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Air Quality and Strategic Environmental Assessment in Artisanal and Industrial Mining Contexts: Evaluating the Effectiveness of ESIAS in the Kedougou Region, Senegal (West Africa)

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Abstract

Air quality degradation in mining regions is a critical challenge for environmental governance and public health, particularly in West Africa. This pioneering study evaluates ambient air quality in Senegal's Kedougou region by triangulating Environmental and Social Impact Assessments (ESIAs) from major mining projects with independent field measurements (2021-2024). We analyze spatiotemporal trends in particulate (PM_{10}, $PM_{2.5}$) and gaseous (NO_2, SO_2, CO) pollutants, compare them to national/WHO standards, and compute the Air Quality Index (AQI) using US EPA methods. Results show frequent exceedances (WHO limits) for PM, especially during dry-season in the mining corridors due to industrial activities (extraction, crushing, transport), while wet-season rainfall reduces concentrations. Artisanal mining zones exhibit unhealthy AQI (>100), contrasting with moderate AQI (51 - 100) in industrial areas, a statistically significant disparity ($p < 0.01$). The study exposes critical gaps in current ESIAs: omission of $PM_{2.5}$, methodological flaws, lack of seasonal monitoring, and incomplete coverage of high-risk zones. As a first-of-its-kind approach, it proposes concrete tools for governance reform, including real-time monitoring, participatory management, and systematic AQI integration into Strategic Environmental Assessments (SEAs). These recommendations aim to guide future research and align policies with Sustainable Development Goals (SDGs 3, 11, and 13). Furthermore, this work synergizes with complementary studies on the Hydrological Pressure Index (HPI) and Soil Quality Index

(SQI), enabling, through local development diagnostics—the development of an Environmental Vulnerability Index (EVI) for mining areas. This framework advances data-driven decision-making for sustainable territorial planning.

Keywords

Air Quality Index, Mining Pollution, Particulate Matter, Environmental Governance, West Africa, Strategic Environmental Assessment

1. Introduction

Air quality refers to the concentration of atmospheric pollutants that may affect human health, ecosystems, and infrastructure. It is a key indicator of environmental conditions and a major public health concern, particularly in regions under intense industrial pressure such as mining zones in West Africa [1] [2]. In these contexts, the air is often degraded by a wide range of pollution sources associated with various stages of the mining cycle: blasting, extraction, crushing, transportation, combustion, chemical processing, and waste storage [3]. These emissions include both primary pollutants (directly emitted in the atmosphere) and secondary pollutants (formed through physicochemical transformations), whose distribution depends on meteorological conditions, topography, and the intensity of extractive activities [4] [5].

Key air pollutants include suspended particulate matter with an aerodynamic diameter < 2.5 µm ($PM_{2.5}$) and <10 µm (PM_{10}), and gaseous pollutants such as nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), and tropospheric ozone (O_3). Globally, around 50% of fine particulates originate from mineral dust, a significant share of which is attributed to mining operations [6]. These particles contribute to a well-documented rise in respiratory and cardiovascular diseases, particularly among vulnerable groups such as children and the elderly [1] [7] [8]. According to the World Health Organization (WHO), air pollution is responsible for more than seven million premature deaths annually, with exposure levels in Sub-Saharan African mining areas considered especially concerning [1] [9]. Beyond its health impacts, air pollution also leads to the degradation of crops, soils, and adjacent ecosystems, and has a direct and indirect effect on the Earth's climate [8].

Air quality standards (**Table 1**), established by international (WHO, International Finance Corporation: IFC) and national bodies (e.g., NS05-062 for Senegal, [10]), provide benchmarks for comparing measured concentrations to acceptable exposure thresholds based on duration (hourly, daily, annual) and expected health effects [11]. However, the implementation of these standards remains uneven. In West Africa, regulatory frameworks struggle to reconcile international norms with local realities, particularly within artisanal mining operations [12].

Table 1. WHO, IFC, and NS05-062 standards for key air pollutants.

Pollutant	W HO (μg/m^3)	IFC (μg/m^3)	NS05-062 (μg/m^3)	Exposure Duration
PM$_{2.5}$	15 (24 h)	25 (24 h)	25 (24 h)	24 h/Annual
PM$_{10}$	45 (24 h)	50 (24 h)	50 (24 h)	24 h
NO$_2$	25 (24 h)	200 (1 h)	200 (1 h)	1 h/24 h
SO$_2$	40 (24 h)	125 (24 h)	125 (24 h)	24 h
CO	4 mg/m^3 (24 h)	10 mg/m^3 (8 h)	10 mg/m^3 (8 h)	8 h/24 h
O$_3$	100 (8 h)	100 (8 h)	100 (8 h)	8 h

Air pollution in mining contexts has been widely studied in Latin America and South Asia, but remains underexplored in Africa, despite recent progress in countries such as Ghana, Burkina Faso, Mali, and Nigeria [13] [14]. In Senegal, studies by [15] [16] have documented local perceptions in the Kedougou region (Khossanto, Diabougou, etc.), reporting recurring respiratory symptoms and high exposure to airborne dust. These alerts are often sidelined by authorities due to the lack of effective environmental monitoring systems, especially in artisanal gold mining zones.

Environmental and Social Impact Assessments (ESIAs) conducted by mining operators also show substantial limitations: absence of temporal series, non-georeferenced data, lack of methodological transparency, and failure to apply WHO standards [17] [18]. National monitoring systems remain rudimentary, with few fixed stations, limited data availability, and low institutional capacity, especially in rural areas.

In this context, the production of long-term and spatially distributed data has become a priority. This study adopts an innovative dual approach: 1) a critical review of the ESIAs of the main industrial mining projects in the Kedougou region, and 2) an independent field measurement campaign conducted between 2021 and 2024. The data are analyzed using an Air Quality Index (AQI), based on the methodology of the US EPA [19], weighted by the health impacts of pollutants. This study is the first of its kind to examine the temporal and spatial changes of air quality in the region of Kedougou based on field measurements over multiple years. The objective is to provide a strategic tool for environmental decision-making, aligned with the principles of Strategic Environmental Assessment (SEA) and the Sustainable Development Goals (SDGs 3, 11, 13). Following [20], our approach emphasizes three dimensions of environmental justice: equitable distribution of pollution burdens, recognition of artisanal miners' vulnerability, and participatory governance to legitimize air quality policies.

