https://doi.org/10.33271/nvngu/2026-5/140

O. Kamli[*1],
orcid.org/0009-0008-3180-6871,
Z. Hadef[2],
orcid.org/0000-0001-7365-8055,
K. Kamli[2],
orcid.org/0000-0002-5625-2907,
A. Azzi[3],
orcid.org/0009-0008-9114-9615,
M. Fredj[1],
orcid.org/0000-0002-0560-4941,
A. Saadoune[1],
orcid.org/0000-0001-7860-6107

1 – University of Bejaia, Faculty of Technology, Mining and Geology Department, Bejaia, Algeria
2 – University 20 August 1955, Laboratory of Mechanical Engineering and Materials, Skikda, Algeria
3 – University of Bejaia, Faculty of Technology, Electrical Engineering Department, Bejaia, Algeria
* Corresponding author e-mail: ouarda.kamli@univ-bejaia.dz

A NOVEL WIF–ESH FRAMEWORK FOR ENVIRONMENTAL HAZARD ZONING OF MINING AEROSOLS IN SEMI-ARID ENVIRONMENTS

Purpose. This study proposes a novel environmental assessment framework for wind-driven iron-rich mining aerosols in the Boukhadra (BK) iron mining district, northeastern Algeria.

Methodology. Dust fallout, soil and ore samples were collected within the mine and up to 2 km from the principal emission sources during the March–April transition period. Mineralogical (XRD), geochemical (XRF, triacid digestion, UV–Visible spectrophotometry and AAS), gravimetric dust-deposition measurements, wind analyses and emission-source characterization were integrated within the proposed WIF–ESH Framework.

Findings. Deposited aerosols are dominated by hematite, quartz and carbonate minerals. Fe_2O_3 concentrations reached approximately 27 %, while dust deposition rates ranged from 92.8 to 239.2 $g \cdot m^{-2} \cdot day^{-1}$, exceeding internationally recognized nuisance-dust guideline values. The results indicate that aerosol dispersion is influenced not only by prevailing winds but also by the transient redistribution of wind-frequency occurrence during seasonal transition periods. Integrating WIF with ESH improves the interpretation of transport pathways and environmental hazard zoning.

Originality. The principal contribution of this study is the introduction of Wind-Influenced Frequency (WIF) as a new environmental descriptor for assessing mining-aerosol dispersion. Combined with Emission Source Hierarchy (ESH) and conventional mineralogical, geochemical and deposition analyses, the proposed WIF–ESH Framework provides an initial methodological basis for future predictive studies of aerosol transport and environmental hazard assessment in semi-arid mining environments.

Practical value. The proposed framework enhances environmental monitoring and hazard assessment of mining-derived aerosols and, following further validation, offers potential applications in source attribution, environmental management, land-use planning and geological mapping.

Keywords: *wind-influenced frequency (WIF), emission source hierarchy (ESH), semi-arid environments, atmospheric dispersion, Boukhadra iron mine*

Received: 28 July 2026
Accepted: 02 October 2026
Available online: 27 October 2026

Introduction. Mining activities constitute one of the principal anthropogenic sources of atmospheric particulate matter, generating large quantities of mineral dust during drilling, blasting, excavation, crushing, hauling and stockpiling operations. In semi-arid environments, limited precipitation, sparse vegetation and seasonal winds enhance particle resuspension, atmospheric transport and deposition, thereby affecting air quality, soils, ecosystems and human health [1–3].

Consequently, atmospheric particulate emissions from mining have become an important concern in environmental geoscience and sustainable mine management [4].

The environmental behavior of mining-derived aerosols is controlled by the combined influence of mineralogical composition, geochemical characteristics, particle-size distribution, emission, intensity and meteorological conditions [5–7]. Accordingly, integrated investigations combining mineralogical characterization, geochemical analyses and dust-deposition measurements have become standard approaches for identifying contamination sources and assessing environmental hazards around mining districts.

The Boukhadra (BK) iron mine in northeastern Algeria represents the country's principal iron ore production district and provides an appropriate natural laboratory for investigating the dispersion of iron-rich aerosols under semi-arid climatic conditions. Open-pit extraction, crushing facilities, ore stockpiles and haul-road traffic generate substantial quantities of particulate matter, while the regional climate promotes its transport and heterogeneous deposition around the mining area.

Although integrated mineralogical, geochemical, and meteorological investigations have considerably improved environmental assessment of mining-derived aerosols, atmospheric dispersion is generally interpreted using prevailing wind direction, mean wind speed, and

© Kamli O., Hadef Z., Kamli K., Azzi A., Fredj M., Saadoune A., 2026

dominant wind frequency [5, 8]. Recent atmospheric studies have shown that seasonal transition periods are characterized by temporary modifications in atmospheric circulation, boundary-layer dynamics, and directional variability, producing transient changes in dust entrainment, transport, and deposition [9–11]. Although these processes are well established in meteorology, they have rarely been incorporated into environmental hazard assessment of mining-derived aerosols.

Building upon these observations, this study introduces Wind-Influenced Frequency (WIF) as a physically based environmental descriptor derived from transient atmospheric behavior during seasonal transition periods. Rather than representing a new meteorological variable, WIF complements conventional atmospheric observations by improving the interpretation of aerosol transport pathways and deposition patterns in semi-arid mining environments.

The proposed methodology also incorporates Emission Source Hierarchy (ESH), defined as the structured classification of mining emission sources according to their relative emission potential, operational intensity and spatial influence. Although source characterization and source apportionment are widely applied in atmospheric pollution studies [7, 12–13], their integration with transient atmospheric behavior remains limited in environmental assessments of mining-derived aerosols [14, 15].

The simultaneous integration of Wind-Influenced Frequency (WIF), Emission Source Hierarchy (ESH), mineralogical characterization, geochemical analyses and measured dust deposition constitutes the proposed WIF–ESH Framework, an integrated environmental assessment framework for hazard zoning of mining-derived aerosols in semi-arid environments. The framework is intended to complement existing environmental assessment methodologies by strengthening the interpretation of atmospheric transport, source attribution and spatial hazard distribution.

The objective of this work is to demonstrate the first implementation of the proposed WIF–ESH Framework through its application to the Boukhadra iron mining district. Mineralogical characterization (XRD), geochemical analyses (XRF, AAS and UV–Visible spectrophotometry), gravimetric dust-deposition measurements, atmospheric observations and emission-source characterization are integrated to establish an improved methodology for environmental hazard zoning of iron-rich mining aerosols. Although developed from observations at the Boukhadra mine, the proposed framework provides an initial methodological basis for future applications involving atmospheric transport modelling, environmental monitoring and environmental hazard assessment in semi-arid mining environments.

