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INTEGRATED ASSESSMENT OF THE LONG-TERM BIOECOLOGICAL EFFECTS OF ATMOSPHERIC EMISSIONS ON URBAN ECOSYSTEMS AND PUBLIC HEALTH IN INDUSTRIAL AREAS OF UZBEKISTAN

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ABSTRACT

This article presents a comprehensive assessment of the long-term bioecological impacts of atmospheric emissions on urban ecosystems and public health in the industrial regions of Almalyk, Chirchik, and Sergeli. During the study, atmospheric concentrations of PM2.5, PM10, SO_2, NO_2, NH_3, and heavy metal aerosols were monitored. Urban tree species were used as bioindicators to evaluate the ecological condition of the studied areas. GIS-based technologies were applied to develop spatial pollution maps and identify ecological risk zones. The results revealed significant deterioration of air quality in residential areas located near industrial zones. The highest ecological risk was recorded in the Almalyk metallurgical region. The obtained findings contribute to the improvement of bioecological monitoring systems and the development of scientifically grounded strategies aimed at reducing atmospheric emissions in urban-industrial ecosystems.

Introduction. Atmospheric air pollution caused by industrial emissions is considered one of the most critical global problems of modern urban ecology and public health (WHO, 2023). According to the World Health Organization, approximately 4.2 million premature deaths occur worldwide each year due to air pollution. In particular, PM2.5 and PM10 particles, SO_2, NO_2, and heavy metal aerosols are regarded as major environmental factors significantly increasing the risk of cardiovascular, respiratory, and oncological diseases (Loomis et al., 2013).

In recent years, industrial urbanization, increasing traffic intensity, and the rapid development of metallurgical and chemical industries have intensified anthropogenic pressure on atmospheric air in Central Asian countries (European Environment Agency, 2020). Particularly in the major industrial regions of Uzbekistan — Olmaliq, Chirchiq, and Sergeli — the level of technogenic atmospheric pollution has been steadily increasing (Uzgidromet, 2024).

According to monitoring data from the World Bank and Uzgidromet, the annual average PM2.5 concentration in Tashkent ranges between 31.4 and 39.3 μg/m^3, which is 6–8 times higher than the 5 μg/m^3 guideline recommended by the World Health Organization (World Bank, 2022).

The distribution of heavy metals in atmospheric aerosols represents a significant environmental risk factor for urban ecosystem components. Atmospheric metals originate from both natural sources, such as soil erosion and dust storms, and anthropogenic sources including industrial enterprises, traffic emissions, metallurgical plants, and energy facilities (Davidson et al., 2007). The International Agency for Research on Cancer has classified arsenic (As), cadmium (Cd), and several other metals as carcinogenic substances (Straif et al., 2009).

The Olmaliq region is a major center of non-ferrous metallurgy characterized by high emissions of SO_2, Cu, Zn, Pb, and Cd aerosols. In Chirchiq, chemical industries and mineral fertilizer production facilities are major sources of NH_3 and NO_2 emissions. Meanwhile, the Sergeli industrial zone is characterized by elevated PM10, CO, and heavy metal dust concentrations associated with transport emissions, logistics infrastructure, and metal-processing activities.

Atmospheric pollutants exert significant adverse effects on urban ecosystem components, particularly soils, bioindicator plants, and public health. Bioaccumulation of heavy metals in soil and atmospheric dust leads to phytotoxicity, photosynthetic disruption, necrosis, chlorosis, and degradation of urban vegetation (Markert, 2007). Long-term inhalation exposure to PM2.5 and gaseous pollutants has also been identified as an important factor contributing to respiratory diseases (Weinmayr et al., 2018).

In recent years, GIS technologies, bioindication monitoring, and ecological risk assessment models have been widely applied in comprehensive air pollution studies. ArcGIS- and QGIS-based hotspot analysis, spatial interpolation, and pollutant dispersion modelling enable the identification of ecological risk zones within urban-industrial regions (MDPI, 2022). Furthermore, the use of bioindicator plants has been recognized as an effective method for assessing the long-term bioecological impacts of atmospheric pollution (Comess et al., 2021; Lequy et al., 2019).