2. Materials and Methods

2.1. General Approach

The methodological approach adopted in this study is based on a robust triangulation of data from two main sources (**Figure 1**). First, we analyzed the Environmental and Social Impact Assessments (ESIAs) conducted for the major industrial mining projects operating in the Kedougou region. Second, we carried out a series of independent air quality measurement campaigns between 2021 and 2024 across several localities affected by both industrial and artisanal mining activities. This dual approach aims to cross-reference the institutional narratives and regulatory data produced through official frameworks with the actual environmental conditions observed in the field.

First, to explore the potential impact of the mining activities on the air quality, the seasonal variation of the concentrations of air pollutants ($PM_{2.5}$, PM_{10}, NO_2, SO_2, and CO) were determined and compared to air quality standards set by the WHO and the national standard NS05-062 (Table 1), and their potential sources were investigated. Then, we calculated the AQI for each site, following a two-step methodology summarized in Figure 1. The first step involved the computation of partial indices (AQI_i) for each pollutant individually. These pollutants were measured directly on-site using spot sampling techniques, with concentrations expressed in micrograms per cubic meter ($\mu g/m^3$). Each recorded concentration (C_i) was then compared to the corresponding WHO guideline threshold (N_i) to determine a partial index. The number 1.5 represents a potentially unhealthy level, capping the index at 150 to avoid excessive distortion by extreme values while still capturing significant exceedances. The AQI is then divided into categories, with each category corresponding to a specific color and level of air quality and associated health concerns (US EPA, 2024, Table 2). The second step consisted of aggregating

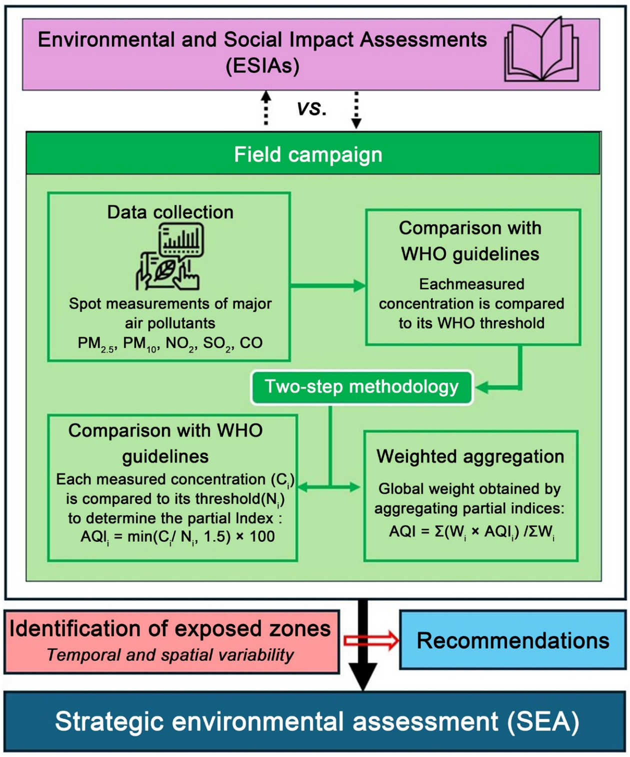

Figure 1. Methodological approach adopted in this study.

Table 2. AQI categories, corresponding color, levels and description of health concerns (US EPA, 2024).

Values of Index	Colors	Levels of Concern	Description
0 - 50	Green	Good	Air quality is satisfactory, and air pollution poses little or no risk.
51 - 100	Yellow	Moderate	Air quality is acceptable. However, there may be a risk for some people, particularly those who are unusually sensitive to air pollution.
101 - 150	Orange	Unhealthy for Sensitive Groups	Members of sensitive groups may experience health effects. The general public is less likely to be affected.
>150	Red to maroon	Unhealthy to Hazardous	Some members of the general public may experience health effects; members of sensitive groups may experience more serious health effects (1.51 - 200). Health alert: The risk of health effects is increased for everyone (201 - 300). Health warning of emergency conditions: everyone is more likely to be affected (>300).

these partial indices into a single global score (AQI_global), using a weighted average, where the weights w_i represent the relative health impact of each pollutant (**Appendix 2**). For instance, pollutants such as $PM_{2.5}$ are typically assigned higher weights due to their well-documented effects on respiratory and cardiovascular health.

This methodological approach (**Figure 1**) allows for a scientifically grounded, spatially differentiated evaluation of air quality in mining zones and provides a basis for SEAs that integrate both institutional and empirical evidence. It provides an anticipatory interpretation of environmental impacts, as many pollutants are initially detected in the atmosphere before migrating to other environmental matrices such as water, soil, or biota [5]. Unlike Environmental Impact Assessments (EIAs), SEA enables the anticipation of cumulative and cross-sectoral impacts at the territorial scale [21] [22]. However, air quality remains largely overlooked, despite its significant health and strategic implications [15] [16]. The integration of the AQI into SEA provides a governance lever based on spatially explicit and standardized data [23].

Given the shortcomings of current methods [3], our protocol (**Figure 1**) combines field air quality data and audit of ESIAs, following an approach recognized for mining contexts [19] [23] [24]. The entire approach (**Figure 2**) is rooted in a territorial perspective, taking into account the specific characteristics of the localities Niemenikein the mining areas, the nature of mining activities (industrial processing, blasting, artisanal gold mining), as well as social vulnerabilities (population density, proximity to infrastructure, etc.). This approach goes beyond a one-time diagnostic to offer a strategic interpretation of air pollution dynamics in the Kedougou region, in relation to environmental governance, public health, and sustainable development challenges. It also provides a relevant analytical framework for potential integration into a future regional SEA, particularly by identifying critical zones with high exposure levels and discrepancies between regulatory data

(ESIAs) and actual measurements. This aims to produce a rigorous, context-sensitive analysis that can inform environmental policy formulation tailored to the realities of the territory.

2.2. Description of the Study Area

Located in the far southeast of Senegal, about 600 km from Dakar (Figure 2), the Kedougou region lies at the geological heart of the Birimian gold belt. Since the early 2000s, it has experienced a rapid intensification of extractive activities, marked by the coexistence of large-scale industrial mining projects and numerous artisanal and semi-industrial gold mining sites. Localities such as Sabodala, Khossanto, Niemenike, Bantaco, Tomboronkoto, and Kharakhena have become epicenters of extractive dynamics, transforming both their natural environment and socio-economic structures. The population density in the villages of Kedougou varies between 10 inhabitants per square kilometer in the non-mining areas of Kedougou and 1000 in the mining areas, especially in artisanal gold mining zone [25].

