

Risk-based assessment of atmospheric air pollution by heavy metals

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ABSTRACT

Environmental pollution by heavy metals represents one of the critical drivers of natural ecosystem degradation and a significant threat to human health. This study investigates the relationship between ambient air quality, shaped by intensive industrial activity and heavy traffic load, and the associated risks to public health. The findings demonstrate consistently elevated levels of atmospheric pollution across the investigated area. Natural factors such as unfavorable meteorological conditions further impede the dispersion of pollutants, while the dominant anthropogenic sources remain industrial facilities and motor vehicles. Risk assessment of both non-carcinogenic and carcinogenic effects was performed in accordance with the U.S. EPA methodology, based on retrospective analysis of Pb, Mn, Cr, Cu, Ni, Zn, and Cd concentrations during 2018–2024. The results reveal a markedly elevated respiratory non-carcinogenic risk in children (HQ = 5.25) and a moderate risk in adults (HQ = 1.12), primarily attributable to atmospheric copper (Cu) exposure. The cumulative non-carcinogenic hazard index was also considerable in children (HI = 7.33) and moderate in adults (HI = 1.56). The most vulnerable systems were identified as the respiratory tract (HI = 7.14 in children; HI = 1.53 in adults) and the central nervous system in children (HI = 1.23). Overall systemic exposure was characterized as high for the child population (HI = 5.25) and moderate for adults (HI = 1.12). In terms of contribution to non-cancer risk, heavy metals followed the order: Cu (72%) > Ni (8%) = Cd (8%) > Mn (6%) > Cr (2%) = Pb (2%) = Zn (2%). The cumulative potential cancer risk (CPCR) was within acceptable limits for both children (CPCR = 7.1E-05) and adults (CPCR = 7.6E-05), with Cr (81–92%), Cd (5–16%), and Ni (2–5%) identified as the principal contributors. Overall, the analysis highlights the urgent need for preventive strategies to mitigate the health impacts of heavy metals in urban air and underscores the importance of revising air quality management practices to better protect vulnerable populations.

Keywords: atmospheric air, level of contamination, meteorological conditions, heavy metals, toxicity, health risk assessment.

INTRODUCTION

In the context of implementing the national strategy for the development of the healthcare system in Ukraine, one of the key objectives is to increase the average life expectancy of the population and reduce premature mortality from cancer by 30%. In parallel, the State Environmental Strategy until 2030 is aimed at achieving environmental safety in line with European Union standards.

Anthropogenic environmental pollution, particularly the contamination of atmospheric

air with heavy metals and their compounds, poses a serious threat to public health. It leads to a decline in health reserves at both individual and population levels, increases the functional burden on the human body, promotes the development of pathological processes, as well as acute and chronic diseases, and ultimately contributes to depopulation (Pandey et al., 2021; Xie et al., 2024).

Heavy metals are widespread atmospheric pollutants, occurring predominantly in particulate form. Their presence in the atmosphere results primarily from industrial activities, fossil fuel

combustion, and vehicle emissions (World Health Organization (WHO), 2021).

In the atmosphere, heavy metals are most commonly found in the form of PM_{2.5} or PM₁₀. Particulate matter may be introduced into the air as primary aerosols, originating from combustion processes or resuspension of soil particles, whereas secondary aerosols are formed directly in the atmosphere through chemical transformations of gaseous emissions, such as sulfur dioxide (SO₂), nitrogen oxides (NO_x), and ammonia (NH₃) (Matei et al., 2025).

These emissions can interact with heavy metals in the atmosphere, potentially increasing the overall heavy metal burden (Bi et al., 2020).

Rapid industrialization and urbanization have led to a significant increase in atmospheric pollution by toxic heavy metal compounds, which has raised serious global concerns, contributed to environmental degradation, and emerged as one of the most pressing challenges to human health (Zheng et al., 2020; Ghosh et al., 2023).

Bioaccumulation of toxic heavy metals in the human body can lead to neurotoxicity and other health problems, such as cardiovascular diseases, cancer, as well as kidney and bone disorders. Heavy metals – particularly As, Cd, Pb, and Hg – can disrupt cellular homeostasis mechanisms, induce oxidative stress, apoptosis, and genotoxicity, all of which are underlying factors in the development of these diseases (Mitra et al., 2022).

Topographic and meteorological conditions, along with the sedimentation properties of aerosols, play a decisive role in the formation, retention, distribution, and dispersion of pollutants, and therefore significantly affect overall air quality (Hernández et al., 2022; Sharma et al., 2022).

At present, risk assessment methodology is considered one of the most effective approaches for establishing the relationship between environmental conditions and public health. It enables the prediction of the likelihood of developing pathological and chronic conditions under various exposure scenarios and supports the development of strategies for managing risk factors at both individual and population levels.