However, comprehensive studies evaluating the long-term bioecological impacts of atmospheric emissions on urban ecosystems and public health in the industrial regions of Uzbekistan using integrated GIS monitoring, bioindication, heavy metal analysis, and ecological risk assessment remain limited. In particular, scientific data comprehensively assessing the long-term effects of atmospheric pollutants on bioindicator plants, soils, and public health in the industrial regions of Olmaliq, Chirchiq, and Sergeli are insufficient.

Therefore, the aim of this study was to conduct a comprehensive assessment of the long-term bioecological impacts of atmospheric emissions on urban ecosystems and public health in the industrial regions of Almalyk, Chirchik, and Sergeli using integrated ecological monitoring, GIS analysis, bioindication assessment, and ecological risk modelling approaches.

Purpose of the study: The purpose of this study was to conduct a comprehensive assessment of the long-term bioecological impacts of atmospheric emissions on urban ecosystems and public health in the industrial regions of Olmaliq, Chirchiq, and Sergeli by integrating atmospheric pollution monitoring, heavy metal analysis, bioindication methods, GIS-based spatial assessment, and ecological risk evaluation. The study aimed to identify major atmospheric pollutants, determine their spatial distribution patterns, evaluate their effects on bioindicator plants and environmental components, assess associated ecological and health risks, and provide a scientific basis for improving environmental monitoring systems and developing sustainable pollution mitigation strategies in urban-industrial ecosystems of Uzbekistan.

Research materials and methods: In the present study, comprehensive ecological, laboratory, bioindication, GIS-based, and statistical approaches were applied to assess the long-term bioecological impacts of atmospheric emissions on urban ecosystems and public health in the industrial regions of Olmaliq, Chirchiq, and Sergeli.

Study areas. The study areas included: the Almalyk mining-metallurgical region;

the Chirchik chemical-industrial zone; the Sergeli industrial area.

Monitoring sites were established near industrial enterprises, residential zones, and control territories.

The study was conducted during 2024–2025. Atmospheric air, soil, and bioindicator plant sampling was performed three times during each season. Monitoring activities were carried out during morning, daytime, and evening periods.

A total of 408 environmental samples were collected during the study, including: atmospheric air samples — 192 (n = 192); soil samples — 72 (n = 72); bioindicator plant samples — 144 (n = 144).

Monitoring points were located at distances of 0.5 km and 3 km from industrial enterprises, as well as within residential and control zones.

Atmospheric air monitoring. Concentrations of PM2.5, PM10, SO_2, NO_2, NH_3, and CO in atmospheric air were determined using stationary and mobile monitoring methods. Sampling was conducted considering both seasonal and diurnal variations.

PM fractions were determined using the gravimetric filtration method.

The obtained results were expressed in $\mu g/m^3$.

Heavy metal analysis. Concentrations of Pb, Cd, Cu, Zn, As, and Ni in soil and plant samples were determined using Atomic Absorption Spectrometry (AAS) and ICP-MS (Agilent ICP-MS) methods. Prior to analysis, samples were dried, homogenized, and mineralized under laboratory conditions.

Bioindication assessment. Plane tree (*Platanus orientalis*), poplar (*Populus spp.*), and juniper (*Juniperus spp.*) species were used as bioindicators. The following bioindication parameters were evaluated: dust deposition on leaf surfaces; necrosis; chlorosis; leaf deformation; pigmentation disorders. Dust deposition on leaf surfaces was determined using the gravimetric method: Results were expressed in mg/cm^2.

GIS analysis. Geographical coordinates of monitoring sites were determined using GPS devices. ArcGIS and QGIS software were applied to develop: pollutant dispersion models; hotspot analysis; spatial interpolation maps; ecological risk zoning maps. Spatial analysis was used to evaluate pollutant dispersion patterns according to dominant wind directions.

Ecological risk assessment. Ecological risk was assessed using inhalation exposure, non-carcinogenic risk (HQ), and carcinogenic risk (CR) models.

Values of $HQ > 1$ were considered indicative of significant ecological health risks.

Statistical analysis. Statistical analyses were performed using SPSS, R Studio, and Microsoft Excel software. Pearson correlation analysis was applied to assess relationships between atmospheric pollutants, heavy metal accumulation, bioindicator plant damage, and respiratory diseases.