Conceptual integration of the WIF–ESH framework. The proposed WIF–ESH Framework complements rather than replaces conventional environmental assessment methods. It integrates established mineralogical, geochemical, atmospheric, and operational observations within a unified environmental interpretation designed to improve hazard zoning of mining-derived aerosols under semi-arid conditions. Although demonstrated here at the Boukhadra iron mine, the framework represents an initial methodological development requiring further validation through long-term monitoring and atmospheric dispersion modelling (Fig. 1).

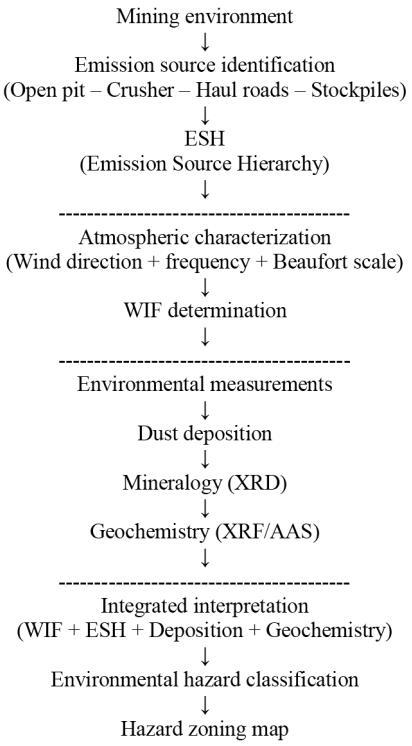


Fig. 1. Conceptual work flow of the proposed WIF–ESH Integrated Environmental Hazard Assessment Framework combining emission-source characterization, atmospheric transport analysis, dust deposition measurements, geochemical indicators and final hazard zoning

Similarly, the environmental hazard assessment can conceptually be expressed as

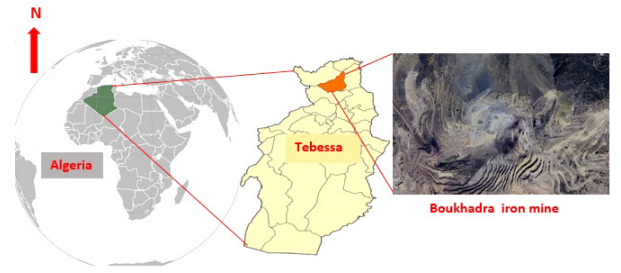
$$HI = f(WIF, ESH, M, G, DDR),$$

where *HI* is Integrated Environmental Hazard Index; *WIF* is Wind-Influenced Frequency; *ESH* is Emission Source Hierarchy; *M* is Mineralogical characterization; *G* is Geochemical characterization; *DDR* is Dust Deposition Rate.

This expression is *not intended as a predictive mathematical model*. Rather, it represents a conceptual integration illustrating the principal environmental descriptors and analytical components considered within the proposed framework. Future investigations may develop quantitative formulations capable of weighting these descriptors according to their relative influence on particulate transport and deposition. The following sections describe the study area, sampling strategy, analytical procedures and atmospheric observations implemented to evaluate the proposed WIF–ESH Framework under the environmental conditions of the Boukhadra iron mining district.

Materials and methods. ***Study Area. Sampling. Analytical techniques.*** The Boukhadra (BK) iron mine, northeastern Algeria, is located in a semi-arid region (annual precipitation <300 mm; mean temperatures from <12 °C in winter to >35 °C in summer). With prevailing northwesterly winds.

Sampling strategy designating the spatial-temporal scope of the present study was carried out during the



a

b

c

Fig. 2. Location of the Boukharda iron mine and distribution of sampling points:

a – regional location of the mine; b – sampling points within the mine; c – sampling points outside the mine

March–April seasonal transition period at six locations (P1–P6), including: two sites within the mine (P2 and P3) and four sites up to 2 km downwind with a 500 m spacing along the poles (P1, P4, P5 and P6). Atmospheric dust fallout was collected by the gravimetric method using open collectors installed and exposed for 30 days following standard procedures [16]. Soil, ore, vegetation and water samples were also collected to support the environmental assessment. While solid samples were prepared in accordance with ISO 11464 [17].

Analytical techniques. The Mineralogical characterization was performed by X-ray diffraction (XRD) using a PANalytical X'Pert Pro diffractometer (Cu Kα radiation, λ = 1.5418 Å). Mineral phases were identified using the ICDD Powder Diffraction File database.

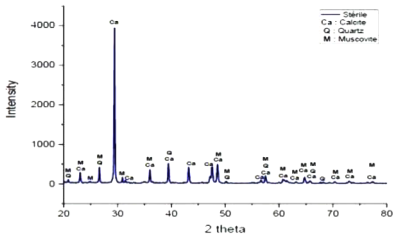
Major oxide compositions were determined by X-ray fluorescence (XRF), with particular emphasis on Fe_2O_3 and SiO_2.

Metal concentrations were measured by Atomic Absorption Spectrometry (AAS) following standard digestion procedures.

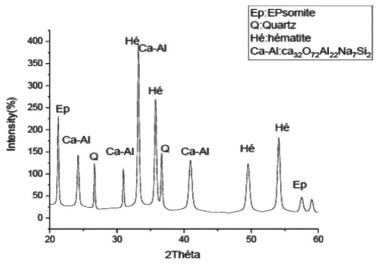
Soluble Fe, Si and Al fractions were determined after tri-acid digestion (HNO_3–$HClO_4$–HF) and quantified by UV–Visible spectrophotometry.

Analytical quality was verified using calibration curves with coefficients of determination (R^2) between 0.996 and 1.000 [17–19].

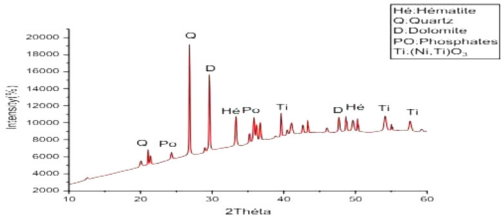
Emission sources, dust deposition and wind data. The principal diffuse dust sources at the Boukhadra mine comprise open-pit extraction, crushing and screening facilities, haul-road traffic and ore stockpiles. These sources were classified according to their relative emission potential within the proposed Emission Source Hierarchy (ESH).