Therefore, it is critically important to investigate the current state of heavy metal air pollution in industrially developed cities, assess the associated health risks and potential sources, in order to enable effective risk management.

The aim of this study is to assess the potential human health risks associated with heavy metal air pollution under current transport and industrial pressures in urbanized areas, using the city of Cherkasy as a case study.

To achieve this aim, the following objectives have been set:

- to evaluate the current state and dynamics of air pollution in the city;
- to analyze the influence of meteorological conditions on the formation of air quality;
- to assess both carcinogenic and non-carcinogenic health risks associated with heavy metal air pollution.

MATERIAL AND METHODS

As part of the study, the city of Cherkasy was selected for assessing the health risks associated with environmental factors. Cherkasy is an administrative center characterized by high population density, developed industrial infrastructure, and significant anthropogenic pressure. The comprehensive environmental profile of the area and the demographic characteristics of the settlement justified its selection as a model site for analyzing potential threats and calculating risk indicators for vulnerable population groups.

A systems approach was applied, incorporating bibliosemantic, comparative-analytical, and statistical methods. Microsoft Office Excel software was used for data visualization and statistical analysis. The study summarized and statistically processed the results of air quality monitoring for heavy metal concentrations conducted during 2018–2024, based on data from the Cherkasy Regional Center for Hydrometeorology and the State Institution ‘Cherkasy Regional Center for Disease Control and Prevention of the Ministry of Health of Ukraine.

Risk assessment and calculations were carried out in accordance with official methodological guidelines (Order of the Ministry of Health of Ukraine № 1811 dated 18.10.2023). Non-carcinogenic health risks were evaluated using the hazard quotient (HQ) for each heavy metal and the hazard index (HI) for combined exposure, taking into account the impact on critical organs and systems. For heavy metals classified as potentially carcinogenic to humans (cadmium, nickel, lead, and hexavalent chromium) (IARC), individual carcinogenic risk (CR) and cumulative

carcinogenic risk (CRA) were calculated for combined exposure to multiple chemical agents.

RESULTS AND DISCUSSION

One of the key components of anthropogenic pressure on urban landscapes is aerotechnogenic pollution, which is among the primary sources of technogenic contaminants-particularly heavy metals-due to its significant environmental impact. Intensive technogenesis within urban areas leads to the formation of persistent geochemical anomalies in urban soils, accompanied by the disruption of natural soil self-purification mechanisms, alterations in the physicochemical properties of the environment, and increased mobility of pollutants. This transformation of urbanized geosystems intensifies ecotoxicological stress and contributes to the accumulation of heavy metals in the near-surface atmosphere, soils, and biota.

The atmospheric air of the Cherkasy industrial agglomeration is subject to significant technogenic pressure from a number of industrial facilities, with the main polluters being enterprises in the energy and chemical industries. In 2023, the largest emission volumes were recorded from the PraT «Cherkaske Khimvolokno» VP «Cherkaska TPP») which emitted over 28.9 thousand tonnes, and PrAT «Azot» with approximately 6.02 thousand tonnes (Regional report on the state of the natural environment in the Cherkasy region in 2023).

According to official data from the Department of Ecology and Natural Resources of the Cherkasy Regional State Administration, based on pollutant

concentrations and the overall level of technogenic pressure, the city of Cherkasy is among the most environmentally burdened settlements in the region. The integrated atmospheric pollution index (API), calculated using average monthly concentrations of sulfur dioxide, ammonia, formaldehyde, nitrogen dioxide, and carbon monoxide, classifies the air pollution level in Cherkasy as elevated (5–7) to high (7–14) (Figure 1).

Additional impact on atmospheric air quality is exerted by enterprises of the chemical and mechanical engineering industries, thermal power generation, and motor vehicles, whose contribution is comparable to or even exceeds the emission volumes of industrial enterprises.

Heavy metals present in emissions from industrial facilities and mobile sources pose a serious environmental threat due to their toxicity, bioaccumulative capacity, and carcinogenic activity. Once released into the environment, these elements can persist for extended periods in various ecosystem components, migrating through surface runoff, infiltration into groundwater, or wind-driven transport of particulate matter. This mobility of pollutants facilitates their widespread dispersion beyond the emission sources and increases risks to the environment and human health, even in remote areas.