Results. Results of atmospheric air analysis. The analysis of atmospheric air samples demonstrated that the highest concentrations of SO_2 and PM10 were recorded in the Olmaliq region. The average SO_2 concentration reached 61.4 ± 7.2 µg/m^3, which was associated with metallurgical activities and sulfide ore processing operations.

Table 1

Atmospheric Air Monitoring Results in Industrial Regions

Region	**PM2.5 (µg/m^3)**	**PM10 (µg/m^3)**	**SO_2 (µg/m^3)**	**NO_2 (µg/m^3)**	**NH_3 (µg/m^3)**	**CO (mg/m^3)**
Almalyk	19.8 ± 2.1	74.2 ± 8.6	61.4 ± 7.2	39.8 ± 4.5	15.2 ± 2.1	3.1 ± 0.4
Chirchik	19.9 ± 1.9	43.8 ± 6.2	34.6 ± 4.8	47.3 ± 5.4	58.1 ± 6.9	2.7 ± 0.3
Sergeli	16.0 ± 1.8	72.1 ± 9.1	11.0 ± 2.4	42.1 ± 4.9	17.4 ± 2.6	4.3 ± 0.5
Bostanliq foothill area (control zone)	5.8 ± 0.7	16.8 ± 2.4	4.1 ± 0.8	9.7 ± 1.5	4.2 ± 0.9	0.7 ± 0.1

In the Chirchiq region, NH_3 and NO_2 concentrations were higher compared to the other study areas. The average NH_3 concentration reached 58.1 ± 6.9 µg/m^3. This was associated with emissions originating from chemical industries and nitrogen fertilizer production facilities.

In the Sergeli industrial zone, elevated concentrations of PM10 and CO were observed. The average PM10 concentration reached 72.1 ± 9.1 µg/m^3. These results were associated with urban-industrial dust, vehicle emissions, and metal-processing activities.

In the Bostanliq foothill area selected as the control zone, all pollutant concentrations were significantly lower compared to the industrial regions. The average PM2.5 concentration was 5.8 ± 0.7 μg/m^3, indicating relatively clean environmental conditions in this territory.

The determination of heavy metal concentrations in atmospheric dust and soil samples using AAS and ICP-MS methods demonstrated a high level of technogenic pollution in industrial regions. Uneven spatial distribution of Pb, Cd, Cu, Zn, As, and Ni was observed among the investigated territories.

The highest concentrations of all heavy metals were recorded in the Olmaliq region. Particularly high levels of Cu — 524 ± 68 mg/kg, Zn — 612 ± 84 mg/kg, and Pb — 182 ± 24 mg/kg were detected. These findings were associated with mining-metallurgical activities, copper smelting processes, sulfide ore processing, and emissions of metallurgical aerosols and dust particles. Extremely high Cu and Zn concentrations indicated long-term accumulation of metallurgical dust in soil and atmospheric deposits. Increased Cd and As concentrations further confirmed the presence of toxic technogenic pressure. The elevated heavy metal concentrations observed in the Almalyk region may contribute to bioaccumulation, phytotoxicity, soil degradation, and increased respiratory ecological risks within urban ecosystems.

In the Chirchiq region, Zn — 148 ± 18 mg/kg, Cu — 96 ± 12 mg/kg, and Pb — 71 ± 9 mg/kg were recorded. Since Chirchik is primarily a chemical-industrial center, chemical technogenic pressure rather than metallurgical pollution predominated. Therefore, Pb concentrations were lower compared to the Sergeli region. Emissions associated with mineral fertilizer production, nitrogen compounds, and urban-industrial dust contributed to the accumulation of heavy metals in atmospheric dust. Cd concentrations exceeding the control zone by several times were considered an important ecological risk factor.

In the Sergeli region, Pb — 94 ± 11 mg/kg, Zn — 176 ± 21 mg/kg, and Ni — 41 ± 5 mg/kg were detected. Higher Pb and Zn concentrations compared to Chirchik were associated with intensive vehicle traffic, logistics infrastructure, urban-industrial dust, and metal-processing activities.

As Sergeli represents one of the major transport-industrial hubs of Tashkent, the ecological impact of vehicle emissions was found to be particularly significant.

