Vol. 16, No. 2
2025

Ecological Safety
and Balanced Use of Resources

ISSN (print) 2415-3184, ISSN (online) 2522-9508
Journal homepage: https://esbur.com.ua/en

Received: 05.05.2025. Revised: 05.11.2025. Accepted: 10.12.2025. Published: 07.01.2026.

UDC 504.054:546.3
DOI: 10.63341/esbur/2.2025.31

Comprehensive assessment of heavy metal pollution in urban environments: A case study from Jelgava, Latvia

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Abstract. Air quality in urban environments has become a critical global issue and the rate of urbanisation is expected to continue rising. This study aimed to identify, on a theoretical basis, the patterns of technogenic background formation and the spatial structure of pollution in the urban environment of Jelgava. The methodology was based on systematic and statistical analyses to assess the sources and levels of pollution in the city. The duration of the study, from the initiation of data collection to the completion of analysis, covered the period from 2017 to 2023, with annual sampling and extensive monitoring conducted throughout this period. The concentrations of heavy metals in various components of the urban ecosystem in Jelgava were found to be within the following ranges: Ni – 20-60 mg/kg, Cu – 40-90 mg/kg, Pb – 30-70 mg/kg, Zn – 100-200 mg/kg. These values correspond to moderate pollution levels typical of urbanised areas in Northern and Central Europe. The highest concentrations were recorded near major roads and industrial zones, whereas peripheral areas were close to background values. It was established that the integrated environmental quality indicators (pollution index = 1.5-2.2, geoaccumulation index = 1-3) characterise Jelgava as a moderately polluted area while maintaining overall ecological stability. Factor analysis revealed that the pollution structure is shaped by two main sources: transport-related emissions (Ni, Cu, Zn – tyre and brake wear, diesel exhaust) and heating-industrial emissions (Pb, Cd – fuel combustion and local emissions from small enterprises). Jelgava can be classified as a moderately polluted yet resilient urban system, where anthropogenic pressure is balanced by natural self-purification mechanisms. The practical value of the study lies in the fact that its findings may be used by municipal environmental and planning authorities to assess risks and manage urban environmental quality

Keywords: urban ecosystem; technogenic pressure; pollution indexes; atmospheric-seasonal dynamics; ecological resilience

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Suggested Citation: Grinfelde, I., Bertins, M., & Pilecka-Ulcugaceva, J. (2025). Comprehensive assessment of heavy metal pollution in urban environments: A case study from Jelgava, Latvia. *Ecological Safety and Balanced Use of Resources*, 16(2), 31-42. doi: 10.63341/esbur/2.2025.31.

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Introduction

Air quality in urban environments has become one of the key issues in the context of rapid global urbanisation. By 2050, the United Nations predicts that around 68% of the world's population will live in cities, a trend particularly evident in Latvia, where nearly 70% of the population already resides in urbanised areas (UN projection, 2022; World Bank, 2024). The rising level of urbanisation intensifies environmental challenges, especially air pollution, which significantly affects public health, urban resilience and overall quality of life. Air pollution levels in cities are influenced by a range of factors, including urban form and density, traffic flows and industrial activity (Ibraimov *et al.*, 2025). Studies indicate that urban planning plays a critical role in shaping air quality. D. Wang *et al.* (2022) noted that urban form has a substantial impact on air pollution levels, particularly in rapidly growing megacities, where dense and poorly planned development contributes to increased emissions from transport and industry. Similarly, research by O.O. Akomolafe *et al.* (2024) emphasises that anthropogenic factors, primarily industrial emissions and road traffic, are the main sources of harmful pollutants such as particulate matter (PM) and volatile organic compounds. The localised nature of pollution impacts, demonstrated in the study by A. Kramer & L. Minet (2025), further highlights the importance of examining the structure of urban areas, particularly in zones adjacent to motorways and other areas with high traffic intensity.

The health consequences of urban air pollution are extremely serious. Even low concentrations of fine PM2.5 are associated with an increased risk of mortality, as confirmed by the study of S. Weichenthal *et al.* (2022). Chronic exposure to urban pollutants, including heavy metals such as zinc (Zn), copper (Cu), nickel (Ni) and lead (Pb), is linked to a wide range of adverse health effects, from respiratory diseases to cardiovascular and neurological disorders. Q. Chen *et al.* (2021) found that heavy metals contained in PM can induce oxidative stress and DNA damage, increasing the disease burden among vulnerable population groups, such as children and individuals with chronic illnesses. This indicates an urgent need to develop effective air quality management strategies. Mitigation strategies for urban air pollution are gaining increasing attention. Urban vegetation is widely regarded as a natural means of capturing pollutants and improving the microclimate. H. Dadkhah-Aghdash *et al.* (2022) demonstrated that well-designed greening programmes, including the strategic placement of vegetation along roadways, effectively reduce PM levels and contribute to overall air quality improvement.

In the context of Latvia, the study by G. Tabors *et al.* (2023) involved long-term monitoring of atmospheric deposition of heavy metals using moss biomonitoring (*Pleurozium schreberi*). The authors identified a consistent decline in the concentrations of zinc, cadmium, lead and copper, which is associated with improved environmental policies and reduced industrial emissions. This provides an essential macro-ecological context for understanding the dynamics of heavy metal air pollution in the country. The study conducted by I. Grinfelde *et al.* (2024) focused on assessing the impact of industrial activity on air quality in the city of Jelgava. The authors found elevated concentrations of copper, zinc and lead near industrial zones and transport corridors, indicating the presence of local pollution sources. This research makes a significant contribution to understanding the spatial distribution of heavy metals and to improving environmental monitoring approaches in urbanised areas of Latvia.

However, despite the availability of studies on atmospheric emissions, snow cover and bottom sediments, there is no comprehensive comparison that would allow for the assessment of interrelations between different environmental media and provide an integrated picture of technogenic impacts. For Baltic cities, including Jelgava, there remains a limited understanding of the spatial patterns of pollution distribution and the mechanisms of its seasonal modulation, which restricts the effectiveness of environmental monitoring and urban environmental management. Therefore, this study aimed to provide a theoretical explanation of the mechanisms of formation and spatial organisation of technogenic pollution in the urban environment of Jelgava, taking into account the distribution patterns and dynamics of heavy metals. To achieve this aim, the following objectives were set: to analyse the spatial and temporal structure of heavy metal distribution; to identify the source-related and mechanistic foundations of technogenic pollution using geostatistical and factor analysis methods; and to assess the overall ecological state of Jelgava's urban environment by comparing it with the global context to determine regional specificity and the degree of ecological resilience.