Air pollution is a dynamic process that depends not only on the quantity of pollutant emissions from various sources, but also on atmospheric physico-chemical and chemical processes that lead to their transformation (Hernández et al., 2022). Topographic and meteorological conditions, as well as the sedimentation properties of aerosols, also play a crucial role in the

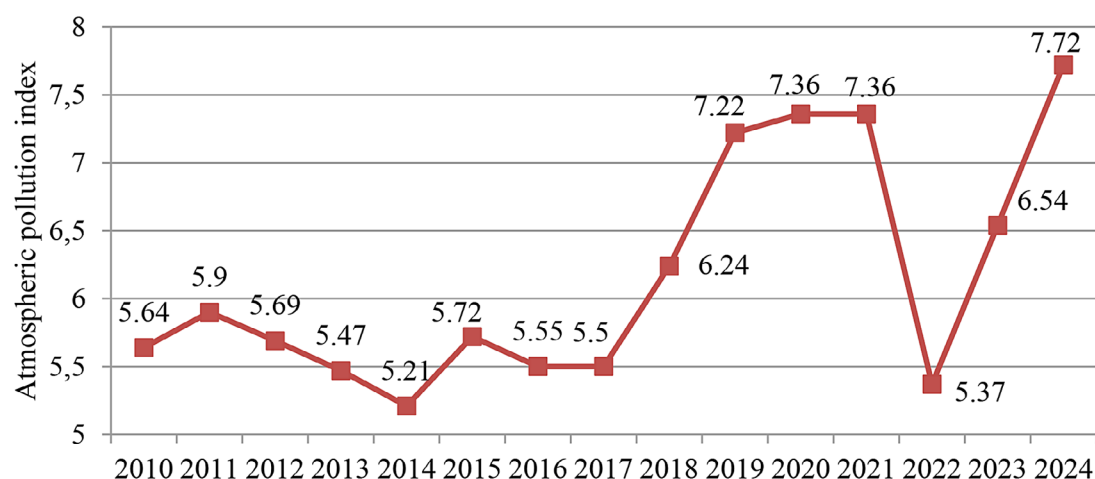


Figure 1. Dynamics of changes in the air pollution index in the city of Cherkasy from 2010 to 2024

formation, persistence, distribution, and dispersion of pollutants, and therefore in overall air quality (Sharma et al., 2022).

Meteorological conditions play an important role in shaping the air quality of the city of Cherkasy. The city is located in a climatic zone unfavorable for pollutant dispersion – characterized by a high atmospheric pollution potential. The potential genetic stability of the natural environment in the Cherkasy region is generally low, and the natural capacity to withstand external technogenic pressure is insufficient. Despite the decline in industrial activity, the concentration levels of certain pollutants in the atmospheric air remain high. One of the main reasons for this is the atmosphere's low self-cleaning capacity. Long-term observations indicate that processes promoting the accumulation of harmful substances prevail over those facilitating their dispersion (meteorological pollution potential $K_m > 1$).

The primary factor influencing the dispersion of atmospheric pollutants is the wind regime. Throughout the year, winds in the city predominantly blow from the northwest, southwest, and northeast directions (Figure 2).

Under moderate and strong persistence of southwesterly winds, there is a direct transport of harmful emissions from PrAT «Cherkaske Khimvolokno» VP «Cherkaska TPP» and PrAT «Azot». The high frequency of maximum allowable concentration (MAC) exceedances under moderate and strong persistence of northwesterly winds is associated with the presence of breeze circulation from the Kremenchuk Reservoir, which leads to an increase in pollutant concentrations by 1.5 to 2.0 times at a distance of 1–2 km from the water

surface. During stable atmospheric stratification and weak winds, significant air pollution events may occur in the city due to emissions from low-level sources, primarily motor vehicles.

Wind speed significantly influences the dispersion of harmful pollutants. The most frequent wind speeds are weak (up to 5 m/s). Annually, the lowest wind speeds occur during the summer period – approximately 3–4 m/s. In winter, the average wind speed reaches 4.5–4.8 m/s. The recurrence of wind speeds in the ranges of 0–1 m/s and 2–5 m/s accounts for an average of 30% of all observed cases, increasing to up to 40% during summer. Therefore, the prevailing wind regime does not favor the dispersion of pollutants from either high-level or low-level emission sources.

Among the important meteorological factors determining the level of air pollution in the city are temperature inversions. The presence of inversion layers in the surface and boundary layers of the atmosphere affects the spatial and temporal distribution of harmful pollutants. The highest frequency of inversions is observed during the autumn-winter period, with lower boundaries ranging from 100 to 500 meters, which contributes to increased pollution levels during this time. In spring, and especially in summer, inversion layers occur less frequently, and their lower boundaries are located at higher altitudes, resulting in a lesser effect on the background concentrations across the city – reduced by approximately 20–30%.

