al. [56], heavy metals have a tendency to attach to soil particles, which makes the soil a sink for these metals and causes their levels to fluctuate slowly. On the other hand, the levels of heavy metals in urban dust are significantly impacted by both natural and human disturbances. Road dust is renewed by rainfall, strong winds, and road cleaning [57]. However, indoor dust, especially in areas with limited air flow, can accumulate for extended periods of time and can be different than outdoor dust.

3.2. Principal Component Analysis with Clusters

The study utilized principal component analysis (PCA) in conjunction with K-means clustering to examine the distribution of several environmental factors in soil and school dust samples obtained from 2017 to 2023, as well as a particular dataset known as Kumpienė et al. [29]. By using this method, it was possible to find patterns and connections between the different elements, which provided information about the effects of the environment and possible sources of contamination (Figure 5).

Three separate clusters were identified by the 2017 data. The first cluster primarily consisted of soil elements such as Cu and Cr from both dust and soil also dust Zn influences this cluster. Zn, Pb, and As—elements found in both soil and school dust—were combined in the second cluster along with Cu from soil, suggesting the presence of common environmental variables and human influences, because of the high traffic density and consequent wear and tear on vehicle components, vehicles are especially important as a source of copper and zinc in metropolitan areas. This may result in higher concentrations of these metals in dust and soil near roadsides. The components of soil made up the third cluster. The 2018 and 2019 data showed that one cluster of elements in the soil and school environments followed a similar pattern of element distribution, while another cluster's components differed from those of the soil, indicating separate environmental impacts. Interestingly, Cu in school dust developed its own cluster, indicating distinct sources or mechanisms contributing to accumulation in the school setting. Similar to the diversity observed in the 2017 data, a broader range of origins and settings were revealed by the examination of soil and dust in 2020. But clusters made of Cu in dust and As and Cr in soil remained distinctive, especially when compared to dust and soil from schools, these elements can be released from fossil fuels during combustion. The trends seen in the data from 2020 and 2017 were also evident in the data from 2021. As, Pb from soil, and Cu from dust were grouped together in the cluster analysis, while a different cluster that represented direct sources from the soil and dust was clearly separated. Due to its strong capacity for long-distance air transport, Pb contributes to pollution levels both locally and globally. The mining and smelting industries are the main producers of Pb pollution [58]. Although its historical usage in from solvent-based paints shows smaller particle sizes and elevated levels of dangerous metals such as As, Cu, Pb, and Zn in comparison to dust from water-based paints [59] and gasoline, it is frequently found in urban soils, vehicle exhaust, tire wear, and bearing wear are also contributing factors to the current pollution [58]. Meteorological conditions, heavily influenced by the Baltic Sea, play a crucial role in the dispersion of these contaminants across Lithuania. This dynamic greatly affects the transmission of industrial pollutants to urban areas, including Vilnius [60]. Additionally, the role of military activities in environmental pollution cannot be overlooked. Studies indicate that such activities contribute significantly to the levels of heavy metals in the environment, including in soil [61].

Elements were classified based on similarities in their environmental distributions in years when there were numerous clusters. For example, certain heavy metals were frequently detected in combination, indicating shared sources or comparable environmental routes indicating differing environmental dynamics in these locations. The distinct environmental characteristics seen in school settings were highlighted by the dust data from the schools, which showed up in different clusters from the soil data. The 2011 dataset and some annual studies made this very clear, pointing to factors like indoor activities or nearby sources of pollution.

Different years' analyses revealed a combination of multiple cluster distributions. A single dominant cluster was seen in years like 2018, 2019, 2023, and 2011, and except dust Cu, it always created another cluster in datasets, indicating a consistent environmental influence in both soil and school's dust contexts. On the other hand, years like 2017, 2020, and 2021 showed several clusters, pointing to a wider variety of environmental effects. High amounts of Cu were found close to bus stops, railroad stations, and a parking lot on a commercial road and Cu has been used in brake friction materials since the 1930s [57]. Furthermore, the closer proximity of certain schools to these bus and rail stations—where dust samples were collected—could potentially be a factor in the higher Cu levels detected in these regions. Adding to this, the study by Jankauskaitė et al. [62] elucidates the intricate relationship between urban landscapes and topsoil contamination. It reveals that industrial, infrastructural, and historical areas in Vilnius are more susceptible to pollution, indicating a clear link between urban development and soil quality.

3.3. Hierarchical Clustering Analysis

The main findings into elemental behavior and environmental contamination found in Vilnius between 2017 and 2021 can be obtained from the hierarchical clustering of soil and school dust samples. Over the years, patterns in the dendrogram show that elements such as Cr, As, Pb, Cu, and Zn in soil and dust have both common and distinct properties (Figure 6).