In the Bostanliq foothill control area, all heavy metal concentrations remained minimal: Pb — 19 ± 3 mg/kg, Cu — 26 ± 4 mg/kg, and Zn — 42 ± 5 mg/kg. The low concentrations in this territory were associated with the absence of major industrial emissions, effective air circulation, low urban technogenic pressure, and preservation of the natural geochemical background.

According to the results presented in Figure 1, the highest concentrations of heavy metals were recorded in the Olmaliq industrial region. Particularly elevated levels of Zn (612 ± 84 mg/kg), Cu (524 ± 68 mg/kg), and Pb (182 ± 24 mg/kg) indicated intensive metallurgical and mining-related emissions. In contrast, the control zone demonstrated significantly lower heavy metal concentrations, reflecting relatively unpolluted environmental conditions.

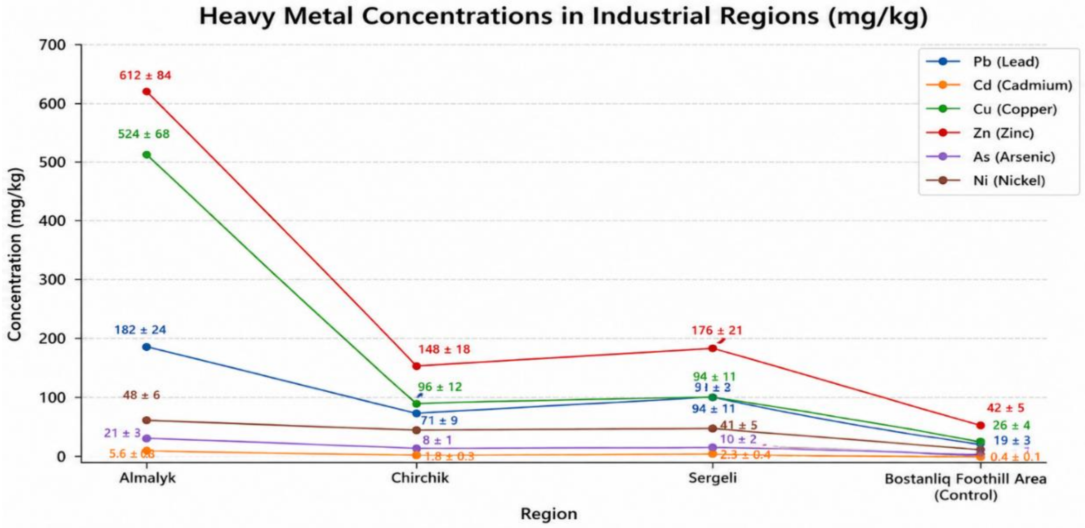


Figure 1. Heavy Metal Concentrations in Atmospheric Dust and Soil Samples (mg/kg)

Bioindication studies revealed visible morphological symptoms of atmospheric pollution in bioindicator plants including plane tree (*Platanus orientalis*), poplar (*Populus spp.*), and juniper (*Juniperus spp.*). Dust accumulation on leaf surfaces was determined using the gravimetric method. Necrosis, chlorosis, leaf deformation, and pigmentation disorders were more pronounced in industrial territories compared to the control zone.

Table 2.

Dust Deposition and Morphological Damage Indicators in Bioindicator Plants

Region	Leaf Dust Deposition (mg/cm²)	Necrosis (%)	Chlorosis (%)	Leaf Deformation (%)	Pigmentation Disorder (%)
Olmaliq	2.84 ± 0.32	38.6	42.1	24.8	46.3
Chirchiq	1.96 ± 0.24	27.4	35.2	18.6	39.7
Sergeli	2.21 ± 0.28	31.8	33.6	21.4	37.2
Bostanliq foothill area (control zone)	0.68 ± 0.11	6.4	8.2	4.1	9.5

According to the results of the bioindication monitoring, dust deposition on plant leaf surfaces in industrial regions was significantly higher compared to the control area. The highest dust accumulation was recorded in the Olmaliq region, reaching 2.84 ± 0.32 mg/cm². This value was approximately 4.2 times higher than that observed in the Bostanliq control zone.

The highest levels of necrosis, chlorosis, and pigmentation disorders were also observed in Almalyk. These findings are associated with the direct effects of metallurgical emissions, SO_2, PM fractions, and heavy metal dust particles on plant leaves.