The accumulation of pollutants in the atmosphere caused by weak winds and inversions is further intensified under foggy conditions. In the presence of both inversion and fog, pollutant concentrations are 20–30%

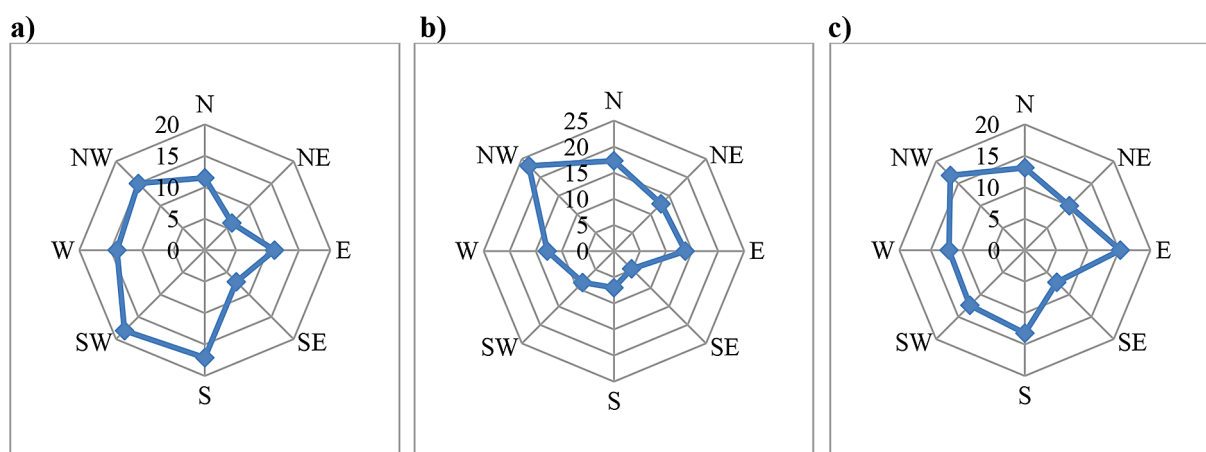


Figure 2. Wind rose: (a) January, (b) July, (c) annual

higher than during fog alone. On average, 35 to 70 foggy days are observed per year, mostly in the autumn-winter period.

The high recurrence of weak winds (in combination with other factors) leads to a very high atmospheric pollution potential in the region, estimated at approximately 3.4.

Heavy metals that enter the atmosphere in the form of aerosols are removed through natural self-purification processes. Due to gravitational sedimentation and washout by atmospheric precipitation, heavy metals settle from the air onto the soil surface and subsequently migrate into deeper soil layers. This leads to contamination of all soil horizons and infiltration into groundwater and soil water, eventually reaching plants. The pollution halo typically extends within a 10–15 km radius from the emission source. However, if heavy metals reach the upper layers of the atmosphere, they can be transported over much greater distances. Later, heavy metals can re-enter the atmospheric air through resuspension with soil and road dust. Atmospheric precipitation plays a crucial role in this process. Precipitation exceeding 5 mm is more effective, as it helps minimize air pollution. Precipitation less than 5 mm not only lacks a cleansing effect but can also contribute to increased pollution. The highest amount of precipitation in the city occurs in summer, while the lowest is observed in winter and early spring—precisely when the greatest quantity of pollutants, including heavy metal aerosols, is released into the atmosphere from thermal power plants.

Air contaminated with toxic heavy metals may pose risks to the ecological balance of urban ecosystems and to human health. In this study, assessments of carcinogenic and non-carcinogenic

health risks were conducted to quantitatively evaluate the level and impact of heavy metal concentrations in ambient air. The assessment was based on a retrospective analysis of data from 2018 to 2024, provided by the Cherkasy Regional Hydrometeorological Center.

The highest concentration recorded in the city's air was for iron and its compounds ($0.26\text{--}0.75\text{ }\mu\text{g}/\text{m}^3$, with an average value of $0.45\text{ }\mu\text{g}/\text{m}^3$). The concentrations of other heavy metals and their temporal dynamics are presented in Figure 3.

Heavy metals that enter the atmosphere can reach the human body through various pathways and pose both direct and indirect health hazards. They accumulate in human tissues and internal organs, may affect the central nervous system, and can act as cofactors, initiators, or triggers of various diseases. Simultaneous exposure to multiple heavy metals may result in numerous adverse health effects due to synergistic interactions, even when the concentrations of individual metals are below their ecotoxicological threshold levels. The primary route of exposure affecting human health is inhalation (Abdulaziz et al., 2022).

In accordance with international practices, the hazard index for non-carcinogenic morbidity and the carcinogenic risk were assessed separately for children and adults. To evaluate these risks, critical parameters were calculated, including the average daily dose (ADD), hazard quotient (HQ), hazard index (HI), and carcinogenic risk (CR).