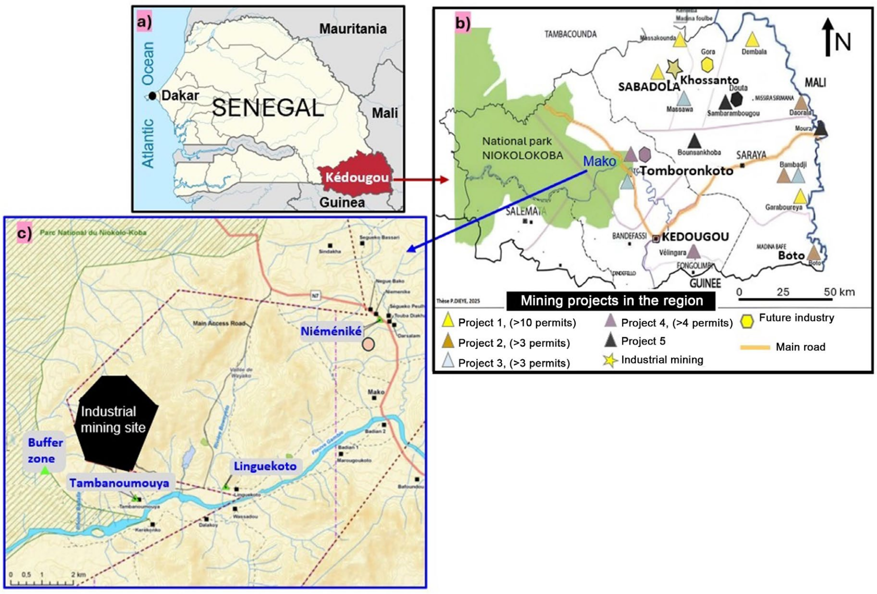

Figure 2. Localisation of the study area: (a) Kedougou region, (b) main mining projects, and c) Mako zone (case study).

In this region, air pollution is significantly exacerbated by the high density of mining projects (Figure 2) and the proliferation of artisanal gold mining sites, which generate diffuse and largely unregulated emissions of dust and gaseous pollutants. Villages located near mining areas—such as Niemenike, Bantaco, Khossanto, and Tomboronkoto—are continuously exposed to atmospheric pollutants. In these localities, diffuse sources of pollution, such as machinery movement, emissions from artisanal mining, transport systems, and uncontrolled waste discharges also contribute to the chronic degradation of air quality. This situation, particularly acute in high-density gold mining zones, presents a documented risk to public health presents a documented risk to public health [26].

In Senegal, there are two main climatic seasons: the dry season and the rainy or dry season. In Kedougou, most of the annual precipitation occurs between May and October (**Table 3**), corresponding to the wet season when the relative humidity (RH) was the highest (66% - 97%). The dry season, from November to April, is characterized by the highest temperature (up to 40˚C) and lowest relative humidity (RH, 12% - 65%). The prevailing wind directions are mostly northwest (NW). However, west-southwest (WSW) and southeastern (SE) winds are frequent during the rainy season [27].

Table 3. Precipitations during the year ANACIM (2025).

Months	Average rainy days	Average rainfall (mm)	Season
January	0.1 j	0.6 mm	Dry
February	0.1 j	0.5 mm	
March	0.2 j	0.8 mm	
April	0.9 j	4.3 mm	
May	7.9 j	43.8 mm	Wet
Jun	19.6 j	128.9 mm	
Juily	26.1 j	230.6 mm	
August	28.3 j	321.5 mm	
September	23.7 j	235.0 mm	
October	11.3 j	72.8 mm	
November	1.5 j	9.2 mm	Dry
December	0.0 j	0.1 mm	

2.3. Data Sources

2.3.1. Data from ESIAs

One of the major contributions of this study is the comparative analysis between data reported in the previous ESIAs of mining projects. A systematic review of ESIA documents has been conducted for major mining projects in Kedougou, focusing on AQI values derived from measured pollutant concentrations. Four dimensions have been considered in our review, including 1) the extent to which air quality issues were addressed, 2) the specific pollutants targeted, 3) the sampling protocols employed, and 4) the regulatory or scientific standards used as reference. To ensure representativeness while optimizing analytical resources, we adopted a stratified sampling of mining sites with validated comparative data, following the purposive sampling approach recommended by [28] for complex environmental studies. **Table 4** presents extracted data from ESIAs of the major project in Kedougou. Among the reviewed projects, only PMC-Mako (2016) and Sored (2018) ESIAs [29] provided field measurements of data of air pollutants [27] [30] respectively, but measurement protocols described in the reports are often not clear or incomplete, lacking details on the instrumentations, confirming [12] regarding the scarcity of atmospheric data in African ESIAs.

Table 4. Comparison of ESIA database of mining projects in Kedougou.

Site/Project	ESIA Sources	Data	AQI Value	Gap or Comments
PMC-Mako	PMC Report, 2016	PM_{10}, $PM_{2.5}$, CO, NO_2	110%	Some measurement data-weak data set
Sored-Khossanto	Sored Report, 2018	PM_{10}	75%	Few fields' values-weak data set, ESIA data lack seasonal consideration
Boto-Madina Bafe	Boto Report, 2019	Modelling (CALPUFF)	30% - 55%	No field data to support modelling
Afrigold-Kolya	Afrigold ESMP, 2021	No data	-	No data on air quality-critical weakness in ESIA
GKK/SGO-Massawa	No data available	-	-	Lack of data

In accordance with WHO and IFC [1] [31] standardized protocols, the ESIA data suffer from significant methodological gaps, including non-representative point measurements (lack of time series or metadata), an overreliance on qualitative assessments, and non-compliance with established scientific protocols (e.g., undocumented EPA or ISO methodologies). This knowledge gap has been reported by [17] in their review of West African ESIAs. These biases, quantified in our critical review, demonstrate the need to complement regulatory data with independent field campaigns, in line with best practices in environmental epidemiology [32]-[34].

2.3.2. Field Data

Due to the lack of air pollution monitoring infrastructure in the country, particularly in Kedougou region, in this study, we took advantage of measurement data collected during regular inspection missions carried out by the Air Quality Management Center of the Ministry of the Environment and Sustainable Development in Senegal. Field data were collected monthly between January 2021 and December 2024 through several measurement campaigns conducted across the main mining zones in the Kedougou region, including artisanal and industrial activities (**Figure 2**, **Table 5**). Measurements were performed at Tomboronkoto including Mako (artisanal and industrial) and Kerekonko (artisanal), at Khossanto (artisanal and industrial) and Boto (industrial). Those locations were selected to provide an insight into the potential population exposure to air pollutants emitted from mining activities in the region. Measurements were carried out at human height (~1.5 m) according to WHO recommendations [1] for a duration up to 30 min per site.

