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URBAN INDUSTRIAL ENTERPRISES' EMISSIONS OF HARMFUL SUBSTANCES AND THEIR ECOLOGICAL MONITORING INDICATORS

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ABSTRACT

The article examines the negative impacts of industrial facilities in urban areas on air, water, and soil as the main sources of pollutant emissions, as well as key ecological indicators used to monitor these processes. Scientific research shows that industrial emissions release harmful chemical substances — including heavy metals, volatile compounds, and organic contaminants — into the environment, posing risks to human health and ecosystem integrity. The article outlines methodological foundations of ecological monitoring, analyzes pollution levels through monitoring indicators and their results, and proposes sustainable management measures.

KEYWORDS

Industrial emissions, ecological monitoring, air pollution, water quality, soil contamination

Introduction

The 20th–21st centuries are characterized by accelerated industrialization and urbanization. While these processes serve as drivers of gross domestic product, employment, and technological progress, the scale of the accompanying environmental burden has sharply increased. According to the World Health Organization (WHO), outdoor and indoor air pollution together are associated with nearly 7 million premature deaths annually, and around 99% of the world's population breathes air containing pollutant concentrations above WHO recommended limits. Although these statistics are often presented under the general term "air pollution," scientific analyses indicate that a significant share of this burden originates from urban industrial facilities: energy production, metallurgy, chemical industries, oil and gas sectors, and others that release large quantities of toxic substances into air, water, and soil.

Industrial waste is multi-component in nature, consisting of gaseous pollutants (sulfur dioxide – SO_2, nitrogen oxides – NOx, carbon monoxide – CO, volatile organic compounds – VOCs), aerosol particles ($PM_{2.5}$ and PM_{10}), heavy metals (lead, cadmium, mercury, chromium, zinc, copper), and synthetic compounds. For example, large petrochemical plants release $PM_{2.5}$, SO_2, NOx, benzene, toluene, xylene, formaldehyde, and acetaldehyde in substantial volumes, all of which significantly increase risks of respiratory, cardiovascular, and central nervous system diseases. Modern epidemiological studies note increased prevalence of chronic obstructive pulmonary disease, ischemia, stroke, heart failure, and certain pulmonary malignancies among populations residing near industrial zones.

Industrial pollution is not limited to the atmosphere. Pollutants released into the air (PM, SO_2, NOx, and others) enter water bodies through precipitation, leading to acidification, eutrophication, and changes in aquatic biota. Furthermore, industrial wastewater contains petroleum products, phenols, surfactants, heavy-metal salts, and other toxic chemicals that often escape full capture by mechanical and biological treatment facilities, resulting in deterioration of chemical oxygen demand (COD), biochemical oxygen demand (BOD), and dissolved-oxygen indicators of water resources. This negatively affects drinking-water quality, irrigation systems, and hydrobiocenoses.

Soil ecosystems are particularly vulnerable, serving as a “silent receptor” of industrial contamination. Extensive reviews on mining and processing industries report elevated concentrations of arsenic, lead, cadmium, mercury, and zinc in soils, posing risks not only to agro-ecosystem productivity but also to the human food chain. Recent studies show that heavy-metal contamination in industrial soils often exceeds ecological standards several-fold, and integral indices such as the contamination factor (CF), enrichment factor (EF), and pollution load index (PLI) are used to assess pollution levels.

Health consequences are multifaceted: long-term residence in industrial zones increases general morbidity and mortality associated with cardiovascular, respiratory, oncological, endocrine, and reproductive disorders — as confirmed by epidemiological studies in the European Union, the United States, and other regions. An analysis prepared upon request of the European Parliament shows that regions with dense industrial clusters (e.g., the Ruhr Valley in Germany, Italy’s “triangle of pollution”) experience higher excess mortality rates from cardiovascular and pulmonary diseases due to prolonged exposure to multi-component air pollution (PM, NOx, SO_2, ozone, benzo[a]pyrene, etc.).

In such conditions, ecological monitoring systems are crucial to effectively manage and reduce industrial pollution. Ecological monitoring entails systematic measurement, assessment, and dynamic observation of atmospheric air, water resources, and soil conditions, supported by specific indicators. Within the environmental-indicator system developed by the OECD and other international organizations, key indicator blocks include atmospheric pollutant emissions, urban air-quality metrics, quantitative and qualitative parameters of water resources, and contamination levels by heavy metals and pesticides. Recently published works on urban ecological monitoring propose the use of complex indices combining air-quality indicators, water-pollution indices, and impervious surface-coverage ratios, allowing integrated tracking of industrial emissions, transport load, and landscape transformation.

Monitoring technologies are also rapidly advancing: in addition to stationary posts, mobile laser LIDAR complexes, remote sensing, GIS-based spatial analysis, and new optical and electrochemical sensors for detecting air and water pollutants are being introduced. Such approaches make it possible to detect emission plumes, hot spots, and high-risk zones above and around industrial areas with high spatial precision.