The results of the non-carcinogenic risk assessment related to inhalation exposure to ambient air contaminated with heavy metals are presented in Table 1. For most of the studied heavy metals, the hazard quotient (HQ) was below the

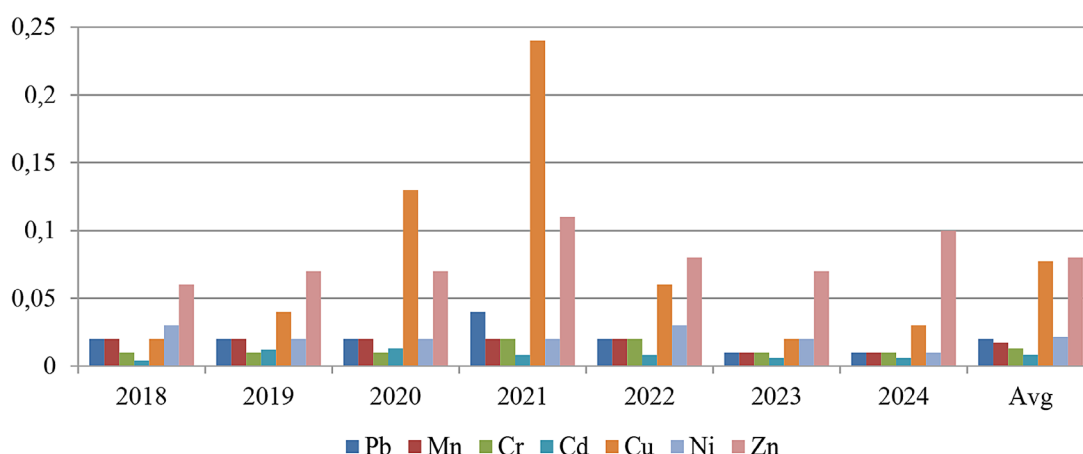


Figure 3. Concentration of heavy metals in the ambient air of Cherkasy, $\mu\text{g}/\text{m}^3$

Table 1. Chronic daily intake (ADD), hazard quotient (HQ), and hazard index (HI) based on average concentrations of heavy metals in the ambient air of Cherkasy

Heavy metals	C _{avg} , mg/m ³	ADD children	ADD adults	Rfc, mg/m ³	HQ children	HQ adults	Target organs/systems
Pb	0.00002	2.7E-05	5.8E-06	0.00015	0.18	0.04	Central nervous system (CNS), circulatory system, endocrine system, reproductive system
Mn	0.00002	2.3E-05	5.0E-06	0.00005	0.47	0.10	Central nervous system (CNS), respiratory system
Cr	0.00001	1.7E-05	3.7E-06	0.0001	0.17	0.04	Respiratory system, immune system, digestive system
Cd	0.00001	1.1E-05	2.4E-06	0.00002	0.55	0.12	Respiratory system, endocrine system
Cu	0.00008	1.0E-04	2.2E-05	0.00002	5.25	1.12	Respiratory system, systemic effect
Ni	0.00002	2.9E-05	6.2E-06	0.00005	0.58	0.12	Respiratory system, circulatory system, immune system, central nervous system (CNS)
Zn	0.00008	1.1E-04	2.3E-05	0.0009	0.12	0.03	Respiratory system, circulatory system, immune system,
Hazard Index (HI) children / adults	General		7.33/1.56	High: There is a significant risk of adverse effects occurring in the majority of the population./			
	Respiratory system		7.14/1.53				
	Systemic effect		5.25/1.12				
	Central nervous system		1.23/0.26	Moderate: There is a risk of harmful effects in particularly sensitive subpopulations.			
	Renal system		0.90/0.20	Moderate: There is a risk of harmful effects occurring in particularly sensitive subpopulations./			
	Circulatory system		0.88/0.19	Low: The risk of harmful effects is considered negligible.			
	Immune system		0.87/0.19	Low: The risk of harmful effects is considered negligible.			
	Endocrine system		0.73/0.16				
	Reproductive system		0.18/0.04				
	Gastrointestinal tract		0.17/0.04				

safety threshold (HQ = 1), indicating no significant non-carcinogenic risks for both adults and children. An exception was copper (Cu), which showed a high respiratory risk of adverse effects in children (HQ = 5.25) and a moderate risk in the adult population (HQ = 1.12).

The total cumulative non-carcinogenic health risk from chronic exposure in humans was high for children (HI=7.33) and moderate for adults (HI=1.56). The cumulative non-carcinogenic risk over the period 2018-2024 (Figure 4) was extremely high for children in 2020 and 2021 (HI>10), which may contribute to the development of chronic diseases.

Copper (Cu) has the most significant impact on human health. Even at the lowest concentrations of this metal in the urban atmospheric air (0.02 µg/m³ in 2018 and 2023), the total cumulative non-carcinogenic health risk for children remained moderate and unacceptable (HI=3.4). It should also be noted

that copper enhances the neurotoxicity induced by zinc (Tanaka et al., 2017).

The contribution to the total cumulative non-carcinogenic health risk depends on the concentration of heavy metals in ambient air (Figure 5 and 6). Based on the risk of developing non-cancer diseases under average atmospheric concentrations, the studied heavy metals are ranked as follows: Cu (72%) > Ni (8%) = Cd (8%) > Mn (6%) > Cr (2%) = Pb (2%) = Zn (2%) (Figure 5).