This study focused on the main atmospheric pollutants typically monitored in international air quality assessments, including fine and coarse particulate matter ($PM_{2.5}$ and PM_{10}), nitrogen dioxide (NO_2), carbon monoxide (CO), sulfur dioxide (SO_2), and ozone (O_3). All measurements were carried out in accordance with the protocols recommended by the World Health Organization (WHO) and the United States Environmental Protection Agency (US EPA). Data collection was conducted using portable instruments in real time, calibrated to ensure compliance with WHO and US EPA reference thresholds. Sampling points were georeferenced using a Garmin GPS tracker to ensure spatial accuracy. Particulate matter ($PM_{2.5}$ and PM_{10}) was measured using the Temtop Airing 1000, a particle detector known for its reliable time resolution and portability in field settings. Gaseous pollutants (NO_2, CO, SO_2, O_3) were monitored using the Aeroqual Series 500 (Aeroqual Ltd., New Zealand), equipped with interchangeable electrochemical sensor heads, allowing high-accuracy monitoring of ambient air quality across multiple parameters.

Table 5. Main mining sites investigated in the study, measured pollutants, and the source of the data used (field or ESIA documentation).

Site/Locality		**Type of Mining Activity**	**Pollutants Measured**
Mako zone	Tambanoumouya	Artisanal	PM_{10}, $PM_{2.5}$, CO, NO_2, SO_2
	Linguekhoto	Industrial	
	Buffer zone	Forest	
	Niemenike	Artisanal	
Sored (Khossanto)		Industrial	PM_{10}, $PM_{2.5}$
Boto (Madina Bafe)		Industrial	PM_{10}
Kerekonko		Artisanal	PM_{10}, $PM_{2.5}$, CO

2.3.3. AQI Calculation

The AQI was calculated as in **Figure 1**. The weighting applied to each pollutant is based on its recognized health impact, following the guidelines of [1] [19]. A summary table of the selected weights, along with their methodological justification, is provided in the appendix (see **Appendix 1**).

3. Results

3.1. Case Study at Mako Zone

3.1.1. Seasonal Variation of the Air Pollutant Concentrations

In Mako zone (Tomboronkoto), a sample was collected every month from January 2021 to December 2024 at four sites including Tambanoumouya, Linguekhoto, Buffer zone and Niemenike (**Figure 2**, **Table 5**). The mean concentrations of PM_{10} and $PM_{2.5}$ and NO_2, SO_2, CO and O_3 measured at Tambanoumouya, Linguekhoto, Buffer zone and Niemenike during wet and dry seasons from 2021 to 2024 are shown in **Figure 3**. The concentrations were generally higher during dry season in comparison to the wet season. The difference between the seasons was significantly higher for the particulate matters (PM_{10} and $PM_{2.5}$) exhibiting a dry season to wet season ratios (Dry/Wet ratio) always higher than 3 (**Table 6**). These seasonal contrasts in PM concentrations were statistically confirmed by ANOVA and Wilcoxon tests (see **Appendix 3**). During this season, PM_{10} mean concentrations ranged from 60.7 ± 40.7 μg/m^3 at Buffer zone to 120.9 ± 79.9 μg/m^3 at Linguekhoto, while $PM_{2.5}$ varied from 43.0 ± 33.2 to 74.4 ± 52.5 μg/m^3, respectively. These concentrations were higher than the WHO (45 μg/m^3 and 15 μg/m^3 for 24 h, respectively) and NS (50 μg/m^3 and 25 μg/m^3 for 24 h, respectively) limit values. During the wet season, PM_{10} (11.8 - 16.6 μg/m^3) and $PM_{2.5}$ (9.4 - 13.6 μg/m^3) mean concentrations from the different sites were relatively comparable and were always lower than the WHO and NS limits. During the wet season, heavy and frequent precipitation (926 mm to more than 1300 mm per year) may decrease PM concentrations in ambient air via rainout or washout mechanisms (Hieu and Lee, 2010). The rainfall may also prevent the resuspension of storage piles, soil and road dust (coarse particles). These results are consistent with the strong negative correlation observed between PM_{10} and $PM_{2.5}$ concentration and rainfalls (**Table 7**), suggesting the use of wetting-type dust suppressant for air quality management during mining operations [35].

The coarse particles with an aerodynamic diameter between 2.5 μm and 10 μm ($PM_{2.5-10}$) contributed about 20% of the PM_{10} during wet season while during dry season they contributed between 32 and 40% (**Figure 3**). $PM_{2.5-10}$ exhibited a higher Dry/Wet (5.5 - 19.3) compared to the fine particles with diameter < 2.5 μm (3.2 - 7.9). These coarse particles are generally emitted through mechanical processes by natural and/or anthropogenic sources [36]. In the study area, mechanical operations associated with the mining processes (excavating, crushing, and sintering), as well as the resuspension of storage piles, soils and unpaved roads, likely represent some significant sources of $PM_{2.5-10}$. These results are consistent with the findings of [37] in Burkina Faso, as well as [2] [3], who highlighted the intensification of airborne particulates in active mining environments. During the dry season, the monsoons are characterized by strong and steady winds from December to April, which are favorable conditions for the resuspension of PMs.

Atmospheric gases such as NO_2 and SO_2 showed similar seasonal variation as the PM_{10} and $PM_{2.5}$ (**Figure 3**), but with a lower Dry/Wet ratio, ranging from 1.2 for NO_2 at Niemenike to 3.1 for SO_2 at Tambanoumouya (**Table 6**). The mean concentrations of NO_2 were always lower than the WHO and NS limits (25 μg/m^3 for 24 h and 200 μg/m^3 for 1 h, respectively) during both seasons, while SO_2 always exceeded the limit values (40 μg/m^3 and 125 μg/m^3 for 24 h, respectively) at all sites with values ranging from 157.8 μg/m^3 during wet season to 487.5 μg/m^3 at Tambanoumouya likely influenced by artisanal mining activities. The strong seasonality in NO_2 and SO_2, with average levels approximately 40% higher during the dry season (November-April) aligns with the results reported by [1] [11] in Sub-

Saharan Africa, where the lack of precipitation, dry winds, and thermal inversions contribute to pollutant accumulation and stagnation.