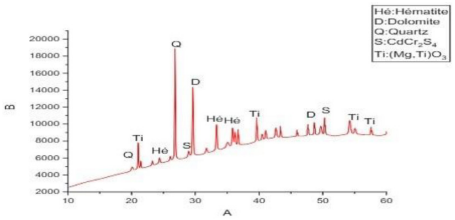
a – XRD analysis results of the ore sample



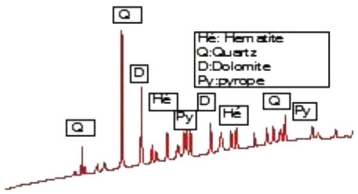
b – XRD analysis results of the sterile sample



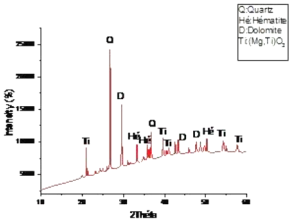
c – XRD analysis results of the P3 sample



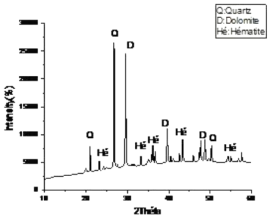
d – XRD analysis results of the P1 sample



e – XRD analysis results of the P2 sample



f – XRD analysis results of the P6 sample



g – XRD analysis results of the S3 soil sample

Fig. 3. shows the XRD analysis results of representative samples, including:

a – characterization of the iron ore sample; b – characterization of the sterile sample; c – characterization of the P3 dust sample- collected from the exploitation road at level. 1030-in pit; d – mineralogical of the P1 dust sample- collected at 0.1 km south outside the mine perimeter; e – characterization of the P2 dust sample – collected near to the crusher station at level. 1060-in pit; f – characterization of the P6 dust sample – collected at 0.2 km east outside the mine boundary; g – characterization of the S3 soil sample – collected at 1.5 km south of the mine boundary

Dust deposition was quantified gravimetrically at the six sampling sites (P1–P6) using 30-day exposure measurements. Deposition rates were calculated from the collected dust mass and the collector surface area and expressed as $mg \cdot m^{-2} \cdot day^{-1}$ [16, 20].

Meteorological characterization was based on prevailing wind direction, wind speed and seasonal wind-frequency data obtained for the study period. These atmospheric observations provided the basis for interpreting particulate transport and deposition through the proposed Wind-Influenced Frequency (WIF) descriptor.

Samples were identified according to sampling medium and location (dust, soil, ore, vegetation and water), while dust-fall samples collected at monitoring sites were designated P1–P6 throughout the study.

Results and discussion. ***Mineralogical characteristics.*** The mineralogical composition of ore, dust and soil samples was investigated by XRD. Representative diffractograms are shown in Fig. 3.

X-ray diffraction (XRD) analyses showed that the ore and deposited dust are predominantly composed of hematite, quartz and carbonate minerals (Fig. 3). The close mineralogical similarity between source materials and atmospheric fallout confirms that mining activities represent the principal origin of iron-rich aerosols in the study area. Quartz and carbonate phases become relatively more abundant at distal sampling sites, reflecting progressive dilution and mixing with local soil particles during atmospheric transport.

Geochemical evidence of mining-derived aerosols.

1. Major oxide compositions are determined by *XRF* and summarized in Table 2.

Table 1

Summary of the dominant mineralogical phases determined by X-ray diffraction (XRD)

Mineral	Iron Ore	Deposited Dust	Soil	Environmental significance
Hematite	✓✓	✓✓	✓	Principal Fe-bearing phase
Quartz	✓	✓✓	✓✓	Wind-transported silicate
Calcite	✓	✓	✓	Carbonate gangue
Dolomite	✓	✓	✓	Secondary carbonate

Table 2

Oxide composition of ore and deposited dust samples determined by X-ray fluorescence (XRF)

Sample	Fe_2O_3, %	SiO_2, %	Al_2O_3, %	Environmental significance
Ore	57	3.78	2.5	Hématite enrichment
P1	9.33	3.18	1.66	Medium distal deposition
P2	26.7	15.4	7.39	Strong mining influence
P3	21.7	16.4	8.79	High iron enrichment
P4	7.1	17.5	4.20	Downwind dilution
P5	9.10	20.5	5.25	Mixed atmospheric fallout
P6	8.84	3.65	1.66	Distal deposition

Major oxide analyses by XRF further supported the mineralogical observations (Table 2). Iron oxide (Fe_2O_3) was the dominant component in ore samples (up to approximately 57 %), whereas deposited dust exhibited Fe_2O_3 concentrations ranging from about 7 to 27 %, indicating progressive dilution with increasing distance from the principal emission sources. In contrast, SiO_2 showed an opposite trend, increasing at downwind locations owing to the growing contribution of silicate-rich background materials.

2. Determination of metal concentrations was conducted by AAS and presented in Table 3.

Metal concentrations determined by Atomic Absorption Spectrometry (AAS) confirmed the geochemical enrichment associated with mining activities (Table 3). Elevated Fe contents were accompanied by moderate concentrations of associated trace elements, whereas soil and water samples generally exhibited lower concentrations, indicating that atmospheric fallout represents the dominant contamination pathway within the investigated area.

3. Necessary information on the soluble fractions of Fe, Si and Al was provided by both *Tri-acid digestion and UV–Visible* spectrophotometry, especially for samples P4 and P5 (Table 4).

Tri-acid digestion followed by UV–Visible spectrophotometry revealed that only a fraction of the total elemental content is readily mobilized after atmospheric deposition. The highest soluble Fe, Si and Al concentrations were measured at sites P4 and P5, suggesting progressive geochemical alteration of transported particles during dispersion. These results indicate that elemental mobility is influenced not only by source composition but also by atmospheric transport distance and post-depositional weathering processes, reinforcing the interpretation provided by the WIF–ESH Framework. Analytical quality was verified by calibration curves with coefficients of determination (R^2) between 0.996 and 1.000.