This distribution varies depending on the specific concentrations of individual heavy metals in the atmosphere. However, Cu, Ni, Mn, and Cd pose the greatest health risks overall, with the following range of contributions: Cu (40–87%) > Ni (3–24%) > Mn (3–16%) = Cd (3–16%) > Cr (1–5%) = Pb (1–5%) = Zn (1–4%).

The dominance of individual metals in the risk structure may vary significantly across different observation zones and time periods. This

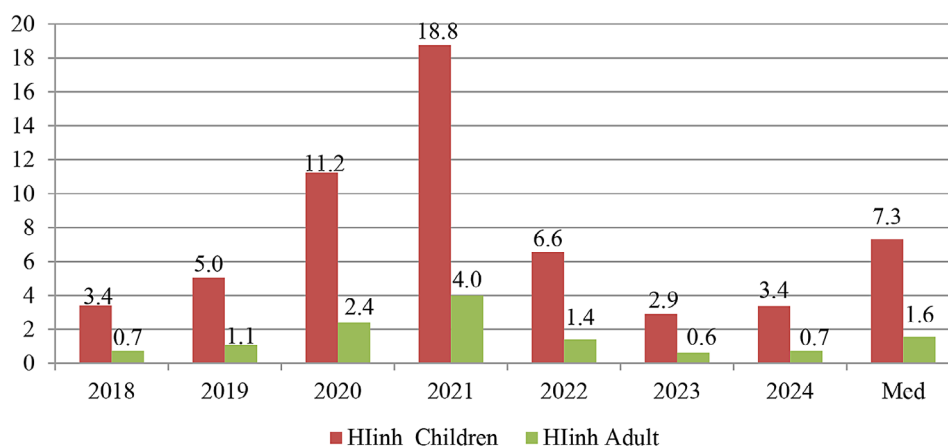


Figure 4. Total cumulative non-carcinogenic health risk for the period 2018–2024

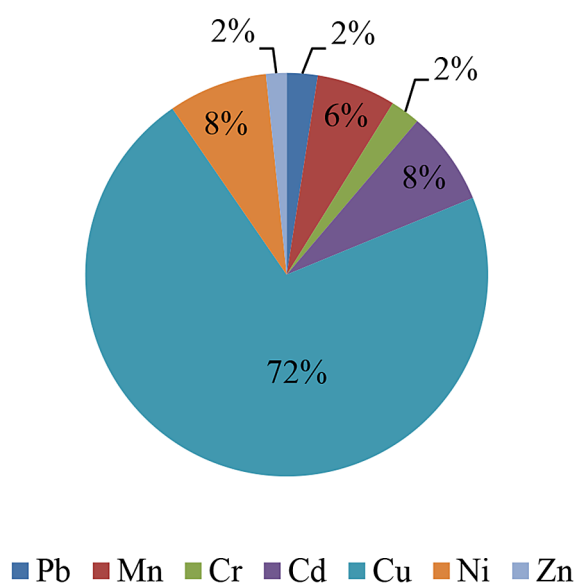


Figure 5. Contribution of heavy metals to the total cumulative non-carcinogenic health risk under average atmospheric concentrations in the city of Cherkasy

indicates the presence of localized sources of pollution, specific to certain areas, and underscores the necessity for continuous monitoring and assessment of potential health threats to the population. Analyzing spatial differences in the composition of health risk allows for more effective planning of environmental protection measures and helps focus efforts on the most problematic regions.

The presence of Ni, Pb, Cd, and Cr in the atmosphere of Cherkasy may contribute to the development of cancer in humans. These heavy metals are classified as potentially carcinogenic compounds (Parida and Patel, 2023). Lead (Pb)

exerts toxic, mutagenic, and carcinogenic effects. Chronic exposure to cadmium (Cd) may promote tumorigenesis in the lungs, kidneys, pancreas, and mammary glands, and increase susceptibility to carcinogenesis in offspring (Cirovic and Satarug, 2024; Ali Hussein et al., 2024).

Excessive exposure to nickel (Ni) may lead to DNA damage, and is associated with lung and nasal cancer in humans (Guo et al., 2023). Hexavalent chromium (Cr (VI)) is a recognized carcinogen with proven mutagenic and genotoxic effects. In recent years, numerous studies have also examined the genotoxicity of trivalent chromium (Cr III) (Sawicka et al., 2023).

The results of the cancer risk assessment (Figure 7) for the population of Cherkasy indicate that only chromium poses a slight carcinogenic risk for both children and adults ($CR = 6.3E-05$ and $CR = 6.7E-05$, respectively). The total cumulative cancer risk (TCR) under combined exposure to the studied heavy metals ($TCR = 7.1E-05$ for children and $TCR = 7.6E-05$ for adults) also remains low and within acceptable levels of carcinogenic risk (Figure 7).