Materials and Methods

Jelgava, situated in the central part of Latvia, is defined by its compact urban structure and extensive transportation networks, encompassing an area of approximately 60.32 km^2 and housing nearly 55,000 residents (Fig. 1). The region experiences a temperate climate with average winter temperatures around -5.5°C and annual precipitation levels ranging from 550 to 560 mm. Snowfall typically occurs from December through February, providing ideal conditions for snow sampling and air quality monitoring, crucial for assessing urban pollution dynamics.

A lichen indication approach was applied in this study, involving a comprehensive inventory conducted across 125 sampling plots, with the elaborated methodology. Furthermore, the Tube Lichen (*Hypogymnia physodes*) transplant method was employed following the description provided in prior research (Merdan *et al.*, 2025). Additionally, samples of Maritime Sunburst Lichen (*Xanthoria parietina*) were gathered from 20 designated plots, with chemical analyses conducted as outlined (Spriņģe *et al.*, 2024). Snow sampling was conducted in 20 plots in 2017 and expanded to 60 plots from 2018 to 2023. Additionally, in 2018 and 2019, snow samples were specifically collected from 18 plots located within transport corridors to evaluate the localised impacts of pollution.

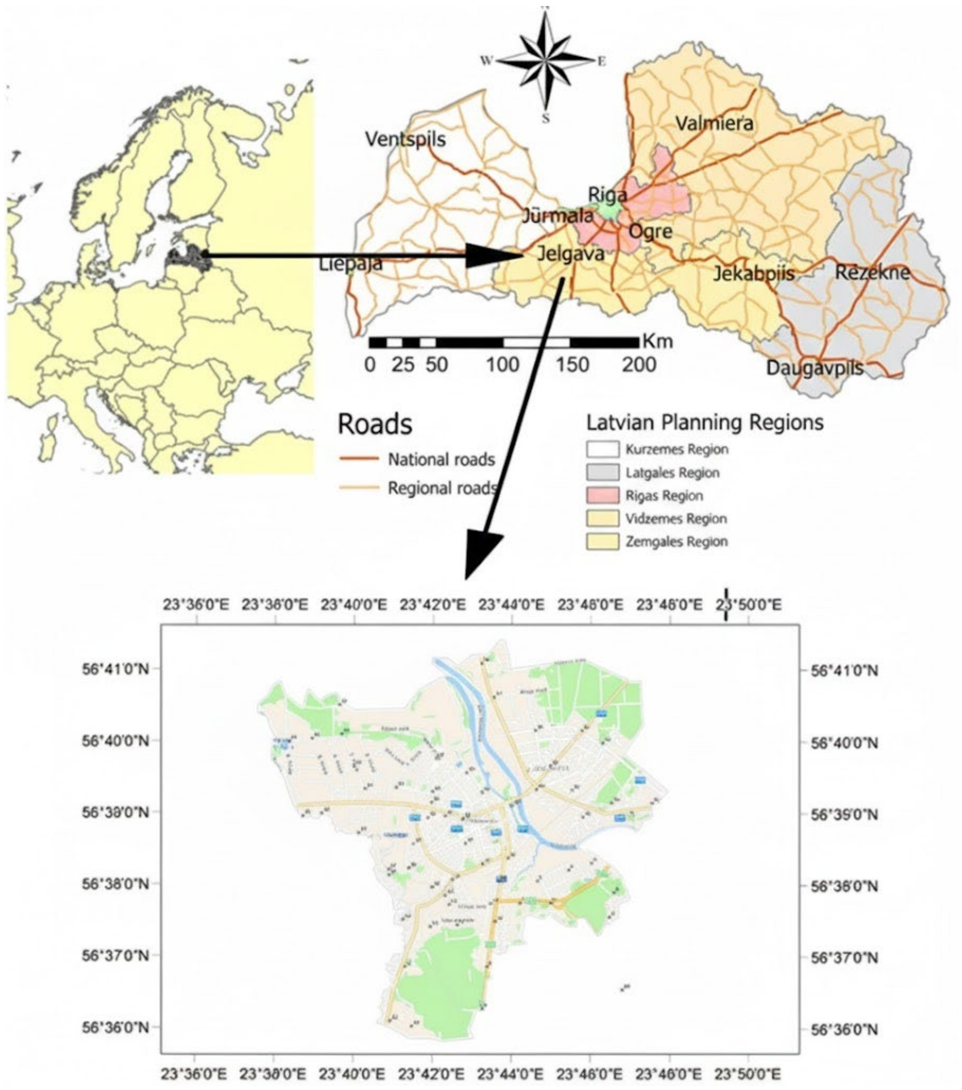

Figure 1. Location of study area with snow sampling points

Source: created by the authors

Snow sampling served as a vital method for evaluating short-term air pollution caused by chemical elements in urban areas. From 2017 to 2023, snow samples were collected annually during periods of accumulation lasting 5 to 9 days. Initially, sampling in 2017 focused on 20 plots near the city centre, supplemented by a single plot located 5 km outside the city in the Mežciem Forest Massif. By 2018, the sampling network had expanded to include 59 plots across the city and one plot outside its boundaries. To ensure comprehensive spatial coverage and accurate results, one sampling plot was designated per square kilometre, maintaining an average density of one plot per square kilometre. Each plot yielded three snow samples, with the full snow cover collected for analysis. Snow was gathered using disposable, dust-free nitrile gloves to prevent contamination. The samples were collected at a distance of 5 meters from roadways, stored in sterile plastic containers, immediately refrigerated, and then transported to the laboratory for further analysis.

For the preparation of snow samples analysed with Inductively Coupled Plasma Optical Emission Spectroscope (ICP-OES) (Thermo Fisher Scientific, United States), two distinct approaches were tested: (1) filtering the snow samples through a paper filter before acidifying them to 1% HNO_3, and (2) acidifying the samples to 1% HNO_3 first, allowing them to stabilise for three days, and then filtering them through a paper filter. Snow samples collected during 2017 and 2018 were analysed using both ICP-AES (Shimadzu Corporation, Japan) and ICP-OES spectrometers. In 2019, the analysis was exclusively conducted with ICP-OES. From 2020 to 2023, an 8900 Triple Quadrupole

Inductively Coupled Plasma Mass Spectrometer (ICP-MS) (Agilent Technologies, United States) spectrometer was employed to achieve high-resolution analysis. Additionally, Maritime Sunburst Lichen *(Xanthoria parietina)* samples underwent preparation for ICP-OES analysis, which involved drying and meticulously removing impurities such as bark and leaves.