Dust deposition and spatial distribution. Dust deposition constitutes the most direct indicator of atmospheric

Table 3

Metal concentrations determined by Atomic Absorption Spectrometry (AAS) in specific representative environmental samples

Sample	Fe, %	Al, %	Ti, %	Environmental Interpretation
Soil (S3)	7.30	2.18	0.14	Direct mining influence
Soil (E1)	<0.5	<0.5	<0.5	Moderate enrichment
Spring Water	<0.5	<0.5	<0.5	Low contamination

Table 4

Soluble fractions of major elements determined after tri-acid digestion and UV–Visible spectrophotometry

Sample	Soluble Fe	Soluble Si	Soluble Al	Environmental interpretation
P4	7.10	17.5	4.20	Enhanced elemental mobility during transport
P5	9.20	20.5	5.20	Highest weathering intensity

Table 5

Dust deposition rates and environmental interpretation of monitoring sites

Sampling Site	Distance/Location	Dust deposition rate, mg·m^{-2} · day^{-1}	Relative deposition level	Environmental interpretation
P1	Outside mine (1,000 m S)	92.8	Low	Distal fallout
P2	Crusher station (Level 1,060 in-pit)	115.5	Moderate	Mining source
P3	Haul road (Level 1,030 in-pit)	233.3	Very High	Major emission zone
P4	Outside mine (1,500 m W)	116.6	Moderate	Wind-controlled transport
P5	Outside mine (500 m N)	175.0	High	Transitional deposition zone
P6	Outside mine (2,000 m E)	239.2	Very High	Maximum atmospheric accumulation

particulate loading around mining operations and provides a quantitative basis for evaluating environmental hazard (Table 5).

Measured deposition rates at the six monitoring sites ranged from 92.8 to 239.2 mg · m^{-2} · day^{-1} (Table 5), revealing pronounced spatial variability across the study area. The highest deposition rates were recorded at sites P3 (233.3 mg · m^{-2} · day^{-1}) and P6 (239.2 mg · m^{-2} · day^{-1}), reflecting the combined influence of nearby high-emission mining activities and dominant wind transport. Intermediate deposition values were measured at P5 (175.0 mg · m^{-2} · day^{-1}), whereas the lowest values occurred at P1 (92.8 mg · m^{-2} · day^{-1}), located farther from the principal emission sources. This spatial distribution demonstrates that dust deposition is controlled by both emission intensity and atmospheric transport conditions.

The observed deposition pattern is consistent with the mineralogical and geochemical characteristics of the collected dust, confirming that iron-rich aerosols originate primarily from mining activities.

Although deposition generally decreases with increasing distance from the principal emission sources, the observed spatial pattern is not exclusively controlled by distance. The influence of seasonal wind redistribution suggests that atmospheric transport processes also contribute significantly to the final deposition pattern, a phenomenon examined through the proposed Wind-Influenced Frequency (WIF) descriptor and through the environmental hazard zoning developed within the WIF–ESH Framework whose interpretation is presented in the following section.

Atmospheric controls on aerosol dispersion: *wind-influenced frequency (WIF) and emission source hierarchy (ESH)*. Wind constitutes the principal environmental factor controlling the entrainment, transport, and deposition of mining-derived aerosols in semi-arid environments although prevailing wind direction and mean wind speed are commonly used to interpret particulate dispersion [20, 21].

The spatial distribution of deposited dust observed at the Boukhadra iron mine indicates that these conventional parameters alone cannot fully explain the measured deposition pattern. Significant dust accumulation was recorded not only along the dominant transport axis but also within intermediate directional sectors, suggesting that additional atmospheric processes contribute to particle redistribution during seasonal transition periods.

Wind speed should not be considered as a single fixed parameter governing particle behavior throughout the transport process. Instead, it operates over a continuum of atmospheric conditions commonly described using the Beaufort scale. Moderate winds (approximately 5–6 m · s^{-1}; Beaufort force 4) generally initiate particle entrainment, whereas wind velocities between about 2 and 5 m · s^{-1} (Beaufort forces 2–3) primarily sustain atmospheric transport, plume dispersion and vertical mixing. Conversely, very weak winds (< 1 m · s^{-1}; Beaufort forces 0–1) favor gravitational settling and local deposition because their transport capacity becomes insufficient to maintain particles in suspension. Consequently, both wind intensity and wind persistence influence the final spatial distribution of atmospheric dust [22, 23].

Atmospheric circulation is dominated by northwestern to west-northwestern winds, defining the principal transport pathway toward the southeastern sector of the mining district. Mean wind velocities range from approximately 3.8 m · s^{-1} during summer to more than 5.9 m · s^{-1} during winter, while directional occurrence frequencies reach approximately 13–27 % for WNW winds and 7–9 % for southeastern winds. During the March–April transition period, average directional frequencies approach approximately 20 %, reflecting the increased variability of atmospheric circulation characteristic of seasonal transitions.

Although the dominant wind regime governs the principal direction of aerosol transport, atmospheric behavior during seasonal transitions differs from that

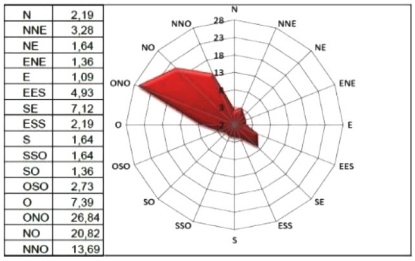


Fig. 4. Wind rose showing the frequency and prevailing directions of winds during the study period in the Boukhadra mining area

observed under stable meteorological conditions. The progressive replacement of humid winter air masses by warmer and drier summer circulation produces lower atmospheric humidity, higher temperatures and enhanced evaporation, thereby increasing the potential for dust entrainment and atmospheric transport. Under these conditions, sectors located between the dominant wind directions experience temporary increases in wind occurrence resulting from the combined influence of adjacent prevailing airflows. These intermediate sectors therefore become more effective transport corridors than would be expected from their original wind frequencies alone.

To describe this behavior, the present study introduces Wind-Influenced Frequency (WIF) as a physically based environmental descriptor derived from observed atmospheric behavior during seasonal transition periods. WIF does not represent a new meteorological variable but rather provides an environmental interpretation of the transient amplification of wind-frequency occurrence within intermediate directional sectors. Consequently, WIF complements conventional wind analyses by explaining why dust deposition may extend beyond the principal atmospheric transport axis despite relatively low original wind frequencies. The descriptor therefore improves the interpretation of aerosol transport pathways and cumulative dust deposition under semi-arid climatic conditions.

Methodological basis and determination of wind-influenced frequency (WIF). Wind-Influenced Frequency (WIF) is introduced as a physically based environmental descriptor derived from the observed redistribution of wind-frequency occurrence along preferential atmospheric transport pathways during seasonal transition periods and does not replace conventional wind-direction, wind-speed or wind-frequency measurements. Rather, it complements these parameters by accounting for the effective atmospheric pathway connecting an emission source to a monitoring location.