The main contributors to the total cumulative carcinogenic health risk are: Cr (81–92%), Cd (5–16%), and Ni (2–5%).

The carcinogenic properties of Cr(VI), as well as the potential genotoxicity of Cr(III), indicate that even low concentrations of chromium in the environment may have long-term adverse effects under conditions of prolonged (chronic) exposure. This is especially relevant for vulnerable population groups, such as children, whose protective mechanisms are not yet fully developed.

Therefore, the risk assessment results emphasize the necessity of continued regular monitoring

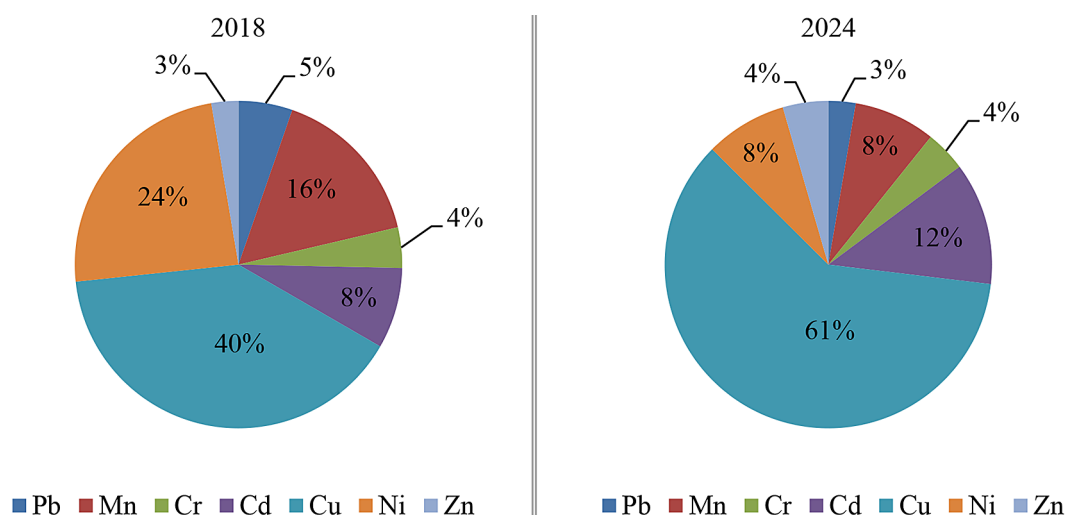


Figure 6. Contribution of heavy metals to the total cumulative non-carcinogenic health risk in 2018 and 2024

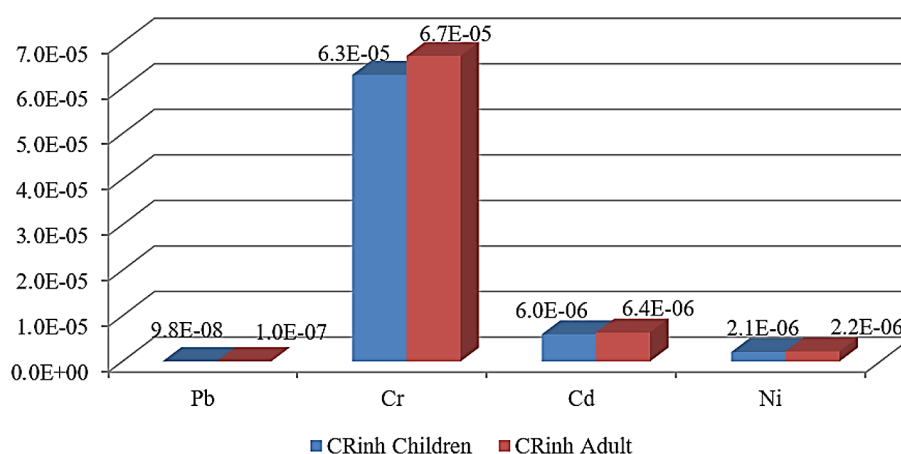


Figure 7. Cancer risk assessment

of chromium and other toxic metal concentrations in the city's air, as well as the importance of implementing preventive measures in public health and environmental management.

The obtained results highlight the necessity of identifying and detecting aerotechnogenic sources of heavy metal pollution in the urban landscapes of Cherkasy. This will facilitate the development of effective measures to reduce technogenic pressure on the city's ecosystems and improve public health.

A bibliosemantic analysis of current scientific literature has shown that the sources of heavy metal emissions vary significantly across different regions. In urban environments, these metals can be released into the atmosphere in considerable amounts due to fossil fuel combustion by energy facilities, industrial activities, and motor vehicles, as well as from brake materials (Cu,

Sb, Si, Fe) and tire wear (Zn) from automobiles (Mahmoud et al., 2023).