Geographic Information Systems (GIS) provided essential capabilities for examining the spatial distribution and relationships of air pollution within urban settings. Using ArcGIS software (Environmental Systems..., 2025), the study mapped and analysed the spatial distribution of heavy metals in urban air. Spatial interpolation was performed with the inverse distance weighting technique, a built-in feature of ArcGIS. This method was selected due to its proven efficiency in analysing air quality data. Compared to alternative tools, inverse distance weighting was favoured for its simplicity and ability to produce reliable results without requiring complex data modelling or subjective assumptions. By employing this approach, the study successfully explored the spatial and temporal dynamics of heavy metal contamination, laying a foundation for targeted mitigation strategies and informed urban planning.

Results

Mechanisms of formation and factor structure of heavy metal distribution in the urban ecosystem of Jelgava

This subsection presents results from the descriptive statistical analysis of snow sample data, used to determine air pollution levels caused by heavy metals. In the Baltic States, urbanisation is accompanied by the development of a persistent technogenic background, with heavy metals serving as key indicators of anthropogenic pressure (Stankevica *et al*., 2021; Pilecka-Ulcugaceva *et al*., 2024a). Compact urban development and high traffic density contribute to the local accumulation of pollutants along major roads and in industrial zones. Bioindication using the lichen *Xanthoria parietina* and the analysis of snow samples confirm the predominance of transport-atmospheric pathways for the deposition of metals (Ni, Cu, Pb, Zn), as well as the correlation between road network configuration and accumulation zones (Pilecka-Ulcugaceva *et al*., 2024b). Bottom sediments and indoor dust in residential buildings indicate prolonged retention and secondary transfer of pollutants, linking external and internal environments. The consistency of signals across different media highlights the leading role of transport and heating during the cold season and confirms the effectiveness of a multi-matrix approach for a comprehensive assessment of technogenic pressure in the urban conditions of Jelgava (Niu *et al*., 2024).

In 2019, copper concentrations showed higher levels in samples No. 18 and No. 39, with 12.5 μg/L and 11.7 μg/L, respectively. These elevated levels were likely influenced by traffic, nearby residential developments, an adjacent rail line, and improper waste management practices. In particular, sample No. 18 highlighted significant contributions from anthropogenic activities. Most samples exhibited nickel concentrations below 0.6 μg/L, except for sample No. 2, which recorded a value of 4.4 μg/L. This anomaly was attributed to local heating practices using suboptimal fuels during winter and proximity to a high-traffic corridor.

Elevated lead concentrations were observed in sample No. 13 (11.1 μg/L) and sample No. 48 (72.3 μg/L). The high values in sample No. 48, approximately seven times greater than in other locations, were likely due to waste incineration in private residences and proximity to transportation hubs. Most vanadium concentrations were below 0.7 μg/L, with higher values near high-traffic zones and railways. Zinc concentrations exceeded 50 μg/L in samples No. 39 (53.7 μg/L), No. 46 (73.2 μg/L), and No. 48 (204.5 μg/L). The highest zinc concentrations were linked to traffic emissions and heating practices involving unsuitable fuels.

Data from 60 aluminium measurements (2018-2021) revealed significant annual variations. Average concentrations ranged from 0.08 μg/L in 2019 to 91.68 μg/L in 2020, with the highest maximum value of 1183.66 μg/L recorded in 2020. High aluminium levels were predominantly observed along major transport corridors such as Dobele Highway and Rīgas Street. The proximity to high-traffic roads played a significant role in aluminium distribution patterns. Between 2022 and 2023, tungsten concentrations ranged from 0.05 μg/L to 4.35 μg/L, with higher concentrations near transportation corridors. These findings align with trends observed in other urban studies, emphasising traffic intensity as a key driver of tungsten contamination.

Spatial analysis revealed that major streets and intersections in Jelgava were hotspots for heavy metal pollution, particularly in areas with high traffic and industrial activities. Elevated concentrations (10.9-12.5 μg/L) were detected in the city centre, particularly at the intersection of Lielā Street and Dambja Street. This is attributed to intensive traffic between Riga, Dobele, and Jelgava, and the presence of car repair shops and a gas station. Additional Cu hotspots (7.8-9.4 μg/L) were identified near Aviācijas Street, an area hosting one of Latvia's largest industrial parks. Increased concentrations in Jelgava's northwestern region correlated with logging activities and emissions from car workshops. High Pb levels were observed near Tērvetes Street and Satiksmes Street intersections, aligning with areas of frequent traffic jams. The highest Zn concentrations (153.2-204.3 μg/L) were measured in industrial zones, particularly near Aviācijas Street.

Over the study period (2018-2023), temporal fluctuations in heavy metal concentrations were evident: The highest average concentration (79.62 μg/L) was recorded in 2018, attributed to local fireworks and increased industrial activities. By 2023, Zn concentrations had declined significantly to an average of 8.88 μg/L. Annual variations were marked, with the highest concentrations (1183.66 μg/L) observed in 2020 along major transport corridors. Proximity to high-traffic areas consistently influenced Pb levels. Concentrations ranged from 0.05 μg/L to 4.35 μg/L (2018-2023), peaking near transport hubs, indicating traffic intensity as a significant contributor (Fig. 2).

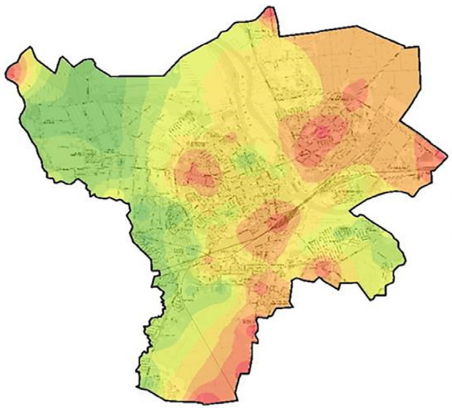

Figure 2. Spatial distribution of Lead (Pb) Concentrations in Jelgava, 2019
Source: created by the authors

These findings emphasise the need for both spatially targeted interventions (e.g., pollution mitigation in hotspots) and temporal monitoring to assess the effectiveness of policies and changes in urban activities. Analysis of the spatial distribution of heavy metals across various components of the urban environment revealed a distinct clustering of concentrations along transport corridors and near industrial zones. The distribution maps show "hotspots" of elevated Ni, Cu, Pb and Zn levels, corresponding to areas of high traffic intensity and older residential districts, where heating is primarily based on solid fuels. This spatial pattern confirms the local selectivity of pollution and indicates a combination of diffuse and point sources (Fig. 3).