In the Chirchiq region, elevated chlorosis and pigmentation disorders were detected, which were mainly associated with chemical-industrial emissions, particularly NH_3 and NO_2 pollutants.

In the Sergeli region, leaf dust deposition reached 2.21 ± 0.28 mg/cm^2. This was associated with intensive urban traffic, metal-processing activities, and industrial dust emissions.

The lowest damage indicators in bioindicator plants were observed in the Bostanliq foothill control area. This was explained by the absence of major industrial emissions, higher green biomass coverage, and efficient atmospheric air circulation.

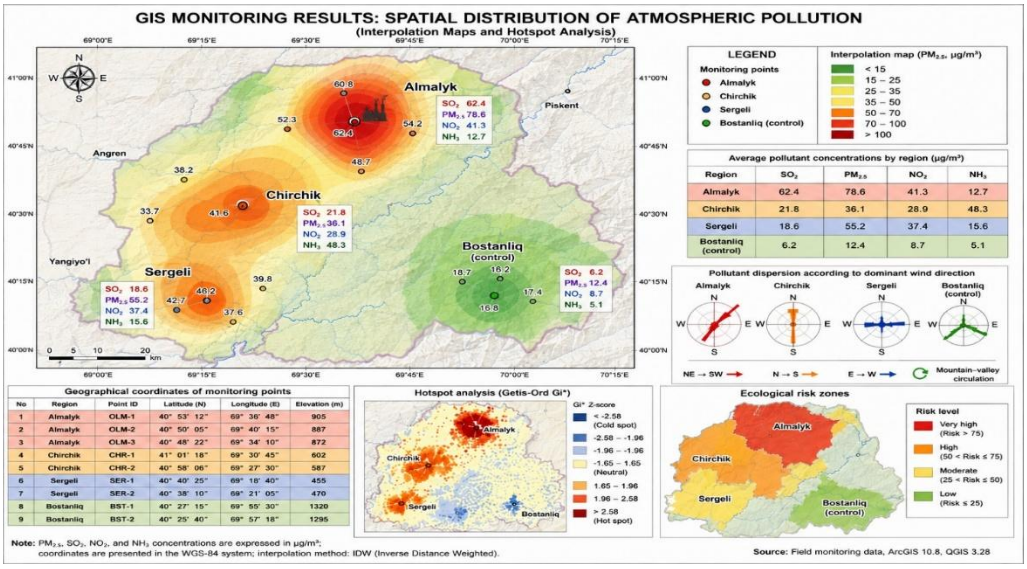
The bioindication results confirmed that atmospheric emissions in industrial regions exert significant negative effects on the morphophysiological condition of urban vegetation. The highest bioecological stress was recorded in the Almalyk region, followed by Sergeli and Chirchik.

According to the GIS-based hotspot analysis, the Olmaliq industrial region was identified as the area with the highest ecological risk associated with atmospheric pollution. Spatial distribution maps demonstrated that the maximum concentrations of SO_2, Cu, Zn, and Pb were concentrated around the metallurgical complex.

The dominant dispersion pathway of pollutants in the Almalyk region was directed from the northeast toward the southwest. A gradual decrease in pollutant concentrations was observed beyond a 5 km radius from the main industrial emission sources.

Chirchik Region. The results obtained in the Chirchiq region revealed that NH_3 and NO_2 represented the major ecological risk factors. GIS maps indicated elevated pollutant concentrations in areas adjacent to chemical-industrial enterprises.

Spatial analysis demonstrated that the dominant pollutant transport direction extended from north to south. Increased NO_2 concentrations were particularly observed in zones located near residential areas.