For each sampling site, the procedure begins with the identification of the emission/source sector, the sampling location and the corresponding original wind-frequency occurrence (FO) obtained from the regional wind-frequency distribution. The preferential transport corridor connecting the source sector to the sampling location is then identified from the observed directional circulation. The wind-frequency occurrences characterizing this effective corridor are considered together with the source-related frequency to determine a representative influenced frequency. In the present study, WIF is expressed as the representative mean frequency associated with the effective atmospheric transport corridor. The resulting WIF therefore differs from the original frequency (FO), because it reflects the atmospheric conditions governing particle persistence and transport along the intermediate pathway rather than only the initial condition at the emission source.

The resulting WIF is subsequently interpreted using the corresponding wind-force conditions of the Beaufort scale. This provides a physically meaningful interpretation of the transition from initial particle entrainment to continued transport or deposition. For example, at P1, located approximately 1,000 m south of the mine, the original southern-sector frequency is approximately 1.6, whereas the preferential NW–SE circulation connects the source area with an effective ESE–SE transport corridor characterized by frequencies of approximately 7.12 and 2.19. Their representative mean gives a WIF of approximately 4.5, corresponding to a higher transport condition than that indicated by the original frequency alone. This interpretation is consistent with the persistence and deposition of mining-derived particles at the P1 location rather than immediate deposition close to the source.

Accordingly, FO characterizes the initial atmospheric condition acting on the particles at or near the source, whereas WIF characterizes the effective frequency condition associated with the continuation of particle transport along the identified atmospheric pathway. The WIF values and corresponding transport interpretations for P1–P6 are summarized in Table 6. The present formulation represents the initial empirical implementation of the descriptor; development of a generalized mathematical formulation incorporating terrain and pathway-correction factors, followed by validation using longer-term observations and additional mining sites, is considered a future development of the WIF–ESH Framework.

Atmospheric transport alone, however, cannot fully explain the environmental hazard associated with mining-derived aerosols because the amount of material available for transport depends fundamentally on the emission characteristics of mining operations. For this reason, the proposed framework incorporates an Emission Source Hierarchy (ESH) that ranks mining activities according to their relative dust-generation potential. Field observations indicate that unpaved haul roads constitute the dominant emission source owing to continuous vehicle-induced resuspension of previously deposited fine particles. Crushing and screening facilities represent the second most important source through continuous mechanical fragmentation of iron ore, followed by ore stockpiles, loading operations, drilling activities and other disturbed surfaces, which contribute progressively lower particulate emissions depending on operational intensity and surface conditions. Under the dry climatic conditions prevailing at Boukhadra, rapid desiccation of exposed materials further enhances the emission potential of these sources.

The combined interpretation of WIF and ESH provides a more comprehensive explanation of aerosol dispersion than either atmospheric or operational parameters considered independently. While WIF explains the transient redistribution of atmospheric transport during seasonal transitions, ESH identifies the relative contribution of individual mining activities to particulate emissions. Their integration therefore establishes the conceptual basis of the proposed WIF–ESH Integrated Environmental Assessment Framework by combining atmospheric dynamics with source intensity and physicochemical evidence.

Field observations strongly support this interpretation. For example, the highest dust deposition rate was measured at sampling site P6, located approximately 2 km from the principal emission sources. Although this site is characterized by relatively low original wind-frequency occurrence, transitional atmospheric conditions increase the effective transport capacity of intermediate sectors, allowing iron-rich aerosols to be transported

over greater distances before deposition. Similar behavior was observed at P2, P4 and P5, where enhanced influenced frequencies produced deposition levels greater than those predicted solely from prevailing wind statistics. In contrast, P3, located along the principal transport corridor adjacent to the haul road, combines intense atmospheric transport with the highest-ranked emission source, resulting in persistent dust resuspension and very high particulate loading. These observations demonstrate that environmental hazard cannot be explained solely by distance from the emission source but instead reflects the combined influence of atmospheric variability, wind persistence and source strength.

The integrated site-scale interpretation derived from Wind-Influenced Frequency, Emission Source Hierarchy, measured dust deposition and geochemical enrichment is summarized in Table 6. The combined evaluation of these complementary descriptors explains the heterogeneous spatial distribution of mining-derived aerosols and provides the scientific basis for the multi-criteria environmental hazard zoning developed in the following section.

Environmental hazard classification criteria. The environmental hazard classification proposed in this study was developed as a site-specific screening and zoning approach integrating dust deposition, geochemical characteristics, atmospheric transport behavior and emission-source intensity. Regulatory reference values were used only as external comparison criteria. The German TA Luft guideline value of 350 mg · m^{-2} · day^{-1} represents a general nuisance-dust reference level, whereas lower local criteria (Algerian limit for nuisance-dust of about 50 mg · m^{-2} · day^{-1}; Executive Decree No. 06-138, 2006) indicate the presence of elevated deposition conditions. However, neither criterion alone provides sufficient strong spatial variability. Therefore, operational classes were established for the Boukhadra dataset based on the observed deposition range: Low (< 120 mg · m^{-2} · day^{-1}), Moderate (120–170 mg · m^{-2} · day^{-1}), High (170–220 mg · m^{-2} × × day^{-1}), and Extreme (> 220 mg · m^{-2} · day^{-1}). These classes were subsequently integrated with geochemical enrichment, WIF-based atmospheric transport interpretation and ESH source characterization to obtain the final environmental hazard zoning.

Overall, the results demonstrate that atmospheric transport and particulate emissions are intrinsically coupled processes. The proposed WIF–ESH Framework therefore extends conventional environmental assessments by integrating transient atmospheric behavior with emission-source characteristics, thereby providing a more physically consistent interpretation of aerosol dispersion and environmental hazard in semi-arid mining environments. This integrated approach forms the foundation for the multi-criteria hazard zoning presented in the next Section.

Integrated environmental hazard zoning using the proposed WIF–ESH framework. The environmental impact of mining-derived aerosols results from the interaction of several interdependent factors, including emission intensity, mineralogical composition, geochemical enrichment, atmospheric transport, and dust deposition [21, 24]. Evaluating these variables independently often provides only a partial understanding of environmental risk. Consequently, the present study integrates these complementary parameters within the proposed *Wind-Influenced Frequency–Emission Source Hierarchy (WIF–ESH) Framework*, allowing a multi-criteria assessment of atmospheric contamination and the delineation of environmentally significant hazard zones.

