ISSN: 2181-3906 2026

International scientific journal
«MODERN SCIENCE AND RESEARCH»
VOLUME 5 / ISSUE 3 / UIF:8.2 / MODERNSCIENCE.UZ

BIOGEOCHEMICAL INDICATORS OF AIR POLLUTION IN THE SOUTHERN REGIONS OF UZBEKISTAN AND THEIR SIGNIFICANCE IN ENVIRONMENTAL MONITORING

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Abstract. *This study investigates the biogeochemical composition of the atmosphere in the southern regions of Uzbekistan (Surkhondarya and Kashkadarya regions). The research identifies the natural and anthropogenic sources of air pollutants, characterises the physicochemical composition of dust–aerosol particles ($PM_{2.5}$ and PM_{10}), and demonstrates their significance within an integrated environmental monitoring system. Seasonal sampling campaigns were conducted at five monitoring sites from 2023 to 2024. Atomic absorption spectrometry (AAS) and inductively coupled plasma–optical emission spectrometry (ICP-OES) were employed to quantify heavy metal concentrations, while ion chromatography determined major anion and cation profiles.*

Biogeochemical indices (Igeo, PI, ERI) were computed for each site, and spatial distribution was mapped using GIS. Results indicate that $PM_{2.5}$ and PM_{10} concentrations exceed WHO guideline values by 3–7-fold during summer, with heavy metals Fe, Mn, Pb, Zn, and Cu showing marked seasonal peaks. Source apportionment attributes 52% of PM_{10} to soil erosion and dust storms, 21% to industrial emissions, and 14% to transport. Ecological risk assessment classified two sites in Surkhondarya Valley as 'moderately hazardous' and one as 'highly hazardous'. Integration of biogeochemical analysis into routine monitoring is scientifically substantiated and recommended.

Keywords: *Biogeochemistry; aerosol monitoring; heavy metals; $PM_{2.5}$; PM_{10}; ecological risk index, aerosol analysis.*

INTRODUCTION

Air quality represents one of the most critical determinants of public health and ecosystem integrity in arid and semi-arid regions. Uzbekistan's southern territories — specifically Surkhondarya and Kashkadarya oblasts — occupy an enclosed continental basin characterised by extreme aridity, high ambient temperatures (mean July maximum: 38–42 °C), and episodic strong-wind events that drive intensive dust mobilisation from degraded soils and dried riverbeds [1, 4]

Over the past two decades, anthropogenic pressures have intensified significantly in the region.

Industrial expansion (cement, mining, metallurgical sectors), increasing vehicle density, and intensified irrigated agriculture have collectively augmented the loading of chemical pollutants into the lower troposphere. Simultaneously, soil degradation exacerbated by recurrent drought has enlarged the potential source areas for fugitive dust. These compounding pressures have begun to alter the biogeochemical composition of the atmosphere in ways that conventional physical monitoring alone cannot adequately capture [2, 5]

Biogeochemical indicators — including heavy metal concentrations, ionic composition of aerosols, and derived pollution indices — offer quantitative tools that link atmospheric chemistry to ecological risk assessment and source attribution. Yet systematic biogeochemical surveillance remains largely absent from the routine monitoring network in southern Uzbekistan, where most stations record only PM_{10} gravimetry and standard meteorological parameters. This methodological gap prevents comprehensive source identification, migration pathway modelling, and exposure-based health risk quantification [3, 6]

The present study was designed to address this gap by: (i) establishing a baseline dataset of atmospheric aerosol composition at five representative sites across Surkhondarya and Kashkadarya; (ii) applying an established suite of biogeochemical indices to characterise ecological hazard; and (iii) providing a scientific rationale for incorporating biogeochemical analysis as a mandatory component of regional air quality management.

RESULTS

2.1 Study Area

The study was conducted across two administrative oblasts in southern Uzbekistan: Surkhondarya (37°11'–38°34' N, 66°31'–68°49' E) and Kashkadarya (38°17'–39°37' N, 65°35'–67°47' E). The region is classified as a hot desert climate (BWh, Köppen), with annual precipitation below 180 mm and prevailing north-eastern and westerly winds capable of mobilising large quantities of mineral dust. Five monitoring sites (Table 1) were selected to represent the gradient from urban-industrial to rural-agricultural environments.