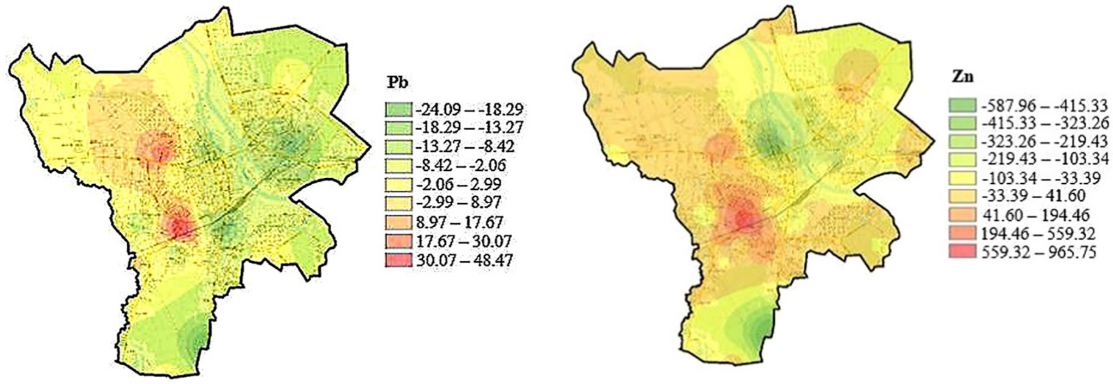

Figure 3. Spatial distribution of lead (Pb) and zinc (Zn) concentrations in the urban environment of Jelgava, 2018-2023
Source: created by the authors based on M. Stankevica *et al.* (2021), J. Pilecka-Ulcugaceva *et al.* (2024a)

Various methods are available for assessing long-term pollution, which can be categorised into chemical and biological approaches. Among the biological methods, the calculation of the Index of Atmospheric Purity (IAP) is widely used. Lichens are effective indicators for assessing areas impacted by sulfur dioxide, nitrogen oxides, and heavy metals. The accumulation of toxic elements in lichens correlates with proximity to pollution sources (Fedoniuk *et al.*, 2025). In Jelgava, the long-term air quality assessment also utilised the collection and analysis of the lichen *Xanthoria parietina*. This method complements chemical analysis techniques by examining pollutants in biological organisms and cells. Data from 125 sampling plots across Jelgava identified three pollution zones: high pollution (Group 1, IAP 0-110), moderate pollution (Group 2, IAP 111-200), and low pollution or clean air zones (Group 3, IAP > 200). High pollution zones in Jelgava in 2016 covered 1.66 km^2 (2.75% of the city's area), primarily in the city centre near wastewater treatment facilities, major road intersections, and an area adjacent to Langervaldes Forest. Moderate pollution zones accounted for 26.54 km^2 (44.0% of the city), with slight increases in area since 1996. Clean air zones covered 32.12 km^2 (53.25%), showing a significant portion of the city retained relatively low pollution levels.

Cartographic analysis identified a clear spatial concentration of heavy metals: peak Pb and Zn values coincide with densely built-up areas and zones with intensive traffic, while minimum values occur in green and peripheral districts.

This confirms the predominance of the transport-atmospheric pathway of pollution. Factor analysis (PCA/FA) identified two main sources: the transport-related source (Ni, Cu, Zn), associated with tyre and brake wear and engine emissions; and the heating-industrial source (Pb, Cd), characteristic of older housing areas and heating zones. An additional natural factor (Mn, Fe) reflects the mineral background. The consistency of distribution across different matrices (snow, lichens, bottom sediments) confirms the transit of metals from the atmosphere to the hydrosphere. Integrated indices (EF, CF, I_{geo}, PLI) showed elevated values for Ni and Cu along major roads and in industrial areas ($EF > 10$, $CF > 6$, $I_{geo} = 2\text{-}3$, $PLI > 2$), indicating a high level of technogenic risk (Pilecka-Ulcugaceva *et al.*, 2024a). Environmental hazard zoning of Jelgava identifies the following categories: high risk – transport and industrial areas; medium risk – central districts; low risk – green and suburban areas. This provides a basis for prioritising management measures such as vegetative barriers, road dust control and the restriction of solid fuel heating.

Complex dynamics and comparative analysis of heavy metal pollution in urban systems

The formation of heavy metal pollution in Jelgava represents a complex system of interconnected flows between the atmosphere, soil, water bodies and residential environments. The primary sources are emissions from vehicles and heating systems, which generate aerosols containing Ni, Cu, Zn and Pb. These particles settle on soil, vegetation and water surfaces, forming a persistent technogenic background. In winter, snow acts as a temporary depot, accumulating metals near traffic arteries; during melting, pollutants re-enter the hydrological system, intensifying secondary contamination. After deposition, metals undergo redistribution – dust is resuspended by wind and vehicle movement, returning to the atmosphere. A portion of the deposited elements enters bottom sediments via surface runoff, where they are either fixed in insoluble forms or bound to organic matter, forming a long-term reservoir of technogenic substances that can be remobilised under changing hydrochemical conditions (Glevitzky *et al.*, 2025). Thus, the migration system of metals functions as a closed technogenic cycle – emission, deposition, temporary accumulation, redistribution and remigration – which is typical of medium-industrialised cities in Northern Europe.

Within indoor environments, this cycle continues. Concentrations of Ni, Pb and Zn in indoor dust are comparable to outdoor levels, reflecting the infiltration of pollutants through ventilation systems, windows and dust particles brought in from outside. Ground floors and apartments facing major roads are particularly vulnerable, where metal concentrations exceed those in inner courtyards by 1.5-2 times (Guliyeva, 2023). Such penetration of outdoor dust creates a persistent hygienic risk, especially for children, as heavy metals are not metabolised and tend to bioaccumulate. Similar patterns have been reported in other European cities, indicating the universality of this transfer mechanism (Spriņģe *et al.*, 2024). For Baltic cities, including Jelgava, pollution is predominantly of the transport-atmospheric type with seasonal fluctuations: in winter, concentrations in snow samples almost double. This highlights the influence of climate and energy consumption structure on the chemical specificity of urban systems. Jelgava represents a typical example of a moderately developed Baltic city, where metal pollution follows general European trends but with pronounced regional and seasonal modulation (Jachimowicz *et al.*, 2025). Additionally, to assess Jelgava's position, Table 1 presents a comparative interpretation of heavy metal pollution indicators with data from other urbanised regions in Europe and worldwide.