Average pollutant concentrations by region (µg/m³)

Region	SO_2	$PM_{2.5}$	NO_2	NH_3
Almalyk	62.4	78.6	41.3	12.7
Chirchik	21.8	36.1	28.9	48.3
Sergeli	18.6	55.2	37.4	15.6
Bostanliq (control)	6.2	12.4	8.7	5.1

Geographical coordinates of monitoring points

No	Region	Point ID	Latitude (N)	Longitude (E)	Elevation (m)
1	Almalyk	OLM-1	40° 53' 12"	69° 36' 48"	905
2	Almalyk	OLM-2	40° 50' 05"	69° 40' 15"	887
3	Almalyk	OLM-3	40° 48' 22"	69° 34' 10"	872
4	Chirchik	CHR-1	41° 01' 18"	69° 30' 45"	602
5	Chirchik	CHR-2	40° 58' 06"	69° 27' 30"	587
6	Sergeli	SER-1	40° 40' 25"	69° 18' 40"	455
7	Sergeli	SER-2	40° 38' 10"	69° 21' 05"	470
8	Bostanliq	BST-1	40° 27' 15"	69° 55' 30"	1320
9	Bostanliq	BST-2	40° 25' 40"	69° 57' 18"	1295

Note: $PM_{2.5}$, SO_2, NO_2, and NH_3 concentrations are expressed in µg/m³; coordinates are presented in the WGS-84 system; interpolation method: IDW (Inverse Distance Weighted).

Source: Field monitoring data, ArcGIS 10.8, QGIS 3.28

Figure 1. GIS Monitoring Results: Spatial Distribution of Atmospheric Pollution Almalyk Region

Sergeli Industrial Zone

In the Sergeli industrial zone, significant urban pollution hotspots associated with PM10, Pb, and NO_2 were identified. GIS analysis showed elevated pollutant concentrations near transport highways, logistics centers, and metal-processing facilities.

The dominant pollutant dispersion direction in this territory was determined to be from east to west.

Bostanliq Foothill Area. In the Bostanliq foothill control area, natural mountain–valley air circulation, extensive vegetation cover, and the absence of significant industrial emissions contributed to minimal atmospheric pollutant concentrations.

Table 3

Ecological Risk Indicators of Atmospheric Pollutants

Region	**Average Daily Exposure Dose (ADD) (mg/kg·day)**	**Hazard Quotient (HQ)**	**Carcinogenic Risk (CR)**	**Ecological Risk Level**
Olmaliq	0.0124	2.18	1.7×10^{-4}	Very high
Chirchiq	0.0087	1.46	8.2×10^{-5}	High
Sergeli	0.0093	1.62	9.4×10^{-5}	High
Bostanliq foothill area (control zone)	0.0021	0.41	1.3×10^{-5}	Low

In the Olmaliq region, the inhalation exposure indicator was the highest among all study areas, with an average daily exposure dose (ADD) of 0.0124 mg/kg·day. The non-carcinogenic hazard quotient reached HQ = 2.18, exceeding the critical threshold value of HQ > 1, indicating the presence of significant ecological health risks for the local population.

The carcinogenic risk value was recorded at $CR = 1.7 \times 10^{-4}$, suggesting a potential long-term oncological risk associated with chronic inhalation exposure. The elevated ecological risk in the Almalyk region was mainly associated with SO_2, PM2.5, Cu, and Pb aerosols.

In the Chirchiq region, the average daily exposure dose (ADD) was 0.0087 mg/kg·day, while the hazard quotient reached HQ = 1.46, indicating a high level of non-carcinogenic ecological risk. The major ecological risk factors in this territory were identified as NH_3, NO_2, and chemical aerosols.

The carcinogenic risk value was estimated at 8.2×10^{-5}, classifying the area as a moderate ecological risk zone.

In the Sergeli region, inhalation risk indicators were elevated due to transport emissions, urban dust, NO_2, and PM10 pollution. The hazard quotient reached HQ = 1.62, confirming the presence of non-carcinogenic ecological risks for public health. The carcinogenic risk value was estimated at 9.4×10^{-5}, indicating the existence of long-term urban-industrial environmental risks.

In the Bostanliq foothill control area, the hazard quotient remained low (HQ = 0.41), indicating minimal ecological risk. The carcinogenic risk value was also low, and no significant adverse impacts of atmospheric pollutants on public health were observed.

Pearson Correlation Analysis Results. Relationships among atmospheric pollutants, bioindicator plant conditions, heavy metal concentrations, and respiratory diseases were evaluated using the Pearson correlation coefficient.