The appearance of elements such as 'Cr_Dust' and 'Cr_Soil' in close proximity in 2017 and 2018 indicates a mirrored Cr presence in both media, most likely as a result of widespread environmental pollution. On the other hand, in 2018, the distinction between 'As_Soil' and 'As_Dust' suggests that there are different sources or concentrations of As in soil and dust; this is also the case for Pb, Cu, and Zn. By 2019, there is a noticeable difference in the way these elements cluster between dust and soil, indicating distinct dynamics or sources of contamination. This divergence is becoming increasingly noticeable. The years 2020 and 2021, on the other hand, show a more detailed pattern. Although some elements are first grouped together with soil samples, suggesting similar environmental features, their eventual inclusion in the dust element cluster indicates other contributing aspects. The 2019-like trends are also evident in soil data from 2023 and 2011. The findings of both PCA and hierarchical clustering consistently group the same elements together and show comparable trends in elemental distribution over time, therefore similarities between the two techniques can be identified.

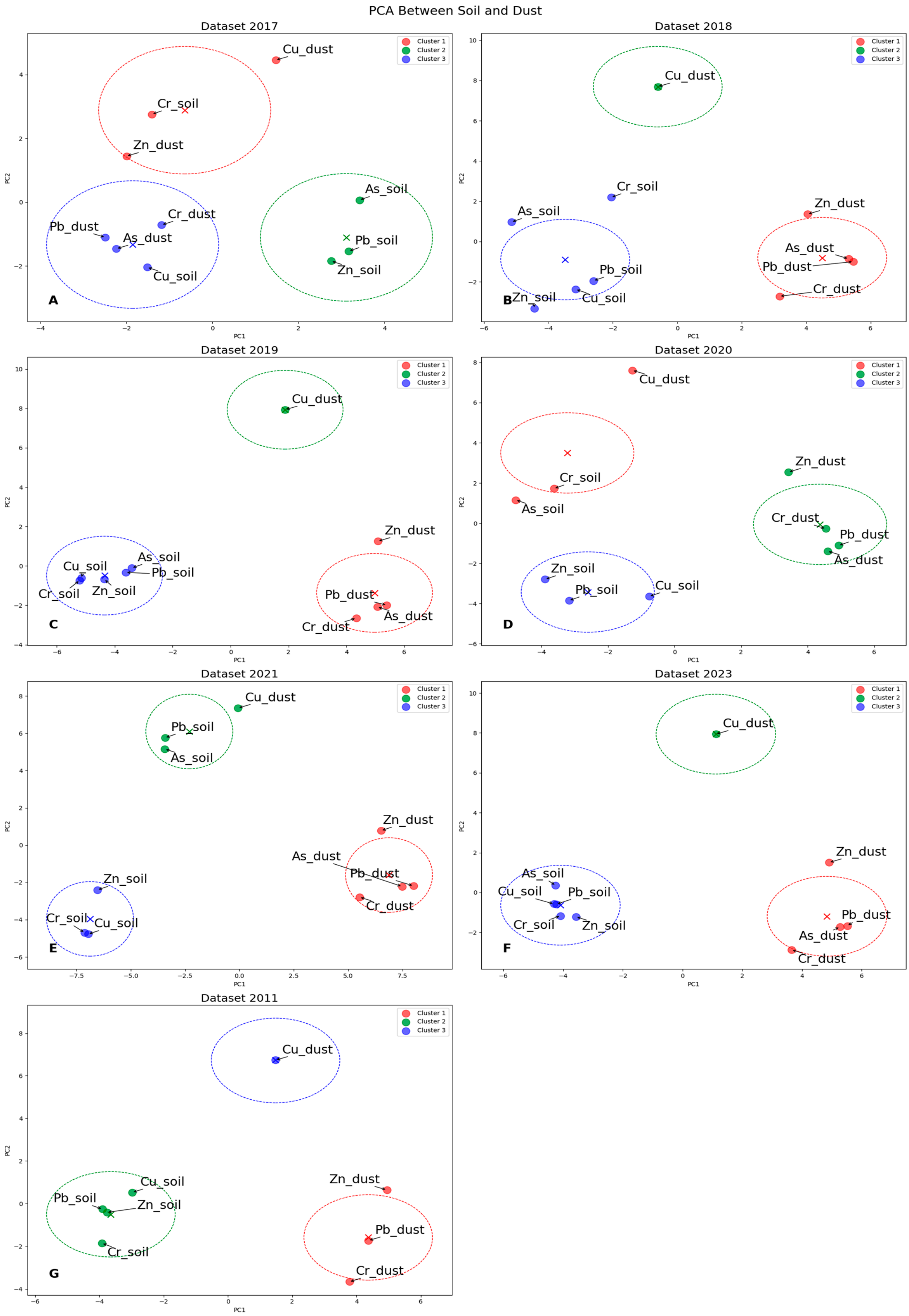

Figure 5. PCA between dust and soil datasets from (**A**) 2017, (**B**) 2018, (**C**) 2019, (**D**) 2020, (**E**) 2021, (**F**) 2023, and (**G**) 2011.