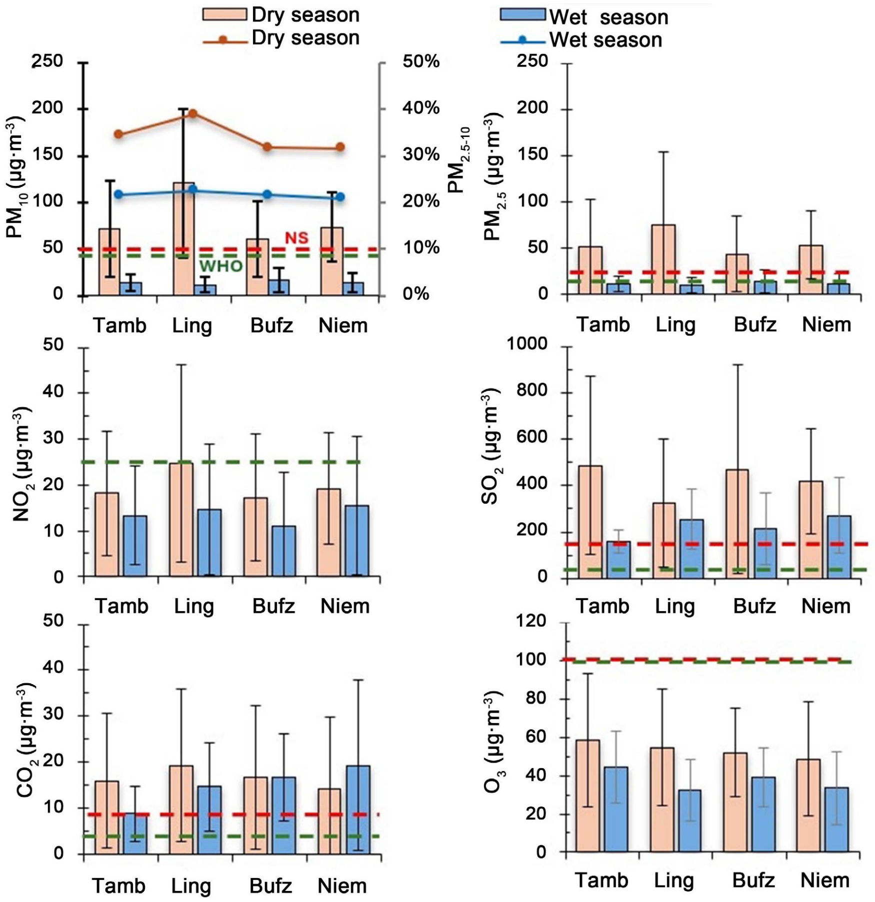

Figure 3. Mean concentrations of PM_{10}, $PM_{2.5}$, NO_2, SO_2, CO, and O_3 measured during wet and dry seasons (2021-2024) at four sites: Tambanoumouya (Tamb), Linguekhoto (Ling), Buffer Zone (Bufz), and Niemenike (Niem). Error bars represent standard deviations. Green and red horizontal lines indicate WHO and NS (Senegalese) limit values, respectively.

Table 6. Dry season to wet season ratios of the concentrations of air pollutants measured at the sampling sites Tambanoumouya (Tamb), Linguekhoto, (Ling) Buffer zone (Bufz) and Niemenike (Niem).

	Dry/Wet			
	Tamb	Ling	Bufz	Niem
PM_{10}	5.3	10.2	3.6	5.2
$PM_{2.5}$	4.7	7.9	3.2	5.0
$PM_{2.5-10}$	8.0	19.3	5.5	6.0
NO_2	1.4	1.7	1.6	1.2
SO_2	3.1	1.3	2.2	1.5
CO	1.8	1.3	1.0	0.7
O_3	1.3	1.7	1.3	1.4

There was no clear seasonal pattern for CO with Dry/Wet ratio ranging from 0.7 at Niemenike to 1.8 at Tambanoumouya (**Figure 3**, **Table 6**). However, its mean concentration (from 8.7 mg/m^3 at Tambanoumouya to 19.2 mg/m^3 at Linguekhoto) also exceeded the WHO and NS limits (4 mg/m^3 and 10 mg/m^3 for 24 h, respectively) at all sites regardless of the season. This could be attributed to the burning of wood and biomass from residential activities (cooking) and bushfires, which are very common in the area. The mean concentrations of O_3 were always below the WHO and NS limits (100 μg/m^3 for 8 h), and show a clear seasonal variation (**Figure 3**, **Table 6**) with higher levels observed during the dry season (Dry/Wet ratio of 1.3 - 1.7). Our measurements reveal significantly higher concentrations of PM_{10} and $PM_{2.5}$ along active mining corridors in the commune of Tomboronkoto especially at Linguekhoto ($p < 0.01$, t-test), with peaks reaching up to three times the thresholds recommended by WHO, likely due to extraction, crushing, and transport phases in the industrial mining area.

3.1.2. An Insight into the Potential Sources of Air Pollutants

Pearson's linear correlation coefficient was used to analyze the relationship of pollutants with each other based on their overall concentrations at the study area (**Table 7**) and between their concentrations at the different individual sites (**Appendix 4**). A significant positive correlation coefficient between pollutants means that their concentrations tend to fluctuate simultaneously due to the influence of common sources, chemical reactions in the atmosphere, and meteorological conditions. Conversely, negative correlation coefficient may suggest different origins or factors influencing the concentration of air pollutants. PM_{10} and $PM_{2.5}$ correlated strongly with each other (R = 0.95 to 0.98) at the study area (**Table 7**), and there was also a strong positive correlation (R = 0.67 to 0.91) between their concentrations at the different sampling locations (**Appendix 4**), suggesting that those locations were likely affected by PM_{10} and $PM_{2.5}$ from the same industrial mining sites of Mako. At individual site, the highest concentrations of PMs (**Figure 3**) and the strongest correlation between them (0.98) were observed at the Linguekhoto which is mostly downwind of the industrial mining site (NW) and is therefore more affected by that source in comparison to other sites. Linguekhoto is also influenced by the traffic of vehicles and motorcycles on unpaved roads.

Gaseous pollutants NO_2, SO_2 and CO which can be co-emitted by various combustion sources in the study area (traffic, wood and biomass combustion, artisanal mining) are sometimes correlated with each other, especially between Linguekhoto and its nearest sites (Tambanoumouya and Buffer zone, **Appendix 4**). Overall (**Table 7**), NO_2 and SO_2 did not correlate with the PMs originating mainly from non-combustion sources of the mining operations (excavating, crushing, sintering, dust resuspension…). At individual sites, this trend is confirmed for NO_2, except at Niemenike where there was a weak correlation (R = 0.20 to 0.30) with the PM fractions. Niemenike is crossed by the national road N7 (**Figure 2(c)**), and traffic may also contribute to both NO_2 and PM concentrations. Interestingly, there was a weak to moderate correlation (R = 0.19 to 0.49) between SO_2 and $PM_{2.5}$.