Table 6

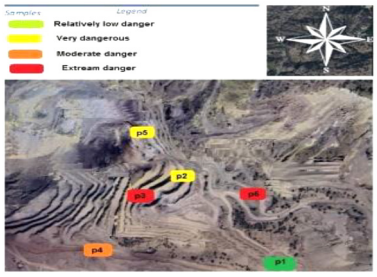
Integrated environmental hazard classification of sampling sites using the proposed WIF–ESH Framework

Sample Code	P1	P2	P3	P4	P5	P6
Sampling location	1,000 m S (outside the mine)	NE sector (crusher station in-pit)	WNW sector (haul road in-pit)	1,500 m W (outside the mine)	500 m N (outside the mine)	2,000 m E (outside the mine)
Dominant WIF value (Wind-frequency occurrence, %)	1.64 (>1.5)	1.64 (>1.5)	26.84 (>18)	1.64 (>1.5)	2.19 (>2)	1.09 (≈1)
Wind-driven transport behavior (WIF interpretation)	Low WIF transport	Low WIF transport	Turbulent transport	Low WIF transport	Active transport conditions	Distal deposition
Atmospheric transport pathway	S–SE transport corridor	Link NE sector – NNW airflow	WNW transport corridor	Link SW sector-SE airflow	NW corridor	Link E sector- SE airflow
Representative WIF	2.19–7.12 (Beaufort 3)	1.64–13.69 (Beaufort 4–5)	26.84 (Beaufort 10–12)	1.64–7.12 (Beaufort 3)	2.19–20.82 (Beaufort 6)	1.09–4.93 (Beaufort 2)
Dominant source	Diffuse fugitive emissions (secondary source)	Fugitive emissions (Major Source 2–3)	Haul-road (Major Source 1)	Diffuse fugitive emissions	Diffuse fugitive emissions	Diffuse fugitive emissions
Site hazard classification	Low–Moderate	High	Extreme	Low–Moderate	Extreme	Low
Overall Integrated environmental hazard classification	Low	High–Extreme	Extreme	Moderate	High–Extreme	Extreme

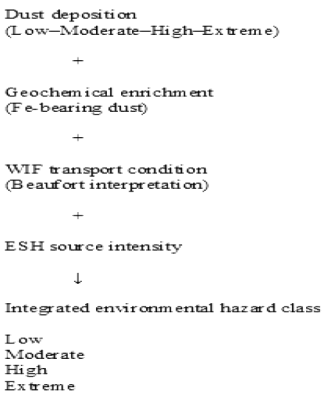
Fig. 5 illustrates the final environmental hazard zoning obtained by integrating mineralogical and geochemical characterization with measured dust deposition rates, prevailing atmospheric circulation, Wind-Influenced Frequency (WIF), and Emission Source Hierarchy (ESH). The resulting spatial distribution distinguishes four hazard categories (Low, Moderate, Dangerous, and Extreme) that reflect both the intensity of particulate emissions and the efficiency of atmospheric transport mechanisms.

The *Extreme Hazard* zone is concentrated within the active mining complex, particularly around the crushing facilities, ore handling installations, and heavily trafficked haul roads. These sectors are characterized by the highest dust deposition rates, elevated Fe_2O_3 enrichment, and continuous mechanical disturbance of exposed ore and waste materials. Their direct alignment with the dominant northwesterly wind regime promotes repeated entrainment and transport of iron-rich particles, producing persistent atmospheric contamination and extensive dust fallout.

The *Dangerous Hazard* zone extends beyond the immediate mining infrastructure into areas subjected to recurrent atmospheric transport. Although dust deposition decreases progressively with increasing distance from the principal emission sources, the reduction is not spatially uniform. Several intermediate sectors exhibit deposition levels significantly higher than expected based solely on prevailing wind direction. This behavior indicates that atmospheric transport during seasonal transition periods cannot be adequately described using conventional wind-frequency statistics alone.



a



b

Fig. 5. Integrated environmental hazard zoning of the Boukhadra mining area showing:

a – hazard zoning map of the mining district of Boukhadra; b – insert diagram illustrating the multi-criteria decision pathway used for assigning the final hazard classes

The observed extension of elevated dust deposition beyond the principal transport axis is consistent with the transient atmospheric redistribution described by the WIF descriptor, confirming that seasonal transition conditions contribute to broader dispersion than predicted by prevailing wind direction alone.

Atmospheric transport was further interpreted together with the Emission Source Hierarchy (ESH), allowing source intensity and transport efficiency to be evaluated simultaneously. The *Emission Source Hierarchy (ESH)* therefore complements WIF by ranking operational units according to their relative dust-generation potential. Crushing installations and haul-road traffic constitute the primary emission sources because of their continuous mechanical fragmentation and vehicle-induced resuspension. Ore stockpiles, loading operations, drilling activities, and disturbed surfaces contribute to progressively lower emission intensities but remain locally important under favorable meteorological conditions [13, 20, 25].

The integration of WIF, ESH, mineralogical composition, geochemical enrichment, and measured dust deposition provides the basis for the multi-criteria environmental hazard zoning presented in Fig. 5.

The resulting hazard map demonstrates that the spatial distribution of mining-derived aerosols reflects the combined influence of source intensity and atmospheric variability rather than simple distance from the emission source. This observation highlights the limitations of traditional single-parameter approaches and emphasizes the importance of integrated environmental assessment in semi-arid mining regions [24, 25].

From an operational perspective, the proposed WIF–ESH Framework provides a practical decision-support tool for environmental management. The framework facilitates the identification of priority monitoring areas, optimization of dust-suppression measures, strategic planning of haul-road watering programs, and improved allocation of environmental control resources. Furthermore, the methodology can assist mining companies and regulatory agencies in establishing scientifically based environmental monitoring strategies adapted to the specific climatic conditions of semi-arid regions.

Although the present study represents the first application of the WIF–ESH Framework, the methodology remains sufficiently flexible to accommodate additional environmental descriptors as new datasets become available. Although successfully demonstrated at the Boukhadra mine, the proposed framework should be further validated using long-term atmospheric monitoring, numerical dispersion modelling, and applications to different geological and climatic settings.

Overall, the WIF–ESH Framework constitutes an original contribution to environmental assessment in mining areas by integrating atmospheric behavior with emission-source characteristics within a unified multi-criteria hazard zoning methodology. The successful application of this framework to the Boukhadra iron mining district demonstrates its potential for improving environmental risk evaluation and supporting sustainable mine management in semi-arid environments.