Table 4

Pearson Correlation Between Atmospheric Pollutants and Bioecological Indicators

Indicators	**r**	**p**	**Correlation Strength**
PM2.5 — respiratory diseases	0.81	<0.001	Very strong positive
PM10 — leaf dust deposition	0.78	<0.001	Strong positive
SO_2 — leaf necrosis	0.76	<0.001	Strong positive
NH_3 — chlorosis	0.69	<0.01	Moderate-to-strong positive
NO_2 — respiratory diseases	0.66	<0.01	Moderate-to-strong positive
Pb — pigmentation disorder	0.79	<0.001	Strong positive
Cu — leaf deformation	0.73	<0.001	Strong positive
Zn — leaf dust deposition	0.68	<0.01	Moderate-to-strong positive
Cd — respiratory diseases	0.57	<0.05	Moderate positive
Ni — necrosis	0.63	<0.01	Moderate-to-strong positive

The Pearson correlation coefficients demonstrated significant relationships between atmospheric pollutants and bioecological indicators. The highest correlations were observed between PM2.5 and respiratory diseases ($r = 0.81$), Pb and pigmentation disorders ($r = 0.79$), and PM10 and leaf dust deposition ($r = 0.78$). These findings indicate that atmospheric aerosols and heavy metals represent substantial ecological risk factors for urban ecosystems, bioindicator plants, and public health.

The strong relationship between SO_2 and leaf necrosis confirmed the phytotoxic effects of sulfur-containing gases. The associations of NH_3 and NO_2 with chlorosis and respiratory diseases highlighted the significant bioecological role of chemical-industrial and transport-related emissions.

Discussion. The findings of the present study confirmed that atmospheric emissions in the industrial regions of Olmaliq, Chirchiq, and Sergeli exert significant bioecological impacts on urban ecosystems and public health. Increased concentrations of PM2.5, PM10, SO_2, NO_2, and NH_3 were statistically associated with bioindicator plant damage, heavy metal accumulation in soils, and respiratory disease incidence.

The highest atmospheric pollution levels were recorded in the Almalyk region. Elevated concentrations of PM10, SO_2, Cu, and Zn aerosols indicated the dominant influence of metallurgical emissions in this territory. High concentrations of Cu (524 ± 68 mg/kg) and Zn (612 ± 84 mg/kg) in atmospheric dust and soil samples reflected the long-term technogenic impact of non-ferrous metallurgical activities. These findings are consistent with international studies reporting intensive heavy metal bioaccumulation in metallurgical regions (*Science of The Total Environment*, 2021).

In the Chirchik region, elevated NH_3 and NO_2 concentrations were associated with chemical-industrial and mineral fertilizer production activities. Increased NH_3 concentrations showed significant correlations with chlorosis and pigmentation disorders in bioindicator plants ($r = 0.69$; $p < 0.01$), confirming the adverse physiological effects of gaseous pollutants on urban vegetation.

In the Sergeli industrial zone, increased PM10 and CO concentrations were associated with urban transport systems and logistics activities. Higher levels of atmospheric dust accumulation and necrosis were observed in this territory compared to other regions. The strong positive correlation between PM10 and leaf dust deposition ($r = 0.78$; $p < 0.001$) demonstrated the direct impact of atmospheric aerosols on urban bioindicator plants.

Pearson correlation analysis revealed strong statistical relationships between atmospheric pollutants, bioindication parameters, and respiratory diseases. Particularly high correlations were identified between PM2.5 and respiratory diseases ($r = 0.81$; $p < 0.001$), supporting previous epidemiological studies that identified PM2.5 as a major environmental health risk factor (Loomis et al., 2013).

Heavy metals also demonstrated significant impacts on bioindicator plant conditions. Strong positive correlations were identified between Pb and pigmentation disorders ($r = 0.79$; $p < 0.001$), as well as between Cu and leaf deformation ($r = 0.73$; $p < 0.001$). These findings confirmed the phytotoxic effects of heavy metals on urban vegetation.

GIS-based spatial analysis demonstrated elevated concentrations of atmospheric pollutants and heavy metals in areas adjacent to industrial zones. Spatial interpolation models showed that pollutants dispersed from industrial territories toward residential areas according to dominant wind directions. Expansion of ecological risk zones was particularly observed in the Almalyk and Chirchik regions.