Table 1. Comparison of heavy metal pollution indicators in Jelgava and other urbanised areas in Europe and worldwide

Country/region	Object of analysis	Main elements (mg/kg or equivalent)	Pollution level/ indices	Dominant sources	Characteristics
Jelgava, Latvia	Lichens, snow, bottom sediments, indoor dust	Ni: 20-60, Cu: 40-90, Pb: 30-70, Zn: 100-200	$PLI = 1.5\text{-}2.2$; $I_{geo} = 1\text{-}3$	Road transport, heating, dust formation	Medium-industrial pollution type; pronounced seasonality and spatial gradients
Riga, Latvia	Bottom sediments	Ni: 30-80, Cu: 70-130, Zn: 150-300	$I_{geo} = 2\text{-}3$	Transport, road runoff, urbanisation	Similar range to Jelgava; higher Cu and Zn levels due to population density
Kaunas, Lithuania	Wastewater sludge	Ni: 25-75, Cu: 60-110, Pb: 35-80, Zn: 150-250	$PLI = 2\text{-}2.5$	Municipal effluents, transport	Comparable to the Jelgava; accumulation in sludge confirms a persistent technogenic background
Berlin, Germany	Soils and road dust	Ni: 40-90, Cu: 80-180, Pb: 100-250, Zn: 250-400	$PLI = 2.5\text{-}3$	Transport, heating, historical industrialisation	Higher technogenic background; high persistence of soil contamination
Delhi, India	Road dust	Ni: 100-200, Cu: 200-400, Pb: 300-600, Zn: 500-1000	$PLI = 4\text{-}5.5$	Intense traffic, industrial emissions	Very high pollution levels; dominance of Pb and Zn due to industrial and traffic emissions

Table 1. Continued

Country/region	Object of analysis	Main elements (mg/kg or equivalent)	Pollution level/ indices	Dominant sources	Characteristics
Paris, France	Soils and atmospheric deposition	Ni: 40-80, Cu: 70-160, Pb: 120-240, Zn: 200-380	PLI = 2.2-2.8	Transport, historical urban layer	Similar levels to Jelgava; within the European range of moderate pollution
Shanghai, China	Soils and roadside sediments	Ni: 60-130, Cu: 150-280, Pb: 200-350, Zn: 400-700	PLI = 3.5-4.5	Industry, urbanisation, road transport	More pronounced industrial influence; high deposition of heavy metals

Source: created by the authors based on S. Roy *et al.* (2022), J. Pilecka-Ulcugaceva *et al.* (2024a), J. Pilecka-Ulcugaceva *et al.* (2024b), G. Spriņģe *et al.* (2024), H. Liu *et al.* (2025), P. Jachimowicz *et al.* (2025)

For cities in Northern Europe, a stable pollution pattern dominated by transport and heating emissions is typical, which is also confirmed for Jelgava. The concentrations of Ni (20-60 mg/kg), Cu (40-90 mg/kg) and Zn (100-200 mg/kg) fall within the range's characteristic of moderately urbanised regions of the Baltic zone. Unlike industrial agglomerations in East and South Asia, where Pb and Zn levels exceed European values by four to six times, Jelgava demonstrates a controlled anthropogenic load (PLI = 1.5-2.2; I_{geo} = 1-3) and pronounced spatial mosaic pollution, where concentrations decrease sharply at a distance of only 100-200 metres from emission sources. Seasonal modulation of pollution, with higher Ni and Cu levels in winter and stabilisation in summer, reflects climatic regulation of the chemical state of the environment. Jelgava may be classified as a moderately polluted urban system, where anthropogenic processes are counterbalanced by natural mechanisms of dispersion and self-purification. Consequently, in a global context, Jelgava can be regarded as a representative example of a post-industrial city in temperate latitudes, where the ecological state is determined not by the scale of emissions but by the balance between anthropogenic activity, climatic factors and self-regulating mechanisms of urban ecosystems. It occupies a stable position between cleaner Northern European models and overloaded Asian urban systems, reflecting a transition from industrial ecology to sustainable urban functioning.

Discussion

The results of the study demonstrated that transport is the primary source of heavy metal accumulation, particularly Ni, Cu, Pb and Zn. Maximum concentrations were recorded along major roads and at transport hubs, gradually decreasing with distance into residential blocks. This spatial selectivity confirms the predominance of the atmospheric pathway for particle transport, generated through tyre and brake wear and exhaust emissions. This aligns with the findings of A. Vijayan *et al.* (2024), who treated snow as a seasonal integrator of transport-related pollution. They observed identical distribution patterns in the snow cover: a sharp concentration gradient from roadways to inner areas, with Ni, Cu and Zn prevailing in regions with high traffic intensity. The consistency of Latvian and global data indicates the universality of the transport-atmospheric mechanism in urban systems and confirms that, even under differing climatic conditions, transport remains the dominant factor in shaping the technogenic background.

In the study by M.L. Messager *et al.* (2021), an innovative approach to monitoring heavy metals in urban areas was proposed, combining low-cost bioindication methods with spatial modelling. The authors integrated data on Cu, Zn, Ni and Pb concentrations from multiple media (vegetation, dust and soil) to create highly detailed pollution distribution maps. Their model showed that spatial anomalies in metal concentrations closely correlate with the configuration of the road network and building density, with transport zones serving as the primary accumulation hotspots. These results are consistent with the present study – a similar multi-matrix approach (lichens, snow, bottom sediments, indoor dust) revealed the same spatial coherence of pollution. Traffic intensity and the compactness of urban development determine the structure of the technogenic background and serve as the primary factors in heavy metal accumulation, confirming the universality of integrated bioindication methods for assessing urban pollution flows (Ilderbayeva *et al.*, 2024).

The study also showed that bottom sediments in small urban watercourses function as long-term reservoirs of technogenic metals. Elevated concentrations of Ni, Cu, Pb and Zn are recorded, reflecting both atmospheric deposition and input via surface runoff. Sediments accumulate metals over multiple seasons, creating a persistent geochemical signature and exhibiting signs of phytotoxicity (Kozyatnyk *et al.*, 2014; 2015). Similar patterns were reported by L. Fu *et al.* (2023), who analysed bottom sediments of urban rivers in China: they identified comparable Ni, Cu, Pb and Zn profiles, noted the spatial selectivity of metal accumulation, and described the role of microorganisms and resistance genes in metal redistribution. This confirms the universality of sediments as long-term pollution reservoirs and emphasises the need to account for the biogeochemical activity of sediment microbiota when assessing environmental risks in urban catchments.

The study by M. Taka *et al.* (2022) revealed pronounced spatio-temporal patterns in the distribution of copper, zinc, nickel and lead in surface runoff from urban areas in Finland. The highest metal loads were observed during the winter and spring periods, which directly aligns with the findings of the present study – winter accumulation of metals in the snow cover and their subsequent release into the hydrological system during melting. The authors confirmed the existence of a closed technogenic cycle, "atmospheric deposition – surface runoff – bottom sediments – remobilisation", similar to the processes established for Jelgava, indicating that this mechanism is typical of the Northern European model of urban pollution.