Achievements and future perspectives of the WIF–ESH framework. The present study demonstrates the practi-

cal applicability of the proposed WIF–ESH Framework for interpreting and zoning mining-derived aerosol hazards in a semi-arid iron-mining environment. The study establishes WIF as a physically based descriptor that complements conventional wind analysis by accounting for the effective atmospheric transport pathway, while ESH provides a structured interpretation of the relative contribution of mining emission sources. Their integration with mineralogical, geochemical and dust-deposition evidence provides a site-scale basis for identifying spatially differentiated environmental hazard zones.

Further development should focus on formalizing WIF into a generalized mathematical formulation incorporating terrain and pathway effects, followed by validation using longer-term observations and a wider range of mining environments. Such development could support the establishment of transferable WIF–ESH-based decision models for environmental monitoring, source attribution, hazard zoning and mining-site management.

Conclusions. This study developed an integrated environmental assessment of iron-rich dust dispersion in the Boukhadra iron mining district, northeastern Algeria, by combining mineralogical, geochemical, atmospheric, and operational observations within a unified hazard-zoning methodology. XRD, XRF, AAS, dust-deposition monitoring, and meteorological analyses confirmed that mining activities constitute the dominant source of atmospheric particulate matter, with deposited dust characterized principally by hematite, quartz, and carbonate minerals. Elevated Fe_2O_3 concentrations and high dust-deposition rates further demonstrated the strong environmental influence of crushing operations, haul-road traffic, and other active mining processes.

Although the overall distribution of deposited dust follows the prevailing northwesterly wind regime, significant accumulation was also observed within intermediate directional sectors that cannot be fully explained by conventional wind statistics alone. To improve the interpretation of these transport patterns, this study introduced Wind-Influenced Frequency (WIF) as a physically based environmental descriptor representing the transient redistribution of wind-frequency occurrence during seasonal transition periods. Complemented by the Emission Source Hierarchy (ESH), which classifies mining activities according to their relative dust-generation potential, WIF provides a more comprehensive interpretation of atmospheric transport and source contributions.

The integration of WIF and ESH with mineralogical composition, geochemical enrichment, and measured dust deposition constitutes the proposed WIF–ESH Framework, representing the principal methodological contribution of this study. Its application enabled the delineation of four environmental hazard classes and demonstrated that contamination patterns are governed by the combined effects of atmospheric variability and emission intensity rather than by distance from the emission source alone.

Beyond its application to the Boukhadra mining district, the proposed framework provides a practical methodology for environmental monitoring, hazard zoning, and mine-management planning in semi-arid environments. Although additional validation under different climatic and geological conditions remains necessary, the WIF–ESH Framework establishes a robust methodological basis for future atmospheric monitoring, dispersion modelling, and sustainable environmental management of mining-derived aerosols.

Acknowledgments. *The authors gratefully acknowledge the management and technical staff of the Boukhadra Iron Mine for facilitating field investigations and providing logistical support. The authors also thank the Department of Mining and Geology of Bejaia University, and are really grateful for Constructive comments from anonymous reviewers. All contributed to improve the quality of this manuscript.*

References.

1. Pérez Velasco, R., & Jarosińska, D. (2022). Update of the WHO global air quality guidelines: Systematic reviews – An introduction. *Environment International, 170*, 107556. https://doi.org/10.1016/j.envint.2022.107556

2. United Nations Environment Programme (2019). *Global Environment Outlook 6: Healthy Planet, Healthy People*. Cambridge University Press. https://doi.org/10.1017/9781108627146

3. Csavina, J., Field, J., Taylor, M. P., Gao, S., Landázuri, A., Betterton, E. A., & Sáez, A. E. (2012). A review on the importance of metals and metalloids in atmospheric dust and aerosol from mining operations. *Science of the Total Environment, 433*, 58-73. https://doi.org/10.1016/j.scitotenv.2012.06.013

4. Entwistle, J. A., Hursthouse, A. S., Marinho Reis, P. A., Stewart, A. G., & Cave, M. (2019). Metalliferous mine dust: Human health impacts and the potential determinants of disease. *Environmental Geochemistry and Health, 41*, 67-83. https://doi.org/10.1007/s10653-018-0195-8

5. Shao, Y., Klose, M., & Wyrwoll, K. H. (2013). Recent global dust trend and connections to climate forcing. *Journal of Geophysical Research: Atmospheres, 118*, 11107-11118. https://doi.org/10.1002/jgrd.50836

6. Middleton, N. J. (2017). Desert dust hazards: A global review. *Research, 24*, 53-63. https://doi.org/10.1016/j.aeolia.2016.12.001

7. Petavratzi, E., Kingman, S. W., & Lowndes, I. S. (2005). Particulates from mining operations: A review of sources, effects and regulations. *Minerals Engineering, 18*(12), 1183-1199. https://doi.org/10.1016/j.mineng.2005.06.017

8. Huertas, J. I., Huertas, M. E., Izquierdo, S., & González, E. D. (2012). Air quality impact assessment of multiple open-pit coal ines in northern Colombia. *Journal of Environmental Management, 93*(1), 121-129. https://doi.org/10.1016/j.jenvman.2011.08.007

9. Baddock, M. C., Strong, C. L., Leys, J. F., Heidenreich, S., Tews, E. K., & McTainsh, G. H. (2014). A visibility and total suspended dust relationship. *Atmospheric Environment, 89*, 329-336. https://doi.org/10.1016/j.atmosenv.2014.02.038

10. Du, C., Wang, J., & Wang, Y. (2022). Study on environmental pollution caused by dumping operation in open pit mine under different factors. *Journal of Wind Engineering and Industrial Aerodynamics, 226*, 105044. https://doi.org/10.1016/j.jweia.2022.105044

11. Shao, Y. (2008). *Physics and Modelling of Wind Erosion*. Springer. ISBN 978-1-4020-8894-0.

12. Dentoni, V., Grosso, B., Pinna, F., Lai, A., & Bouarour, O. (2022). Emission of fine dust from open storage of industrial materials exposed to wind erosion. *Atmosphere, 13*(2), 320. https://doi.org/10.3390/atmos13020320

13. Paluchamy, B., Mishra, D. P., & Panigrahi, D. C. (2021). Airborne respirable dust in fully mechanised underground metalliferous mines – Generation, health impacts and control measures for cleaner production. *Journal of Cleaner Production, 296*, 126524. https://doi.org/10.1016/j.jclepro.2021.126524

14. Shekarian, Y., Rahimi, E., Rezaee, M., Su, W.-C., & Roghanchi, P. (2021). Respirable coal mine dust: A review of respiratory deposition, regulations, and characterization. *Minerals, 11*(7), 696. https://doi.org/10.3390/min11070696