Ecological risk assessment indicated elevated inhalation exposure levels in several industrial territories. HQ values exceeding 1 demonstrated the presence of significant non-carcinogenic ecological risks for public health. These findings highlight the necessity of strengthening atmospheric monitoring systems, reducing industrial emissions, and improving urban ecological management strategies.

The present study represents one of the first comprehensive investigations in Uzbekistan integrating GIS monitoring, bioindication, heavy metal analysis, and ecological risk assessment to evaluate the long-term bioecological impacts of atmospheric emissions on urban ecosystems and public health. The obtained results may serve as an important scientific and practical basis for atmospheric pollution monitoring, ecological risk zoning, and environmental safety management in urban-industrial regions.

First, the implementation of modern gas-cleaning and dust-capturing technologies at industrial enterprises is of critical importance for reducing atmospheric emissions. In particular, the application of electrostatic precipitators, cyclone separators, HEPA filters, and desulfurization systems in metallurgical and chemical industries could substantially decrease SO_2, PM10, and heavy metal aerosol emissions into the atmosphere.

In urban territories, the development of environmentally friendly public transportation systems, increased use of electric vehicles, establishment of green transport corridors, and reduction of traffic congestion represent important ecological measures for decreasing transport-related emissions. Elevated PM10 and CO concentrations observed in the Sergeli industrial zone highlighted the significant ecological pressure associated with urban transport systems.

Green spaces and bioindicator trees play an essential role in the natural biological filtration of atmospheric air. Trees are capable of trapping dust particles, absorbing CO_2, producing oxygen, accumulating heavy metal aerosols, and improving the urban microclimate.

Bioindicator species used in this study, including plane tree (*Platanus orientalis*), poplar (*Populus spp.*), and juniper (*Juniperus spp.*), demonstrated high efficiency in trapping atmospheric dust and reducing urban aerosol loads. The broad leaf surface of plane trees particularly enhances the accumulation of PM10 and heavy metal particles, while juniper species effectively capture atmospheric aerosols throughout the year due to their needle-like structure.

The establishment of green protective zones in urban territories is considered an effective ecological approach for reducing atmospheric pollution. Multi-row tree plantations, phytomeliorative green corridors, and urban green buffer zones surrounding industrial enterprises can significantly reduce pollutant dispersion toward residential areas.

The development of GIS-based monitoring systems also represents an important component of environmental management. Real-time monitoring, hotspot analysis, pollutant dispersion modelling, and ecological risk zoning systems enable effective spatial control of atmospheric pollution.

To protect public health in industrial territories, it is necessary to strengthen respiratory disease monitoring, biomonitoring programs, and ecological epidemiological surveillance. Improving sanitary-hygienic monitoring is particularly important in regions characterized by long-term inhalation exposure to PM2.5 and heavy metal aerosols.

Furthermore, the use of renewable energy sources, implementation of environmentally friendly industrial technologies, reduction of industrial waste, and strengthening of environmental regulations represent priority directions for reducing atmospheric pollution in urban-industrial territories.

Overall, the expansion of green plantations, implementation of modern ecological monitoring systems, and control of industrial emissions are of considerable scientific and practical importance for improving atmospheric air quality and ensuring the ecological sustainability of urban ecosystems.

Conclusions: The results of the present study confirmed that atmospheric emissions in the industrial regions of Olmaliq, Chirchiq, and Sergeli exert significant bioecological impacts on urban ecosystems and public health. The highest levels of atmospheric pollution and ecological risk were recorded in the

Almalyk region. Increased concentrations of PM2.5, PM10, SO_2, and heavy metal aerosols demonstrated strong statistical relationships with bioindicator plant damage, heavy metal accumulation in soils, and respiratory diseases.

GIS monitoring and hotspot analysis revealed the formation of ecological risk zones surrounding industrial territories. Ecological risk assessment showed HQ values exceeding 1 in several regions, indicating the presence of significant non-carcinogenic risks to public health.

The obtained findings highlight the necessity of reducing atmospheric emissions, expanding urban green buffer zones, improving bioindication monitoring systems, and strengthening urban ecological management strategies. This study has important scientific and practical significance for the comprehensive assessment of atmospheric pollution in industrial regions using integrated GIS technologies, bioindication approaches, and ecological risk assessment models.

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