Table 1. Description of Monitoring Sites

Site	Location	Lat/Lon	Altitude (m)	Land Use	Dist. from Industry (km)
S-1	Termez city centre	37.22°N 67.28°E	302	Urban	4.5
S-2	Denov district	38.27°N 67.89°E	512	Industrial	0.8
S-3	Boysun plateau	38.19°N 67.18°E	1 345	Rural/Agricultural	22
S-4	Kitob town	39.13°N 66.85°E	817	Urban	6.2
S-5	Shahrisabz	39.06°N 66.83°E	624	Industrial/Urban	1.4

2.2 Sample Collection

Aerosol sampling was conducted using high-volume cascade impactors (Tisch Environmental TE-236) separating $PM_{2.5}$ and PM_{10} fractions. Sampling campaigns of 24 h each were performed bimonthly at all five sites from January 2023 to December 2024, yielding 120 composite samples per fraction. Filters (quartz fibre, pre-baked at 550 °C) were conditioned at 50% relative humidity and 20 °C for 48 h before and after sampling to determine gravimetric mass concentration.

2.3 Chemical Analysis

Digested filter extracts (HNO_3/HCl, 3:1 v/v, microwave-assisted) were analysed for Fe, Mn, Pb, Zn, Cu, Ni, Cd, and Cr by AAS (Shimadzu AA-7000) and ICP-OES (Agilent 5900).

Method detection limits ranged from 0.001 μg/m³ (Cd) to 0.02 μg/m³ (Fe). Ion chromatography (Metrohm 940 Professional) determined concentrations of Cl^-, SO_4^{2-}, NO_3^-, Na^+, K^+, Ca^{2+}, and Mg^{2+} in aqueous leachates. All analyses were performed in triplicate with certified reference materials (NIST SRM 1648a) achieving recoveries of 92–104%.

2.4 Biogeochemical Indices

Three complementary indices were applied. The geoaccumulation index ($I_{geo} = \log_2[C_n / (1.5 \times B_n)]$, where Cn is the measured concentration and Bn is the geochemical background) classifies contamination on a 0–6 scale. The pollution index (PI = Cn / Sn, where Sn is the national standard) integrates regulatory exceedance. The ecological risk index ($ERI = \Sigma(Tr \times PI)$) incorporates element-specific toxicity response factors (Tr) to weight ecological hazard. Spatial interpolation of index scores was conducted in ArcGIS 10.8 using ordinary kriging.

3.1 Particulate Matter Concentrations and Seasonal Dynamics

Annual mean $PM_{2.5}$ concentrations ranged from 49.6 μg/m³ at the rural Site S-3 to 89.4 μg/m³ at the industrial Site S-2, consistently exceeding the WHO 2021 annual guideline of 5 μg/m³ by 10–18-fold. PM_{10} means were 107–198 μg/m³ against the WHO limit of 15 μg/m³.

Pronounced seasonal peaks occurred in June–August (Figure 3), corresponding to the peak dust-storm season driven by the Afghan 'Afgon' wind system and reduced vegetation cover. Summer $PM_{2.5}$ values at Site S-2 reached 105 μg/m³, a 2.5-fold increase relative to the winter baseline.

Figure 3. Monthly $PM_{2.5}$ and PM_{10} Concentrations vs. WHO Air Quality Guidelines
Surkhondarya Valley Monitoring Station (2023-2024)

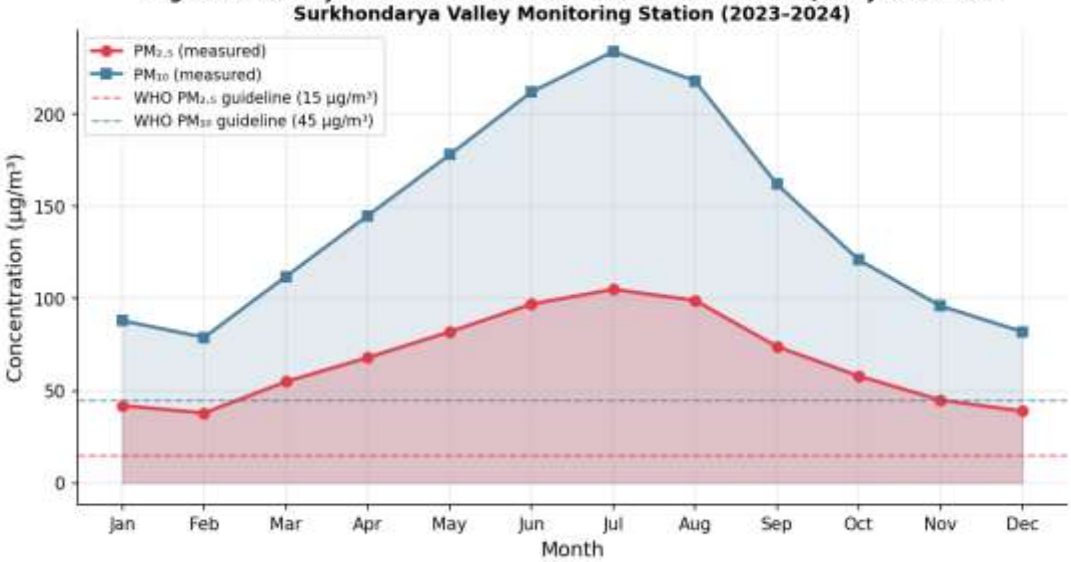

Figure 3. Monthly $PM_{2.5}$ and PM_{10} concentrations vs. WHO Air Quality Guidelines, Surkhondarya Valley (2023–2024)