$_{10}$, except at Niemenike. Besides mining operations emitting coarse particles, heavy trucks and engines could also be an important source of SO_2, particularly due to the use of diesel fuel, which often contains sulfur. CO and the PMs are sometimes weakly to moderately correlated between Tambanoumouya, Linguekhoto and Buffer zone (**Table 5**), likely due to wood and biomass burning [38].

O3 was moderately correlated with NO_2 in the study area (**Table 7**). Tropospheric or ground-level O_3 can be formed by photochemical reactions involving gaseous pollutants such as volatile organic compounds (VOCs) and nitrogen oxides (NO and NO_2). Therefore, the higher levels of NO_2 together with the maximum sunshine (minimum cloud cover) and temperature reached during dry season certainly promote O_3formation during this season.

Table 7. Overall Pearson correlation coefficients between air pollutants in the study area.

	PM_{10}	$PM_{2.5}$	$PM_{2.5\text{-}10}$	NO_2	SO_2	CO	O_3	Rainfall
PM_{10}	1.00							
$PM_{2.5}$	0.97	1.00						
$PM_{2.5\text{-}10}$	0.80	0.65	1.00					
NO_2	−0.17	−0.17	−0.07	1.00				
SO_2	−0.07	−0.12	0.07	0.12	1.00			
CO	0.15	0.23	−0.09	−0.08	−0.19	1.00		
O_3	−0.06	0.01	−0.19	0.46	−0.10	−0.07	1.00	
Rainfall	−0.81	−0.73	−0.82	−0.37	0.09	0.37	−0.05	1.00

3.1.3. Air Quality before and during the Industrial Mining Activities

Inspecting changes in air quality can help to revise air quality guidelines and enable policymakers and researchers to examine the effects of the evolution of air pollution on public health. This subsection compares the air quality data extracted from ESIAs conducted before implementation of the major mining industry at Mako to the data from our field campaign in 2021-2024 (**Figure 4**). For each pollutant (PM_{10}, $PM_{2.5}$, $PM_{2.5\text{-}10}$, NO_2, SO_2 and CO), the concentration enhancement coefficient (EC) is calculated as the ratio between mean concentration measured during 2021-2024 ($C_{2021\text{-}2024}$) and its baseline ($C_{baseline}$) taken as the concentration measured before implementation of the mining industry:

$$\text{EC} = \frac{C_{\text{2021-2024}}}{C_{\text{baseline}}}$$

In theory, EC value higher than 1 suggests an increased concentration due to the emissions from the mining industries or activities connected to its implementation in the area.

The PM_{10} shows a distinct seasonal variation of the EC with values above 1 during the dry season, ranging from 1.19 at Tambanoumouya to 2.02 at Linguekhoto, while EC was below 1 during the wet season (**Figure 4**). $PM_{2.5\text{-}10}$ shows similar seasonal patterns as PM_{10}, but with a higher EC (1.82 at Tambanoumouya to 4.31 at Linguekhoto). For $PM_{2.5}$, there was no clear seasonal variation of EC ranging from 1.04 Tambanoumouya during the dry season to 4.70 at Buffer zone during the wet season. These fine particles may pose the greatest health problems, because they are more likely to absorb more harmful substances and they can penetrate deeper into the respiratory tract, reaching the lungs and some of them are small enough to get into the bloodstream [7] [39]. The higher EC for the PMs may suggest an impact of the industrial mining activities on the air quality in the Mako zone, leading to negative effects on community health. This value is consistent with [37], who highlighted impact of gold extraction activities on PM_{10} concentrations.

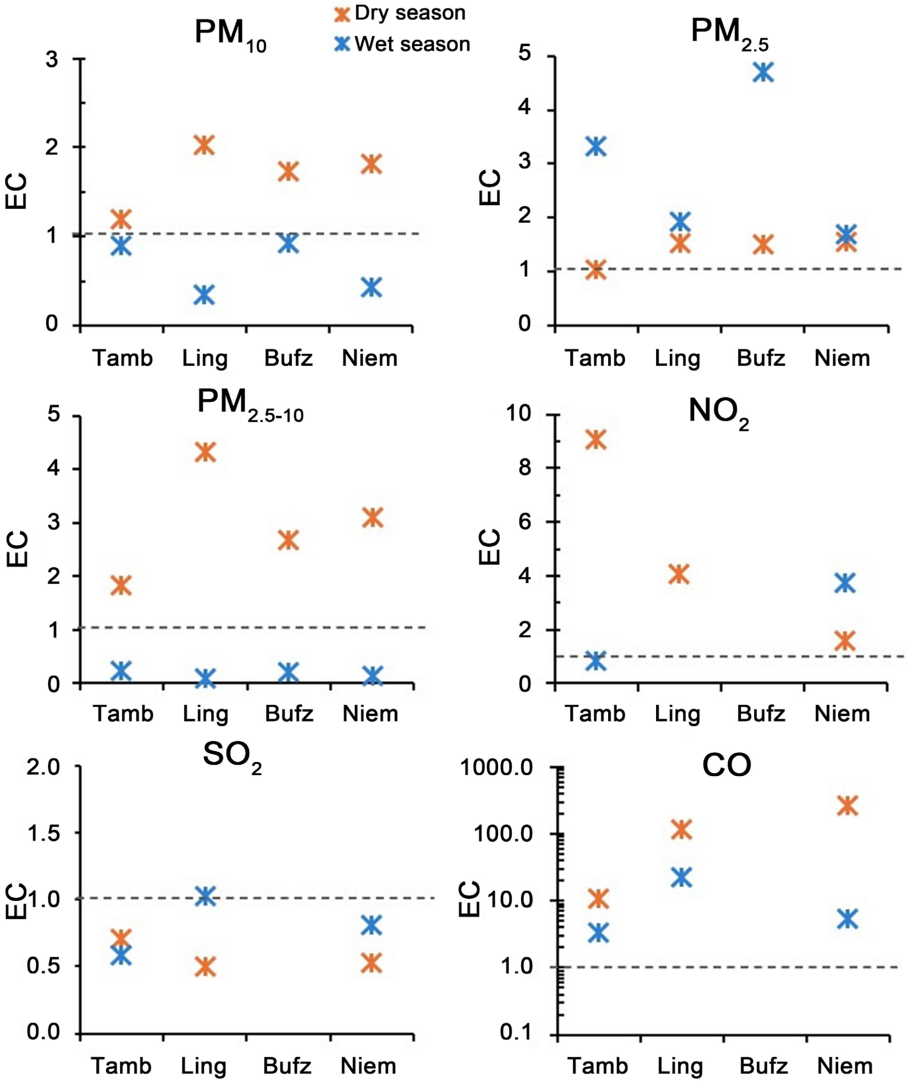

Figure 4. Concentration enhancement coefficient (EC) for PM_{10}, $PM_{2.5}$, $PM_{2.5-10}$, NO_2, SO_2, and CO measured during wet and dry seasons at Tambanoumouya (Tamb), Linguekhoto, (Ling) Buffer zone (Bufz) and Niemenike (Niem).