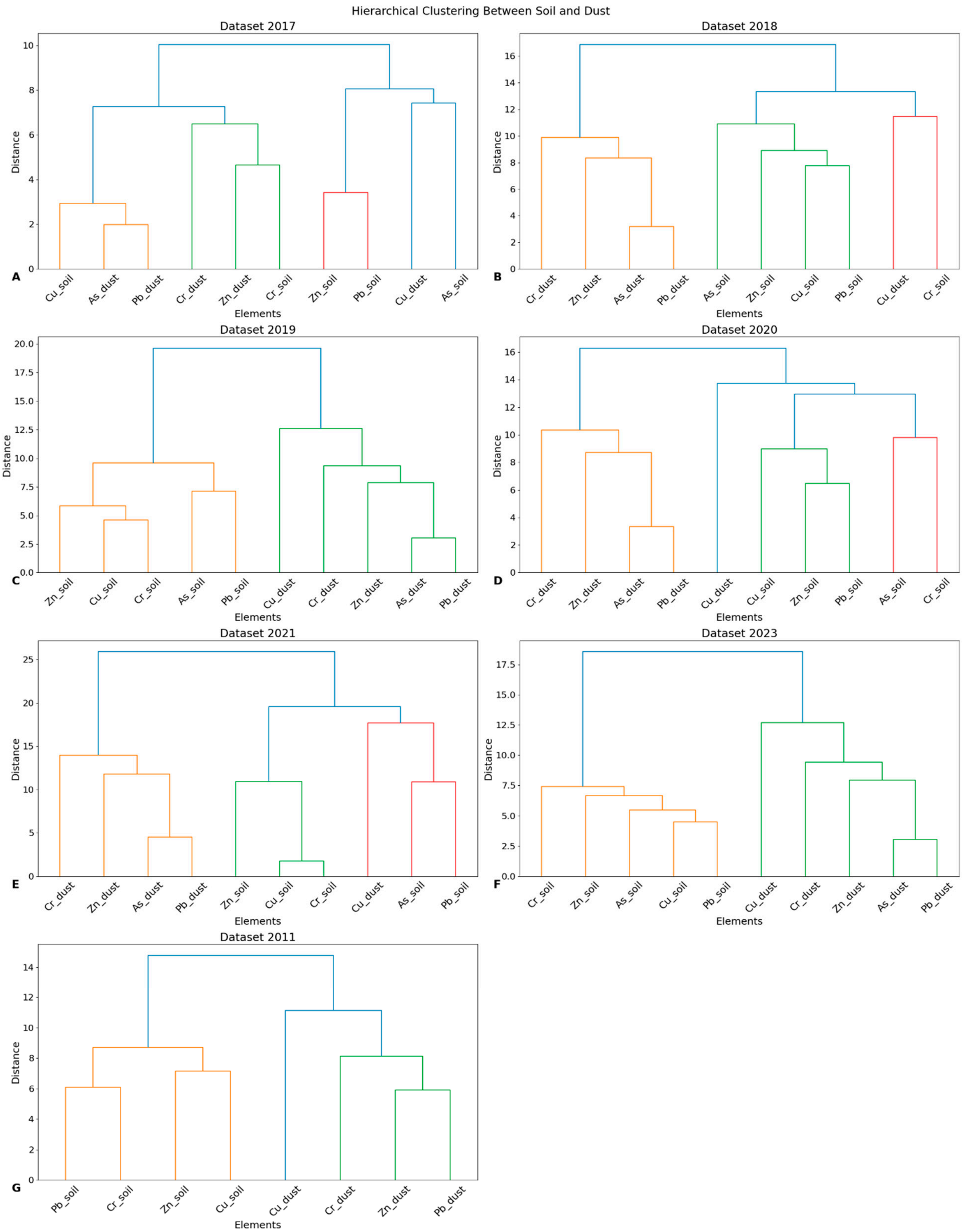

Figure 6. Hierarchical clustering analysis between dust and soil datasets from (**A**) 2017, (**B**) 2018, (**C**) 2019, (**D**) 2020, (**E**) 2021, (**F**) 2023, and (**G**) 2011.

Even though the majority of the heavy metals in urban soil and dust came from similar sources—such as transportation, vehicular and industrial emissions, air depositions, power plants that use fossil fuels, infrastructure construction, destruction or renovation, windstorms, cooking, or even dust carried in by shoes—the distribution of heavy metal concentrations in urban soil and indoor dust shows similarity and differences from each other according to years and studies. Further emphasizing the complexity of urban pollution, Vilnius and Kaunas, like many urban centers, exhibit high levels of heavy metals due to industrial activities and traffic emissions. The transportation sector, particularly motor vehicles and railways has been a significant source of soil contamination in these areas [31,60]. In line with this, significant heavy metal contamination has been observed in soil particles from urban areas of Vilnius, especially in high-traffic zones. This contamination, carried by surface runoff sediments, underscores the magnitude of soil pollution in the city [63].