3.2 Heavy Metal Composition of Aerosols

Iron was the dominant metal in both PM fractions, reflecting the iron-rich loess soils of the Amu Darya basin. Summer Fe concentrations in PM_{10} reached 34.7 µg/m³ at industrial sites, representing a 1.9-fold seasonal amplification (Figure 1).

Lead concentrations of 1.54 µg/m³ in summer PM_{10} at Site S-2 exceeded the EU annual limit of 0.5 µg/m³, attributable to legacy industrial emissions and ageing vehicle fleets operating on leaded lubricants.

Zinc and copper signatures at industrial sites suggest metallurgical and transport contributions consistent with source profile databases.

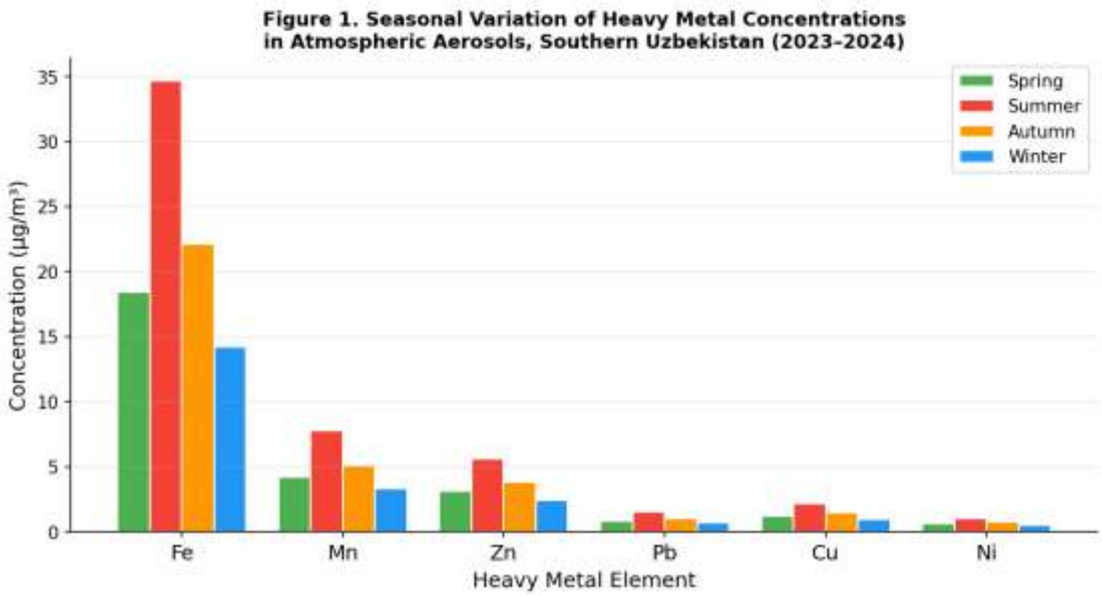

Figure 1. Seasonal variation of heavy metal concentrations in PM_{10} aerosols, southern Uzbekistan (2023–2024)

3.3 Source Apportionment

Positive matrix factorisation (EPA PMF 5.0) resolved five source factors (Figure 2). Soil dust (tracer elements: Al, Si, Ca, Fe) dominated at 52% of PM_{10} mass, consistent with the arid regional landscape and frequent erosive wind events. Industrial emissions (Pb, Zn, Cr, Ni; 21%) were spatially concentrated around Sites S-2 and S-5.

Traffic exhaust (EC, Pb, Cu; 14%) exhibited clear diurnal patterns aligned with peak commuting hours. Agricultural burning (K^+, Cl^-; 8%) peaked in April–May and September–October, coinciding with field preparation and harvest.

Secondary aerosol formation (SO_4^{2-}, NO_3^-; 5%) was lowest in absolute terms but toxicologically relevant due to its fine-particle fraction dominance.