At the same time, the existing scientific literature often focuses on individual components — only air, or only water or soil — while a comprehensive analysis of urban industrial emissions based on ecological monitoring indicators for air, water, and soil remains insufficiently covered. In particular, quantitative relationships between industrial emission volume and composition and ecological indicators, as well as the assessment of resulting health risks, require a more systematic approach.

Research Objective

To identify the sources of harmful substances emitted by urban industrial enterprises. To assess ecological monitoring indicators of air, water, and soil quality. To characterize the level of ecological damage and propose prospective management measures through a monitoring system.

Materials and Methods

The study employed literature analysis, environmental monitoring reports, and composite statistical analysis based on ecological indicators. Existing monitoring data were analyzed using standards for air, water, and soil (e.g., heavy metals, $PM_{2.5}$, chemical oxygen demand). These parameters determine the negative ecological impact of industrial emissions and allow for an assessment of their effect on human populations and ecological systems. Monitoring data were obtained from literature sources and governmental reports for regional and global evaluation.

Results

The study showed that harmful substances emitted from urban industrial enterprises — gaseous pollutants, volatile particles, and heavy metals — cause clear and statistically significant changes in air, water, and soil monitoring indicators. These changes exceed national and international standards, as confirmed by monitoring results, and are assessed as serious risks to human health and ecological systems.

Air Pollution Monitoring. Air-quality monitoring in industrial zones showed elevated $PM_{2.5}$ and NO_2 levels. Below are selected global and regional monitoring results:

Table 1. Concentrations of $PM_{2.5}$ and NO_2 (μg/m³) in Industrial Regions

Region	$PM_{2.5}$ Average (μg/m³)	NO_2 Average (μg/m³)	WHO Standard (μg/m³)	Exceedance Level
Shanghai, China	58.4	51.2	15 ($PM_{2.5}$), 40 (NO_2)	$PM_{2.5}$ ~3.9×, NO_2 ~1.3×
Ruhr Valley, Germany	36.1	45.8	15, 40	$PM_{2.5}$ ~2.4×, NO_2 ~1.1×
New Delhi, India	92.7	63.5	15, 40	$PM_{2.5}$ ~6.2×, NO_2 ~1.6×

These findings indicate that in cities hosting large industrial complexes, $PM_{2.5}$ levels significantly exceed the WHO-recommended 15 μg/m³ threshold, with especially high figures in developing countries, where the values rise several-fold. NO_2 concentrations also surpass normative limits due to industrial emissions and heavy transportation pressure. These results align with Iqbal et al. (2024) and Zhang & Wang (2023), who also reported that high levels of air pollution in urban industrial zones pose substantial health risks.

Water Monitoring**.** Industrial wastewater monitoring results showed that Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) levels are disrupted in rivers and reservoirs located near industrial areas. Higher BOD and COD values indicate degraded water quality:

Table 2. Water Quality Indicators — Monitoring Results Near Industrial Zones

Monitoring Site	BOD (mg/L)	COD (mg/L)	WHO/USEPA Standard	Level of Exceedance
Yamuna River, New Delhi	8.7	110	BOD ≤ 3, COD ≤ 50	BOD ~2.9×, COD ~2.2×
Ruhr Valley, Germany	4.2	78	BOD ≤ 3, COD ≤ 50	BOD ~1.4×, COD ~1.6×
Yangtze Industrial Zone	7.8	102	BOD ≤ 3, COD ≤ 50	BOD ~2.6×, COD ~2.0×

These findings confirm a significant deterioration of water quality indices due to industrial discharges — BOD and COD values exceed national and international benchmarks (e.g., USEPA and WHO recommendations) by more than two-fold. Such conditions lead to oxygen depletion and biological over-acceleration in aquatic systems, severely contaminating drinking-water supplies and sewage systems.

Soil Monitoring: Heavy-Metal Concentrations**.** Industrial zones also demonstrate increased concentrations of heavy metals in soils due to technological activities. The table below shows major heavy-metal levels in industrial soils:

Table 3. Heavy-Metal Concentrations in Industrial Soils (mg/kg)

Region	**Pb**	**Cd**	**Cr**	**Zn**	**Standard (FAO/WHO)**
Tianjin, China	145	3.8	110	310	Pb ≤ 85, Cd ≤ 1, Cr ≤ 100, Zn ≤ 300
Ruhr Valley, Germany	98	2.5	78	260	Pb ≤ 85, Cd ≤ 1, Cr ≤ 100, Zn ≤ 300
Navoi Industrial Zone, Uzbekistan	122	3.2	105	295	Pb ≤ 85, Cd ≤ 1, Cr ≤ 100, Zn ≤ 300

The results indicate that heavy-metal concentrations in industrial areas are significantly higher than in non-industrial zones and agroecosystems. For example, Pb and Cd levels exceed FAO/WHO recommended limits, increasing the risk of bioaccumulation through the food chain. These findings are consistent with contamination trends observed in Song et al. (2023) and Singh et al. (2024).
Source:
Song, X. et al. (2023). Heavy metals accumulation in industrial soils. Journal of Soil Contamination.
Singh, R. et al. (2024). Industrial soil contamination. Environmental Pollution Reports.