3.4. Potential Health Implications

The clear differences in the distribution of heavy metals between dust and soil, as shown in our research, have significant implications for public health, particularly for children in educational environments. Children are particularly vulnerable to heavy metal toxicity because their immature organ systems make them more susceptible to its harmful effects. Exposure to these pollutants can result in significant health implications, such as intellectual disability, neurocognitive impairments, behavioral abnormalities, respiratory ailments, cancer, and cardiovascular illnesses [64]. Moreover, the negative consequences of inorganic pollutants on newborns and children might result in anemia, kidney damage, developmental and reproductive harm, decreased intelligence quotient (IQ), and different harmful effects on the nervous system [65]. Xenobiotic metals have been found to be hazardous and can lead to multiple illnesses such as gastrointestinal, respiratory, cardiovascular, reproductive, renal, and neurological problems. In addition, certain heavy metals can worsen the development of tumors and decrease their responsiveness to treatment [66]. It is crucial to prioritize the understanding of health risks associated with heavy metals in order to effectively manage the safety of school environments, considering that children spend considerable time outside and have eating habits that may increase their exposure to such metals [67]. The article offers crucial insights into the process of renovating old Soviet-era buildings. It emphasizes the necessity of thoroughly cleaning and removing dust from structures like schools, because children are particularly vulnerable to the harmful effects of pollution. Governments and local authorities should implement routine environmental monitoring in urban schools. This will help in early detection and management of heavy metal contamination, ensuring the safety of children. Schools need to implement systematic dust cleaning routines and contemplate the installation of air filters. Implementing these steps can effectively decrease the level of airborne contaminants in classrooms, therefore protecting the health of children.

4. Conclusions

This extensive investigation has examined the concentrations of harmful metals in dust found indoors and in the uppermost layer of soil in Vilnius. The study covers a time frame from 2011 to 2023 for topsoil. Our investigation uncovers complex patterns of environmental pollution, specifically within educational settings.

The identification of elevated levels of particular metals in indoor dust suggests distinct origins or mechanisms of deposition that diverge from those impacting surface soil. The difference in concentration levels between indoor and outdoor environments is particularly noticeable in the case of zinc (Zn). The comparative and correlational analysis conducted in our study over multiple years not only detected occasional instances of pollution but also revealed larger environmental patterns. The data unveiled correlations between metal concentrations and particular years or locations in close proximity to dust sites, indicating the presence of pollution from specific sources in those areas. Furthermore, the study revealed both symmetrical and unique grouping patterns for specific metals, suggesting different sources or techniques of contamination. These patterns highlight the intricate interaction of various elements that contribute to the accumulation of metals in diverse environments.

An important discovery of this study is the distinct separation in the distribution patterns of zinc (Zn), lead (Pb), copper (Cu), chromium (Cr), and arsenic (As) between dust found indoors and the upper layer of soil. This differentiation implies that although there may be certain shared sources of pollution for both mediums, indoor dust in schools possesses distinct contamination characteristics. Evidently, the buildup of harmful elements in dust found in schools seems to occur over an extended period of time. This process is affected by various factors, including the age of the school buildings, their restoration history, proximity to highways or train stations, weather conditions, wind patterns, air circulation within the buildings, and the use of cleaning agents, among others. Older schools or schools that have been renovated to different extents over the years exhibit differences in the levels of heavy metals, which indicate the evolving indoor conditions over time.

To summarize, this study sheds light on the ever-changing state of environmental pollution in Vilnius, specifically inside school environments. This highlights the significance of focused environmental investigations for efficient policy formulation and management approaches. Our research shows a correlation between soil pollution and the presence of metal in interior dust. Additionally, we have identified specific elements that affect indoor settings, such as the age, restoration history, and location of school buildings. These observations require a sophisticated method for dealing with environmental health risks in schools, considering both the gradual build-up over time and the structural differences in educational buildings. Regarding the dust-borne heavy metal contamination in Vilnius schools, we advise the implementation of strict rules and the establishment of routine monitoring programs in proximity to the sources of these metals. Additionally, enhanced indoor air quality measures and targeted soil remediation are critical near the schools. We urge educational communities to actively participate in recognizing and mitigating exposure risks. Future studies should assess the long-term health consequences for children as well as the effectiveness of mitigation tactics. To acknowledge the geographical limitations of this study, additional research could be conducted in other cities to authenticate and contrast these findings.

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