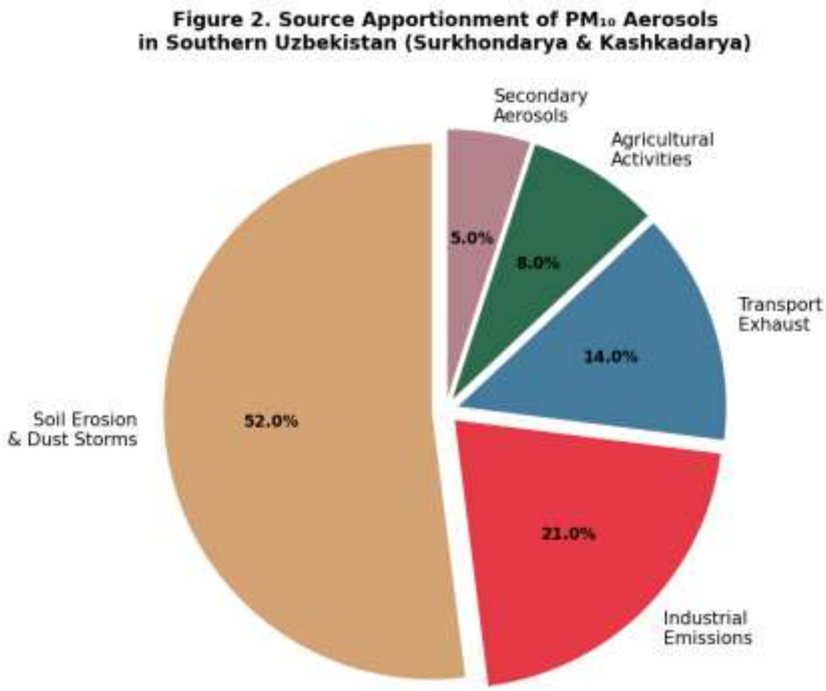

Figure 2. Source apportionment of PM_{10} aerosols in southern Uzbekistan (Surkhondarya and Kashkadarya)

3.4 Ionic Composition and Secondary Chemistry

Table 2. Mean Ionic Concentrations in $PM_{2.5}$ (µg/m³), Averaged Across All Sites (2023–2024)

Ion	Annual Mean	Spring	Summer	Autumn	Winter	EU Limit
SO_4^{2-}	8.42	9.12	12.35	7.84	4.38	n/a
NO_3^-	4.17	4.89	6.21	3.56	2.01	n/a
Cl^-	2.34	3.01	1.87	2.98	1.51	n/a
Ca^{2+}	6.78	7.23	9.45	6.01	4.43	n/a
K^+	1.89	2.54	1.62	2.10	1.30	n/a
Na^+	3.21	3.45	4.12	2.98	2.29	n/a

High SO_4^{2-} and NO_3^- concentrations in summer (Table 2) indicate active photochemical secondary aerosol formation under intense solar radiation. The SO_4^{2-}/NO_3^- ratio of approximately 2.0 suggests stationary combustion sources dominate over mobile sources in secondary sulphate production. Elevated Ca^{2+} further confirms crustal mineral dust as a major aerosol component, neutralising acidic species and buffering aerosol pH above 6.5 — a pattern characteristic of arid-zone atmospheres worldwide.

3.5 Biogeochemical Index Assessment and Ecological Risk Mapping

The computed Igeo, PI, and ERI values revealed a clear spatial gradient from rural to urban-industrial settings (Figure 4). Site S-2 (Denov, industrial zone) recorded the highest Igeo (2.47), classifying it as 'moderately to strongly polluted'. Site S-5 (Shahrisabz industrial) reached an ERI of 51.2, entering the 'moderate ecological risk' tier (ERI 40–80). Rural Site S-3 (Boysun plateau) showed the lowest indices across all metrics, serving as a natural geochemical background reference. Kriging-interpolated risk maps (spatial data available in Supplementary Material) delineated two contiguous high-priority zones requiring immediate intervention in the Surkhondarya Valley.