15. Kung, H.-C., Lin, W.-C., Huang, B.-W., Mutuku, J. K., & Chang-Chien, G.-P. (2024). Techniques for suppressing mineral dust aerosol from raw material stockpiles and open pit mines: A review. *Aerosol and Air Quality Research, 24*, 230166. https://doi.org/10.4209/aaqr.230166

16. Pey, J., Larrasoaña, J. C., Pérez, N., Cerro, J. C., Castillo, S., Tobar, M. L., de Vergara, A., ..., & Causapé, J. (2020). Phenomenology

and geographical gradients of atmospheric deposition in southwestern Europe: Results from a multi-site monitoring network. *Science of the Total Environment, 744*, 140745. https://doi.org/10.1016/j.scitotenv.2020.140745
17. Ogrizek, M., Kroflič, A., & Šala, M. (2022). Critical review on the development of analytical techniques for the elemental analysis of airborne particulate matter. *Trends in Environmental Analytical Chemistry, 33*, e00155. https://doi.org/10.1016/j.teac.2022.e00155
18. Stach, R., Barone, T., Cauda, E., & Mizaikoff, B. (2021). A novel calibration method for the quantification of respirable particles in mining scenarios using Fourier transform infrared spectroscopy. *Spectroscopy, 75*(3), 307-316. https://doi.org/10.1177/0003702820968062
19. Trechera, P., Moreno, T., Córdoba, P., Moreno, N., Zhuang, X., Li, B., Li, J., Shangguan, Y., ..., & Querol, X. (2020). Mineralogy, geochemistry and toxicity of size-segregated respirable deposited dust in underground coal mines. *Journal of Hazardous Materials, 399*, 122935. https://doi.org/10.1016/j.jhazmat.2020.122935
20. Wang, Z., Zhou, W., Jiskani, I. M., Luo, H., Ao, Z., & Mvula, E. M. (2022). Annual dust pollution characteristics and its prevention and control for environmental protection in surface mines. *Science of the Total Environment, 825*, 153949. https://doi.org/10.1016/j.scitotenv.2022.153949
21. Yu, H., & Zahidi, I. (2023). Environmental hazards posed by mine dust, and monitoring method of mine dust pollution using remote sensing technologies: An overview. *Science of the Total Environment, 864*, 161135. https://doi.org/10.1016/j.scitotenv.2022.161135
22. Weaver, I. S., Williams, H. T. P., & Arthur, R. (2021). A social Beaufort scale to detect high winds using language in social media posts. *Scientific Reports, 11*, 3647. https://doi.org/10.1038/s41598-021-82808-x
23. Dunlop, S. (2017). *Weather: A Very Short Introduction*. Oxford University Press. ISBN 978-0-19-957131-4 (print); ISBN 978-0-19-178335-7 (online). https://doi.org/10.1093/actrade/9780199571314.001.0001
24. Kia, S., Flesch, T. K., Freeman, B. S., & Aliabadi, A. A. (2021). Atmospheric transport over open-pit mines: The effects of thermal stability and mine depth. *Journal of Wind Engineering and Industrial Aerodynamics, 214*, 104677. https://doi.org/10.1016/j.jweia.2021.104677
25. Liu, Y., Xu, R., Ziegler, A. D., & Zeng, Z. (2022). Stronger winds increase the sand-dust storm risk in northern China. *Environmental Science: Atmospheres, 2*, 1259-1262. https://doi.org/10.1039/D2EA00058J

Новий методологічний підхід WIF–ESH до зонування екологічної небезпеки аерозолів гірничого виробництва в напівпосушливих умовах

О. Камлі[*1], *З. Хадеф*[2], *К. Камлі*[2], *А. Аззі*[3], *М. Фредж*[1], *А. Саадун*[1]

1 – Університет Беджаї, Технологічний факультет, кафедра гірничої справи та геології, м. Беджая, Алжир
2 – Університет «20 серпня 1955 року», лабораторія машинобудування та матеріалів, м. Скікда, Алжир
3 – Університет Беджаї, Технологічний факультет, кафедра електротехніки, м. Беджая, Алжир
[*] Автор-кореспондент e-mail: ouarda.kamli@univ-bejaia.dz

Мета. У даному дослідженні запропонована нова система оцінювання впливу на навколишнє середовище аерозолів гірничого виробництва, багатих на залізо, що утворюються під дією вітру, у залізорудній області Бухадра (ВК) на північному сході Алжиру.

Методика. Зразки осаду пилу, ґрунту й руди були зібрані на території шахти й на відстані до 2 км від основних джерел викидів у перехідний період березень–квітень. У межах запропонованої системи WIF–ESH були комплексно застосовані мінералогічний (XRD), геохімічний (XRF, трикислотне розщеплення, УФ-видима спектрофотометрія та ААС) аналізи, гравіметричні вимірювання осадження пилу, аналіз вітрових характеристик і характеристика джерел викидів.

Результати. Серед осаджених аерозолів переважають гематит, кварц і карбонатні мінерали. Концентрації Fe_2O_3 досягали приблизно 27 %, тоді як інтенсивність осадження пилу становила від 92,8 до 239,2 г · м$^{-2}$ · добу$^{-1}$, перевищуючи міжнародно визнані орієнтовні значення для шкідливого пилу. Результати свідчать про те, що на розсіювання аерозолів впливають не лише панівні вітри, але й мінливий перерозподіл частоти виникнення вітрів під час сезонних перехідних періодів. Інтеграція моделі WIF з ESH покращує інтерпретацію шляхів перенесення аерозолів і зонування екологічних ризиків.

Наукова новизна. Головним внеском цього дослідження є запровадження показника «частоти вітрового впливу» (WIF) як нового екологічного дескриптора для оцінки розсіювання аерозолів гірничого виробництва. У поєднанні з ієрархією джерел викидів (ESH) і традиційними мінералогічними, геохімічними й аналізами осадження запропонована модель WIF–ESH забезпечує початкову методологічну основу для подальших прогнозних досліджень перенесення аерозолів та оцінки екологічної небезпеки у напівпосушливих гірничодобувних регіонах.

Практична значимість. Запропонована система сприяє покращенню екологічного моніторингу й оцінювання небезпеки аерозолів, що утворюються в результаті гірничодобувної діяльності, а після подальшої валідації може бути застосована для визначення джерел забруднення, управління станом навколишнього середовища, планування землекористування й геологічного картографування.

Ключові слова: *частота вітрового впливу (WIF), ієрархія джерел викидів (ESH), напівпосушливі умови, залізорудна шахта «Бухадра»*