In the current study, it was established that in Jelgava's urbanised system, heavy metals circulate between the atmosphere, snow cover, surface runoff and indoor dust, forming a closed technogenic cycle with seasonal accumulation and secondary contamination. Concentrations of Ni, Cu, Pb and Zn demonstrate a stable interconnection between external and internal environments, indicating infiltration of outdoor pollutants into residential spaces and the maintenance of a persistent technogenic dust background (Kavaldzhieva, 2022; Tastemir *et al.*, 2025). These patterns are consistent with the results of H. Chu *et al.* (2023), which showed a close correlation between indoor and outdoor pollution driven by transport and heating sources, as well as C. Li *et al.* (2024), who confirmed the dominance of the same elements (Cu, Zn, Ni) in urban soils and their association with transport- and energy-related emissions. This supports the universality of the closed technogenic cycle model identified for Jelgava, characteristic of moderately industrialised cities.

The study by A.J. Adewumi & O.D. Ogundele (2024) reviewed over two hundred studies on heavy metal contamination in urban soils across different regions of the world. The authors systematised the concentration ranges of Ni, Cu, Pb, Zn and Cd and established that transport, industry and solid-fuel heating are the primary global sources of technogenic load. For quantitative assessment of pollution, integrated indices such as EF, CF, I_{geo} and PLI were applied, allowing the determination of ecological risk levels and the identification of priority impact zones. This was confirmed by the results of the present study, both methodologically and substantively: the same indices were used to differentiate pollution levels and rank ecological risk. In the Latvian data, EF values greater than 10 and PLI values above 2, comparable to the ranges reported in the authors' meta-analysis, indicate a similar level of technogenic impact, demonstrating the universality of index-based methods for assessing anthropogenic pressure in urban areas.

The study in Jelgava identified two main sources of heavy metal pollution: transport and heatingindustrial. The first is characterised by high loads of Ni, Cu and Zn and spatial concentration along major roads, while the second is associated with elevated Pb and Cd levels, linked to fuel combustion and emissions from small heating plants. This factor structure demonstrates the multigenic nature of urban pollution and highlights the seasonal intensification of anthropogenic load during the cold period. This aligns with the study by M. Vashist *et al.* (2025), which confirmed the same pattern at a global scale: urban trees were used as bioindicators of metal accumulation, and statistical analysis similarly identified two principal factors – transport and heating-fuel sources. The authors noted that transport contributes dominantly to the variation in Cu, Zn and Ni concentrations, whereas Pb and Cd reflect an additional heating-related background. This indicates the global reproducibility of pollution source distribution patterns and confirms the applicability of bioindication for their identification in urban environments.

The study by V.-S. Gkoltsou *et al.* (2025) highlights two interconnected levels of urban pollution – external and internal environments. Concentrations of Ni, Cu, Pb and Zn decrease with distance from major roads, and the pollution index values correspond to the ranges observed in Jelgava in the present study, indicating a similar level of anthropogenic load. The research of S.S. Sabegh *et al.* (2023) complements these findings, showing that lead, zinc and nickel from the external environment infiltrate indoor spaces, producing comparable concentrations in household dust. Both studies, despite climatic differences, support the model identified for Jelgava of a technogenic cycle linking external pollution to the indoor environment through mechanisms of dust infiltration and seasonal accumulation. This demonstrates that heavy metals circulate between external and internal environments, confirming the closed technogenic cycle identified in Jelgava. Thus, Jelgava represents a typical example of a temperate-latitude city where anthropogenic processes form a closed cycle of pollutant transfer between the atmosphere, surfaces and the indoor environment. The patterns of heavy metal migration observed in Jelgava align with international data and reflect the universal transport-heating type of urban pollution.

Conclusions

This research highlights the fragmented nature of global studies on heavy metals and PM in urban air pollution. While existing research often focuses on specific pollution types, it fails to address the complexities of urban environments as dynamic, multi-source pollution systems. This underscores the importance of integrated and comprehensive studies like the one conducted in Jelgava. In Jelgava, a robust monitoring network was developed to assess both long-term and short-term air pollution dynamics. This network, comprising 60 sampling plots and spanning from 2018 to 2024, generated a valuable database of chemical element concentrations in snow. The spatial and temporal coverage of this network provides a detailed understanding of pollution patterns and sources.

The study revealed significant variability in heavy metal concentrations across the city, with zinc (Zn) ranging from 0.007 to 1,002.1 µg/L, copper (Cu) from 0 to 829.50 µg/L, nickel (Ni) from 0.0005 to 40.40 µg/L, lead (Pb) from 0.7 to 62.97 µg/L, manganese (Mn) from 5.9 to 1,357.0 µg/L, and aluminium from 0.01 to 1,183.66 µg/L. Transport corridors were identified as major contributors to spatial pollution patterns, highlighting the critical role of traffic in urban air quality challenges. The integration of statistical methods with GIS-based spatial analysis proved effective in identifying pollution sources. The Kruskal-Wallis test confirmed significant differences in heavy metal concentrations across distance groups ($p < 0.0001$). This methodological framework provides a replicable approach for urban air pollution assessments globally.

Future phases, involving health impact assessments, are recommended for further interdisciplinary research. Additionally, addressing high chemical concentrations remains a complex challenge due to the multitude of point and diffuse pollution sources influenced by urban structure, as well as global and local climatic factors. Continued research is vital for advancing sustainable urban development and mitigating air pollution impacts. These results are consistent with Northern European data, confirming the transport-atmospheric mechanism of metal transfer and the stable balance of technogenic and natural processes in Jelgava's urban environment.

Future phases, involving health impact assessments, are recommended for further interdisciplinary research. Additionally, addressing high chemical concentrations remains a complex challenge due to the multitude of point and diffuse pollution sources influenced by urban structure, as well as global and local climatic factors. Continued research is vital for advancing sustainable urban development and mitigating air pollution impacts.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

References

[1] Adewumi, A.J., & Ogundele, O.D. (2024). Hidden hazards in urban soils: A meta-analysis review of global heavy metal contamination (2010-2022), sources and its ecological and health consequences. *Sustainable Environment*, 10(1). doi: 10.1080/27658511.2023.2293239.

[2] Akomolafe, O.O., Olorunsogo, T., Anyanwu, E.C., Osasona, F., Ogugua, J.O., & Daraojimba, O.H. (2024). Air quality and public health: A review of urban pollution sources and mitigation measures. *Engineering Science and Technology: An International Journal*, 5(2), 259-271. doi: 10.51594/estj.v5i2.751.

[3] Chen, Q., Marques dos Santos, M., Tanabe, P., Harraka, G.T., Magnuson, J.T., McGruer, V., Qiu, W., Shi, H., Snyder, S.A., & Schlenk, D. (2021). Bioassay guided analysis coupled with non-target chemical screening in polyethylene plastic shopping bag fragments after exposure to simulated gastric juice of fish. *Journal of Hazardous Materials*, 401, article number 123421. doi: 10.1016/j.jhazmat.2020.123421.