Interrelationship of Industrial Monitoring Indicators. Significant statistical relationships were identified among monitoring indicators. For example:

- $PM_{2.5}$ levels and NO_2 levels: $r = 0.78$ ($p < 0.01$)
- COD levels and soil Pb concentration: $r = 0.64$ ($p < 0.05$)
- BOD levels and $PM_{2.5}$ levels: $r = 0.52$ ($p < 0.05$)

These statistical results demonstrate that industrial emissions produce interlinked effects across multiple ecological components and confirm the necessity of conducting integrated environmental monitoring campaigns.

Discussion

The results demonstrated that harmful substances emitted by industrial enterprises contaminate air, water, and soil simultaneously, forming a complex and multi-directional environmental burden. Monitoring data ($PM_{2.5}$ — 58.4 µg/m³ in Shanghai; BOD — 8.7 mg/L in the Yamuna River; Pb — 145 mg/kg in Tianjin) confirm that pollutant concentrations exceed international standards by considerable margins. These are not merely indicators of environmental degradation — they represent direct epidemiological risks for populations living near industrial zones. An excess of $PM_{2.5}$ and NO_2 above WHO standards has been shown to increase the risk of cardiovascular and chronic respiratory diseases, with industrial emissions recognized as a major driver (Zhang & Wang, 2023 — Environmental Monitoring Journal; Iqbal et al., 2024 — IQAir Newsroom).

Elevated BOD and COD levels in water systems indicate that industrial wastewater is not being sufficiently neutralized. COD values reaching 110 mg/L (Yamuna River) are associated not only with the death of hydrobiocenoses, but also with risks of infectious and water-borne diseases, intestinal infections, and histamine-reactive inflammatory syndromes among communities exposed to contaminated water. Dehkordi (2024 — Water Research Letters) emphasizes that industrial wastewater contamination directly undermines socio-hygienic stability. Furthermore, statistical correlations (e.g., COD – Pb $r = 0.64$) demonstrate that industrial emissions can trigger a "cascading pollution" mechanism spreading through water-to-soil pathways.

Soil monitoring showed heavy-metal concentrations (Pb 145 mg/kg, Cd 3.8 mg/kg) exceeding FAO/WHO limits. Such values indicate that soil becomes a long-term "silent reservoir" of contamination. As highlighted by Song (2023 — Journal of Soil Contamination) and Singh (2024 — Environmental Pollution Reports), Pb and Cd levels in industrial soils may re-enter the human body through agricultural products — elevating endocrine and oncological risks into a long-term epidemiological dimension.

A key conclusion of the discussion is that industrial pollution does not affect air, water, and soil separately — it acts upon them as an interconnected ecological system. Therefore, monitoring must also be integrated. Relying only on air-quality posts or only on water laboratory measurements is insufficient. In many countries (e.g., EU industrial regions), industrial-emission monitoring is performed using a "multi-pollutant" model, in which GIS, laser-lidar, wastewater sensors, and optical spectrometric measurements of heavy metals in soil are unified into a single monitoring network (OECD indicator framework; Titar et al., 2020 — Laser Monitoring System Development).

The results also show that monitoring alone is not enough — the collected data must be made transparent, publicly accessible, evaluated by scientists and communities, and transformed into ecological policy. If monitoring becomes merely a technical protocol, it will have no real environmental impact. In other words, the system must move from "we observed it" to "we prevented it."

Conclusion

This research was dedicated to analyzing the contribution of urban industrial enterprises to environmental pressure, the spread of harmful substances through air, water, and soil, and how these are reflected in ecological monitoring indicators. The intersection of findings and discussion reveals that industrial pollution impacts ecological systems in a multi-directional, integrated, and high-risk epidemiological manner.

1. Concentrations of $PM_{2.5}$, NO_2 and other atmospheric pollutants in urban industrial areas were found to exceed World Health Organization standards by several fold, increasing cardiovascular and respiratory disease risks.
2. Industrial wastewater significantly disrupts key water-quality indicators (such as BOD and COD), causing oxygen depletion, eutrophication, and threats to drinking-water safety; therefore, real-time water monitoring systems are essential.
3. Soil contamination — particularly Pb, Cd, and Cr — exceeded FAO/WHO limits; the potential for these metals to re-enter the human body through the food chain transforms them into a long-term "silent epidemiological threat."

4. Correlations among monitoring indicators (e.g., COD – Pb r = 0.64; $PM_{2.5}$ – NO_2 r = 0.78) show interconnected pollution pathways — thus, monitoring must be implemented as a unified, integrated system rather than isolated measurements.

Automation of ecological monitoring systems, open-access environmental data, and stricter emission-control regulations are the only scientifically grounded pathway toward limiting industrial pollution. Protecting the environment is not merely about protecting nature — it is, fundamentally, protecting human health and the future of society.

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