Electronic and electrical waste, particularly portable batteries and accumulators, along with improper disposal methods, are sources of heavy metals such as Ni, Pb, Cd, and Cr found in landfills (Dockrell et al., 2023).

A significant source of heavy metal emissions (Zn, Cr, Ni, Pb, Cu, and Mn) in Cherkasy is the thermal power plant (TPP), which primarily operates on coal. Cr, Ni, Zn, and Pb are also generated from fuel combustion by motor vehicles, as well as from the normal operational wear of wheel chassis tires and brake pads during vehicle movement.

Previous research (Mislyuk et al., 2023) has demonstrated that significant carcinogenic health risks to the population are also posed by soot and formaldehyde found in vehicle emissions. This

increases the total cumulative risk of developing cancer in Cherkasy under simultaneous exposure to the studied heavy metals, soot, and formaldehyde. Over the past five years, formaldehyde concentrations in the city have increased by 1.5 times. Considering the rising trend in this toxic gas and the high levels of nitrogen dioxide, which acts as a carcinogenesis modifier, rigorous monitoring of atmospheric pollution levels is required.

It should be noted that according to statistical data, respiratory diseases dominate other disease classes in Cherkasy, accounting for 58%. In the overall mortality structure, diseases of the circulatory system rank first (59.1%), followed by neoplasms in second place (18.8%). The incidence rate of malignant neoplasms exceeds the national average in Ukraine, including among the pediatric population. Over the last three years, the cancer incidence rate per 10,000 population has increased by 20% and is 64% higher than the national average. According to medical forecasts, the incidence rate is expected to exceed 50,000 cases next year.

Thus, the population of the city faces a risk of deteriorating health due to respiratory system pathologies and cancer. The results emphasize the need to improve air quality in Cherkasy and to consider health risks associated with inhalation of heavy atmospheric metals, which may be crucial for informed decision-making in environmental protection and public health management.

There is a pressing need for broader implementation of real-time monitoring systems and predictive models of heavy metal concentrations based on artificial intelligence, alongside comprehensive studies to identify pollution sources and assess their contribution to atmospheric contamination in industrialized cities. The establishment of effective environmental monitoring systems, transition to environmentally friendly industrial technologies, adoption of electric transport, and the use of cleaner heavy-duty diesel vehicles and low-emission cars will help reduce atmospheric pollution hazards and the population's disease burden.

Limitations of this study include uncertainties regarding the impact of particulate matter (PM_{2.5} and PM₁₀), soot, climate change, and meteorological factors on the estimated health risk level. However, these factors were beyond the scope of the present study and could be addressed in future research.

This study also has certain limitations. The accuracy of risk assessment largely depends on

the availability of key information on pollutant characteristics. There are no standardized values for all parameters used in risk assessment formulas. Specifically, factors such as carcinogenic potential, reference dose, and critical organs and systems are periodically refined and updated. Consequently, values selected by other researchers may yield different risk estimates. Variations in results may also arise from regional features such as topography, meteorological conditions affecting pollutant dispersion, level of industrial development, and differences in heavy metal sources across regions.

CONCLUSIONS

For the first time, this study provides an assessment of both non-carcinogenic and carcinogenic risks associated with heavy metal (Pb, Mn, Cr, Cu, Ni, Zn, and Cd) air pollution in the city of Cherkasy. It was shown that there is a high non-carcinogenic risk of adverse chronic effects in children (HQ = 5.25) and a moderate risk in adults (HQ = 1.12) associated with copper (Cu) concentrations in the ambient air. The total cumulative hazard index is also high for children (HI = 7.33) and moderate for adults (HI = 1.56). The most critical target organs are the respiratory system (HI = 7.14 in children and HI = 1.53 in adults), and the central nervous system in children (HI = 1.23). The overall systemic health impact is assessed as high for children (HI = 5.25) and moderate for adults (HI = 1.12). In terms of the risk of developing non-cancerous diseases, the studied heavy metals, based on their average concentrations in the atmosphere, are ranked as follows: Cu (72%) > Ni (8%) = Cd (8%) > Mn (6%) > Cr (2%) = Pb (2%) = Zn (2%). The total cumulative carcinogenic risk of developing cancer is low (acceptable) for both children (TCR = 7.1E-05) and adults (TCR = 7.6E-05). The main contributors to this risk are Cr (81–92%), Cd (5–16%), and Ni (2–5%). There is a clear need for expanded spatiotemporal monitoring and further research to identify long-term trends in atmospheric pollution and assess the cumulative health impact on the population.

Strict regulatory measures are required to reduce anthropogenic emissions of heavy metals from both stationary and mobile sources, implement environmentally friendly technologies,

manage waste effectively, and develop appropriate risk management strategies. This study provides a valuable resource for informing about ambient air quality with respect to heavy metal content, understanding their health effects, and identifying pollution sources. It supports the development of effective air quality management strategies through the implementation of targeted preventive measures.

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