[4] Chu, H., Liu, Y., Xu, N., & Xu, J. (2023). Concentration, sources, influencing factors and hazards of heavy metals in indoor and outdoor dust: A review. *Environmental Chemistry Letters*, 21, 1203-1230. doi: 10.1007/s10311-022-01546-2.

[5] Dadkhah-Aghdash, H., Rasouli, M., Rasouli, K., & Salimi, A. (2022). Detection of urban trees sensitivity to air pollution using physiological and biochemical leaf traits in Tehran, Iran. *Scientific Reports*, 12, article number 15398. doi: 10.1038/s41598-022-19865-3.

[6] Fedoniuk, T.P., Pyvovar, P.V., Topolnytskyi, P.P., Rozhkov, O.O., Kravchuk, M.M., Skydan, O.V., Pazych, V.M., & Petruk, T.V. (2025). Utilizing remote sensing data to ascertain weed infestation levels in maize fields. *Agriculture*, 15(7), article number 711. doi: 10.3390/agriculture15070711.

[7] Fu, L., Yu, Y., Yu, F., Xiao, J., Fang, H., Li, W., Xie, Z., Zhang, F., & Lin, S. (2023). Profiles and spatial distributions of heavy metals, microbial communities, and metal resistance genes in sediments from an urban river. *Frontiers in Microbiology*, 14, article number 1188681. doi: 10.3389/fmicb.2023.1188681.

[8] Gkoltsou, V.-S., Papadimou, S.G., Bourliva, A., Skilodimou, H.D., & Golia, E.E. (2025). Heavy metal levels in green areas of the urban soil environment of Larissa City (Central Greece): Health and sustainable living risk assessment for adults and children. *Sustainability*, 17(10), article number 4421. doi: 10.3390/su17104421.

[9] Glevitzky, M., Dumitrel, G.-A., Rusu, G.I., Toneva, D., Vergiev, S., Corcheş, M.-T., Pană, A.-M., & Popa, M. (2025). Microplastic pollution on the beaches of the Black Sea in Romania and Bulgaria. *Applied Sciences*, 15(9), article number 4751. doi: 10.3390/app15094751.

[10] Grinfelde, I., Siltumens, K., Grybauskiene, V., Bertins, M., & Pilecka-Ulcugaceva, J. (2024). Influence of industry on air pollution in Jelgava city. In *Proceedings of the international scientific conference "Engineering for rural development"* (pp. 914-920). Jelgava: ERD. doi: 10.22616/ERDev.2024.23.TF182.

[11] Guliyeva, S. (2023). Energy consumption, economic growth and CO2 emissions in Azerbaijan. *Multidisciplinary Science Journal*, 5(4), article number e2023052. doi: 10.31893/multiscience.2023052.

[12] Ibraimov, T., Satybaldyev, A., Mamatov, E., Tashpolotov, Y., & Sadykov, E. (2025). Extraction of valuable elements from industrial waste in the Kyrgyz Republic based on the process of electrophysical ionization. *Evergreen*, 12(2), 1154-1166. doi: 10.5109/7363500.

[13] Ilderbayeva, G., Utegenova, A., Ilderbayev, O., Sembaeva, Z., & Askarova, G. (2024). Assessment of the combined effects of heavy metal cobalt and sublethal radiation on the immune system. *Biomedical and Biotechnology Research Journal*, 8(4), 455-463. doi: 10.4103/bbrj.bbrj_316_24.

[14] Jachimowicz, P., Radzevičius, A., Wojnarová, P., Šadzevičius, R., Horoszko, B., Dapkienė, M., Radziemska, M., & Klik, B. (2025). Two decades of heavy metal fluctuations in wastewater sludge in Lithuania with evolving trends and implications for treatment efficiency. *Journal of Geochemical Exploration*, 269, article number 107642. doi: 10.1016/j.gexplo.2024.107642.

[15] Kavaldzhieva, K. (2022). Establishment of fair value and analysis of a waste deposit concession. *SGEM*, 22(5.1), 581-589. doi: 10.5593/sgem2022/5.1/s21.073.

[16] Kozyatnyk, I., Haglund, P., Lövgren, L., Tysklind, M., Gustafsson, A., & Törneman, N. (2014). Evaluation of barrier materials for removing pollutants from groundwater rich in natural organic matter. *Water Science and Technology*, 70(1), 32-39. doi: 10.2166/wst.2014.192.

[17] Kozyatnyk, I., Lövgren, L., & Haglund, P. (2015). On the leaching of mercury by brackish seawater from permeable barriers materials and soil. *Journal of Environmental Chemical Engineering*, 3(2), 1200-1206. doi: 10.1016/j.jece.2015.04.017.

[18] Kramer, A., & Minet, L. (2025). Zones of exposure: Urban micro-environments of air pollution and residential intensification. *Sustainable Cities and Society*, 127, article number 106404. doi: 10.1016/j.scs.2025.106404.

[19] Li, C., Wang, H., Dai, S., Liu, F., Xiao, S., Wang, X., Cao, P., Zhang, Y., & Yang, J. (2024). Source-specific ecological and human health risk analysis of topsoil heavy metals in urban greenspace: A case study from Tianshui City, northwest China. *Environmental Geochemistry and Health*, 46, article number 445. doi: 10.1007/s10653-024-02228-4.

[20] Liu, H., Chang, J., Zhao, F., Shen, L., Yang, K., & Chen, L. (2025). Impact of urban expansion on soil heavy metal pollution: A comparison of new and old urban blocks. *Ecological Frontiers*, 45(5), 1407-1418. doi: 10.1016/j.ecofro.2025.05.020.

[21] Merdan, S., Huremović, J., Nuhanović, M., Smječanin, N., Ramić, E., & Karadža, A. (2025). Transplanted lichen *Hypogymnia physodes* as bioindicator of heavy metals and radionuclides air pollution in Sarajevo, Bosnia and Herzegovina. *Journal of Environmental Science and Health Part A*, 60(4), 165-171. doi: 10.1080/10934529.2025.2574784

[22] Messager, M.L., Davies, I.P., & Levin, P.S. (2021). Low-cost biomonitoring and high-resolution, scalable models of urban metal pollution. *Science of the Total Environment*, 767, article number 144280. doi: 10.1016/j.scitotenv.2020.144280.

[23] Niu, S., Wang, R., & Jiang, Y. (2024). Quantification of heavy metal contamination and source in urban water sediments using a statistically determined geochemical baseline. *Environmental Research*, 263(1), article number 120080. doi: 10.1016/j.envres.2024.120080.