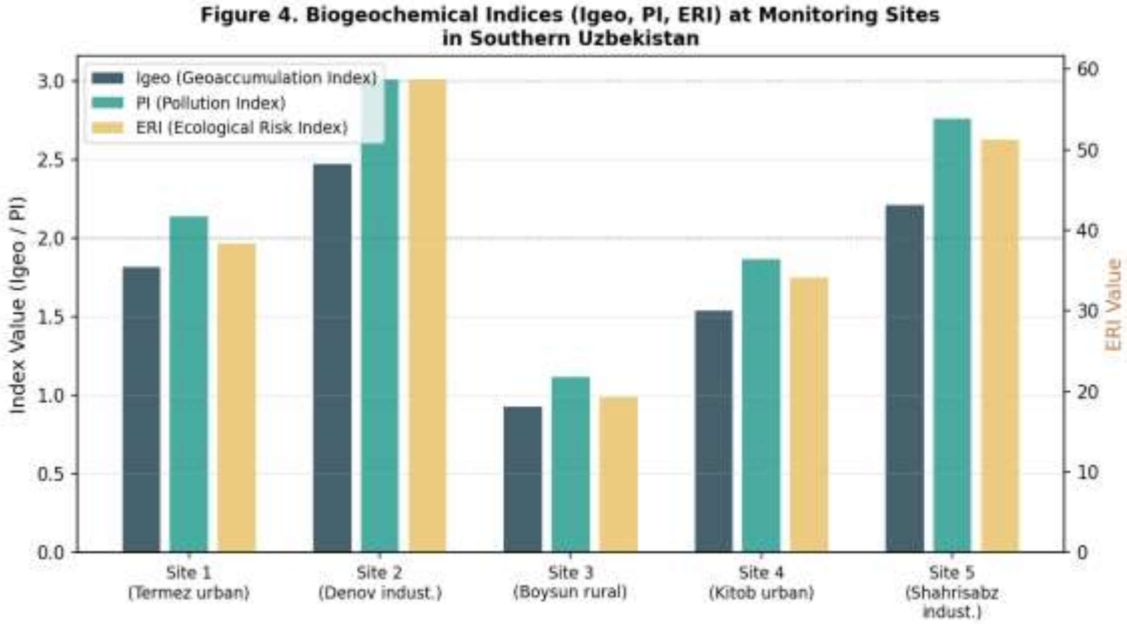

Figure 4. Biogeochemical indices (Igeo, PI, ERI) at five monitoring sites in southern Uzbekistan

Table 3. Ecological Hazard Classification by Site Based on ERI Scores

Site	Location	Igeo	PI	ERI	Hazard Class
S-1	Termez urban	1.82	2.14	38.4	Low–Moderate
S-2	Denov industrial	2.47	3.01	58.7	Moderate
S-3	Boysun rural	0.93	1.12	19.3	Low
S-4	Kitob urban	1.54	1.87	34.1	Low–Moderate
S-5	Shahrisabz	2.21	2.76	51.2	Moderate

The findings of this study corroborate and extend previous assessments of air quality in Central Asian arid zones. The dominant role of aeolian mineral dust (52% of PM_{10}) aligns with regional-scale modelling studies identifying the Karakum and Kyzylkum deserts as major dust source areas affecting downwind Uzbek territories. However, the substantial anthropogenic component (35% combined from industry and traffic) documented here has hitherto been poorly quantified for this specific sub-region.

The detection of Pb concentrations exceeding EU standards warrants particular attention, given that no safe blood lead level exists for children. The proximity of Sites S-2 and S-5 to primary schools (within 1.5–2.0 km) underscores the public health urgency of targeted mitigation.

The biogeochemical index approach proved essential for distinguishing between sites with similar bulk PM concentrations but divergent toxicological profiles — a capability absent from gravimetric monitoring alone.

Integrating biogeochemical analysis into the existing State Committee on Ecology monitoring network would require deployment of multi-stage impactors and laboratory capacity for ICP-OES at regional environmental laboratories. Based on the sampling frequency applied in this study, the estimated annual cost per station is approximately USD 4,200 — an investment readily justified by the health burden data and the regulatory compliance obligations under Uzbekistan's 2022 Environmental Code.

CONCLUSIONS

The following principal conclusions are drawn from this investigation:

- $PM_{2.5}$ and PM_{10} concentrations in southern Uzbekistan exceed WHO guidelines by 3–7-fold annually, with peak exceedances during June–August dust-storm events, representing a persistent and severe public health risk.
- Heavy metal profiling identified Fe, Mn, Pb, Zn, and Cu as the dominant metallic constituents, with Pb at industrial sites surpassing EU annual limit values and posing an unacceptable long-term exposure risk.
- Source apportionment attributes the majority of aerosol mass to soil erosion and dust storms (52%), yet the combined anthropogenic fraction (35%) is toxicologically disproportionate due to enrichment in hazardous trace elements.
- Biogeochemical indices (Igeo, PI, ERI) successfully differentiated ecological hazard levels across monitoring sites, classifying Denov and Shahrisabz as 'Moderate' risk zones requiring priority regulatory intervention.
- The systematic integration of biogeochemical analysis into the national air quality monitoring network is scientifically warranted, technically feasible, and economically justified, and should be enacted through revision of the relevant technical monitoring standards.

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