For NO_2, EC ranged from 0.81 to 4.05 with no clear seasonal pattern (**Figure 4**). For SO_2, EC varied between 0.53 and 1.03 despite some exceedances of the WHO limits during both seasons. The highest EC values were observed for CO displaying a clear seasonal variation, with values varying from 3.42 during wet season at Tambanoumouya to 259.09 during dry season at Niemenike. CO concentrations seem to be more affected by anthropogenic activities in the Mako zone.

3.2. Spatial Variability of AQI Values: Industrial vs. Artisanal Mining Sites

The AQI from six mining sites have been compared based on our field campaign (**Figure 5**), including three industrials (Mako, Khossanto and Boto) and three artisanal (Mako/Tambanoumouya, Khossanto and Kerekonko and a background site (Mako periphery, >10 km to mining site). AQI was always higher at artisanal sites with relatively comparable AQI ranging from 128 at Khossanto to 145 at Kerekonko. These results suggest potential health effects on members of sensitive groups in those sites and villages (people with heart or lung disease, older adults, children and teenagers, pregnant women, and outdoor workers, US EPA, 2024). The industrial sites showed moderate air quality with AQI varying from 60 in Boto to 85 in Mako. In those areas, chronic exposure could be particularly of concern for nearby populations and vulnerable groups (unusually sensitive people), as supported by the findings of [40].

However, AQI had a high spatial variability within a given zone. In artisanal zones, the higher AQI values (>130) were obtained at Tambanoumouya and Kerekonko. Beyond artisanal activities, these villages could also be affected by emissions from the industrial activities and traffic within the mining corridor. In this area, there was a strong proximity-pollution correlation ($r = 0.82$; $p < 0.01$) with "Good" air quality zones (AQI < 50) observed at Mako periphery over 5 km radius of mining sites. In the industrial zone of Mako, AQI varied from 10 to 90, but pollution peaks (higher AQI, $p < 0.05$, ANOVA) were observed near crushing area. Similar results were also observed at Khossanto industrial zone (Sored) despite an AQI of 75%. Localized pollution peaks near crushing areas have been reported by [28] [40]-[42] in West African mines. The spatially heterogeneous exposures, due to the combination of stationary and diffuse emission sources in the regions, could be effectively captured through spatial mapping, which serves as a critical tool for SEA by revealing spatial inequalities in pollutant exposure and reinforcing the need to integrate air quality data into territorial prevention and adaptation strategies [27] and [30].

This graph highlights a significant disparity in air quality between industrial and artisanal mining areas, with artisanal sites consistently showing higher AQI values, suggesting increased exposure and potential health risks for local populations. The 'Mako periphery' site (35) serves as a comparison point for an area not directly impacted by mining activities.

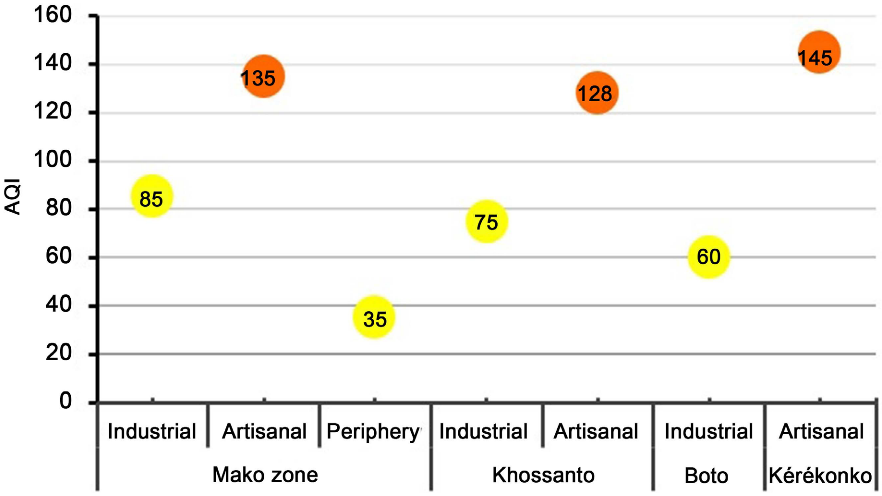

Figure 5. Spatial variability of the Air Quality Index (AQI) comparing industrial and artisanal mining sites in the Kédougou region (2021-2024).

3.3. Comparison of AQI Values between ESIAs and Field Data

This subsection discusses AQI values in the Kedougou region, comparing data from official ESIAs to independent field measurements (2021-2024). The comparison was conducted among the ESIA database, and observations have been made at several levels including data availability, number and diversity of pollutants measured and seasonality.

The AQI is estimated only for PM_{10} for ESIA from PMC-Mako and Sored, while our field campaigns (2021-2024) include AQI for additional indicators such as $PM_{2.5}$, CO, NO_2, etc (Figure 6). At Mako, the ESIA reported an AQI-PM10 of 110 (Table 4). This is comparable to the average annual AQI-PM_{10} (102) measured during our field campaign, indicating unhealthy for sensitive groups. However, our field investigation shows higher AQI-PM_{10} and AQI-$PM_{2.5}$, especially during the dry season (Figure 6), likely due to the impact of mining activities. For NO_2, SO_2 and CO, AQI ranged generally from moderate to unhealthy for sensitive groups with no clear seasonal pattern, although the highest values were mostly obtained in dry season, especially for SO_2 (145) and CO (137).

At semi-industrial sites such as Sored-Khossanto, similar AQI-PM_{10} was obtained for both ESIA and our field study indicating a moderate air quality. For the Boto project (IAMGOLD [43]), AQI estimates presented in the ESIA are based solely on digital modelling (CALPUFF [31]), without any validation through field measurements. The estimated AQI (30% - 55%) indicates good to moderate air quality, but this purely theoretical approach contrasts with the [19] recommendation of coupling models with measurements in mining studies, as demonstrated by [44] in similar geological contexts. Our field investigation showed a slightly higher AQI (60).