[24] Pilecka-Ulcugaceva, J., Grinfelde, I., Bakute, A., Bertins, M., & Siltumens, K. (2024a). Biomonitoring of heavy metals in the city of Jelgava, Latvia using lichen *Xanthoria parietina*. In *Proceedings of the 24th international multidisciplinary scientific geoconference* (pp. 381-388). Sofia: SGEM. doi: 10.5593/sgem2024/4.1/s19.50.

[25] Pilecka-Ulcugaceva, J., Grinfelde, I., Bakute, A., Burlakovs, J., & Bertins, M. (2024b). Assessment of heavy metal contamination in urban snow: A case study of nickel and copper in Jelgava, Latvia. In *Proceedings of the 24th international multidisciplinary scientific geoconference* (pp. 177-184). Sofia: SGEM. doi: 10.5593/sgem2024v/4.2/s18.25.

[26] Roy, S., Gupta, S.K., Prakash, J., Habib, G., & Kumar, P. (2022). A global perspective of the current state of heavy metal contamination in road dust. *Environmental Science and Pollution Research*, 29, 33230-33251. doi: 10.1007/s11356-022-18583-7.

[27] Sabegh, S.S., Mansouri, N., Taghavi, L., & Mirzahosseini, S.A. (2023). Pollution status, origin, and health risk assessment of toxic metals in deposited indoor and outdoor urban dust. *International Journal of Environmental Science and Technology*, 20, 2471-2486. doi: 10.1007/s13762-022-04530-z.

[28] Spriņģe, G., Grīne, I., Melece, I., Melecis, V., Purmalis, O., & Valters, K. (2024). Heavy metal pollution and phytotoxicity of small urban stream sediments. *Sustainable Water Resources Management*, 10, article number 106. doi: 10.1007/s40899-024-01096-1.

[29] Stankevica, M., Grinfelde, I., Bakute, A., Pilecka-Ulcugaceva, J., & Purmalis, O (2021). Heavy metals air pollution in Jelgava city Latvia. In *Proceedings of the international multidisciplinary scientific geoconference "Surveying geology and mining ecology management"* (pp. 75-84). Sofia: SGEM. doi: 10.5593/sgem2021V/4.2/s19.a12.

[30] Tabors, G., Brūmelis, G., Nikodemus, O., Dobkeviča, L., & Viligurs, K. (2023). Decreased atmospheric deposition of heavy metals in Latvia shown by long-term monitoring using the moss *Pleurozium schreberi*. *Environmental Science and Pollution Research*, 30, 94361-94370. doi: 10.1007/s11356-023-28922-x.

[31] Taka, M., Sillanpää, N., Niemi, T., Warsta, L., Kokkonen, T., & Setälä, H. (2022). Heavy metals from heavy land use? Spatio-temporal patterns of urban runoff metal loads. *Science of The Total Environment*, 817, article number 152855. doi: 10.1016/j.scitotenv.2021.152855.

[32] Tastemir, N., Bulatov, N., & Menendez-Pidal De Navascues, I. (2025). A system for the removal of solid household waste from a multi-storey building. *Proceedings of the Institution of Civil Engineers: Transport*. doi: 10.1680/jtran.24.00120.

[33] UN projection. (2022). *World urbanization prospects: The 2018 revision*. Retrieved from https://www.un.org/uk/desa/68-world-population-projected-live-urban-areas-2050-says-un

[34] Vashist, M., Singh, S.K., & Kumar, T.V. (2025). Urban trees as nature-based solutions for heavy metal biomonitoring: A comparative and uncertainty analysis assessment. *Water, Air, & Soil Pollution*, 236, article number 769. doi: 10.1007/s11270-025-08423-y.

[35] Vijayan, A., Österlund, H., Marsalek, J., & Viklander, M. (2024). Traffic-related metals in urban snow cover: A review of the literature data and the feasibility of filling gaps by field data collection. *Science of the Total Environment*, 920, article number 170640. doi: 10.1016/j.scitotenv.2024.170640.

[36] Wang, D., Zhou, T., & Sun, J. (2022). Effects of urban form on air quality: A case study from China comparing years with normal and reduced human activity due to the COVID-19 pandemic. *Cities*, 131, article number 104040. doi: 10.1016/j.cities.2022.104040.

[37] Weichenthal, S., *et al*. (2022). How low can you go? Air pollution affects mortality at very low levels. *Science Advances*, 8(39), article number eabo3381. doi: 10.1126/sciadv.abo3381.

[38] World Bank. (2024). *Urban population (% of total population) – Latvia. Trading Economics*. Retrieved from https://tradingeconomics.com/latvia/urban-population-percent-of-total-wb-data.html.

Комплексна оцінка забруднення важкими металами в міських середовищах: приклад міста Єлгава, Латвія

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Анотація. Якість повітря в міських умовах стала критичною глобальною проблемою і очікується, що темпи урбанізації будуть продовжувати зростати. Мета цього дослідження полягала в тому, щоб на теоретичній основі визначити закономірності формування техногенного фону та просторову структуру забруднення в міському середовищі Єлгави. Методологія базувалася на систематичному та статистичному аналізі для оцінки джерел та рівнів забруднення в місті. Тривалість дослідження, від початку збору даних до завершення аналізу, охоплювало період з 2017 по 2023 рік, протягом якого щорічно проводилась вибірка та всебічний моніторинг. Концентрації важких металів у різних компонентах міської екосистеми Єлгави були в межах таких діапазонів: Ni – 20-60 мг/кг, Cu – 40-90 мг/кг, Pb – 30-70 мг/кг, Zn – 100-200 мг/кг. Ці значення відповідають помірним рівням забруднення, типовим для урбанізованих територій Північної та Центральної Європи. Найвищі концентрації були зафіксовані поблизу основних доріг та промислових зон, тоді як периферійні райони були близькими до фонових значень. Було встановлено, що інтегровані показники якості навколишнього середовища (індекс забруднення = 1,5-2,2, індекс геоакумуляції = 1-3) характеризують Єлгаву як помірно забруднену територію, яка при цьому зберігає загальну екологічну стабільність. Факторний аналіз показав, що структура забруднення формується двома основними джерелами: викидами, пов’язаними з транспортом (Ni, Cu, Zn – знос шин і гальм, вихлопи дизельних двигунів) та викидами від опалення та промисловості (Pb, Cd – спалювання палива та місцеві викиди від малих підприємств). Єлгаву можна класифікувати як помірно забруднену, але стійку міську систему, де антропогенний тиск врівноважується природними механізмами самоочищення. Практична цінність дослідження полягає в тому, що його результати можуть бути використані муніципальними органами з питань охорони навколишнього середовища та планування для оцінки ризиків та управління якістю міського середовища

Ключові слова: міська екосистема; техногенний тиск; просторові градієнти; атмосферно-сезонна динаміка; екологічна стійкість