The Afrigold case (Kolya) reveals a total lack of air quality data. This methodological gap, already reported by [15] [17] for Senegalese ESIAs regionally, is of

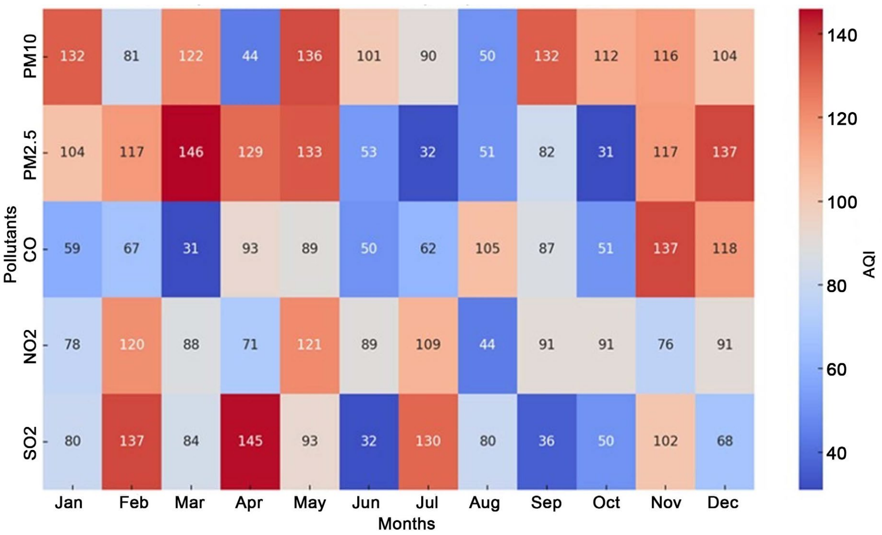

Figure 6. Heatmap of monthly AQI values measured at PMC-Mako (2021-2024), highlighting pollution peaks for PM_{10} and $PM_{2.5}$ during the dry season. The AQI is presented as a percentage to facilitate its analysis where 100% represents reaching the reference threshold, and higher values indicate exceeding.

big concern in poorly regulated mining countries [45]. Similar limitations are observed in SGO projects [43] [46], where unverified extrapolations increase uncertainty, as reported by [23]. These findings reveal a critical misalignment between local monitoring practices and international standards [1] [47], suggesting the urgent need for methodological harmonization, and the implementation of continuous air quality monitoring.

Therefore, AQI integration can serve as a tracking protocol, in line with emerging requirements under the forthcoming EU regulatory frameworks on responsible mining (e.g., Critical Raw Materials Act, COM/2023/160 final). As emphasized by [40], the effectiveness of any monitoring system relies primarily on the quality and transparency of the data it produces. Future ESIAs should systematically integrate a broader range of air pollutants (e.g., $PM_{2.5}$, combustion-related gases, heavy metals, and VOCs), extend the spatial scope of monitoring, and promote the use of low-cost, validated sensors [3], in alignment with environmental justice frameworks [20]. As emphasized by [48], cross-validation between field data and ESIA reports is essential to reduce methodological uncertainties and strengthen environmental interpretation. This approach—validated by [23] in mining contexts and supported by [27] [30]—reinforces the relevance of mapping tools for SEA and sustainable territorial governance.

4. Discussion

This discussion critically examines the findings of the study in light of the structural limitations of ESIAs, disparities in population exposure, and the potential of the AQI to enhance strategic environmental evaluation in mining areas.

4.1. Structural Limitations of Current ESIAs

The analysis reveals that 78% of the reviewed ESIAs (n = 15) remain confined to minimal regulatory compliance (OECD, 2022), marked by opaque modeling procedures—as illustrated in the Afrigold and Boto cases—that conflict with transparency principles in ISO 14016:2020. Furthermore, these assessments systematically exclude artisanal mining zones, despite unhealthy air (AQI > 100) being documented in such areas with no official coverage. In contrast, the PMC-Mako case illustrates that a rigorous and transparent approach—combining modeling, field data, and community engagement—is feasible when three enabling conditions are met: 1) strengthening technical capacities through training aligned with US EPA standards; 2) establishing a public environmental data platform (cf. Ghana Minerals Commission, 2023); and 3) implementing graduated sanctions for regulatory non-compliance (Ministry of Environment, 2022, Art. 45).

4.2. Differentiated Exposure and Environmental Injustice

Results of this study suggest that air quality in Kedougou is affected by mining activities, traffic and emissions from residential areas. High concentrations and frequently exceeded limit values, especially for PMs were most observed during the dry season. AQI values across the region indicate statistically significant disparities in pollutant exposure (Wilcoxon test, $p < 0.01$) between industrial and artisanal areas. In industrial sites (e.g., Mako, Boto), average AQI levels remain within IFC (2007) standards (60 to 85), with residential zones located 1.2 to 2.5 km away. By contrast, artisanal zones exhibited higher AQI values between 128 and 145 with residential exposure occurring at distances of less than 500 meters, and in the complete absence of formal monitoring mechanisms. This duality illustrates a structural environmental injustice, where vulnerable populations are simultaneously subjected to higher health risks—with an odds ratio of 3.2 (95% CI: 2.1 - 4.8) indicating they are over three times more likely to suffer from respiratory illnesses—and to major gaps in environmental oversight, as only 12% of ESIAs include artisanal mining zones. Spatial analysis using 100 m resolution heatmaps reveals a strong positive correlation ($r = 0.78$) between population density and air pollution levels (AQI), reinforcing the conclusions of Lidskog *et al.* (2022) regarding the unequal distribution of environmental burdens in mining territories.

These results suggest a recalibration of monitoring perimeters to include peripheral residential areas, the establishment of differentiated thresholds adapted to exposure contexts, and the implementation of targeted health compensation schemes in line with the "polluter-pays" principle. Although comprehensive epidemiological data (e.g., hospital records, prevalence rates) were unavailable, the health risks associated with chronic exposure to elevated AQI levels—particularly $PM_{2.5}$ and PM_{10}—are well documented (WHO, 2021; Cohen *et al.*, 2017). Future studies incorporating community-level health data and participatory surveys are recommended to reinforce the observed exposure–health linkages (**Appendix 2**).

4.3. Air Quality and Environmental Governance in Mining Areas

As a proxy of air pollution level and potential health risks associated with it, AQI has demonstrated its value as a key tool within the framework of SEA for mining activities, considering three dimensions:

- **Environmental assessment**: it enables a multicriteria synthesis of air pollution aligned with prescribed thresholds and supports objective prioritization of health risks;
- **Comparative and temporal analysis**: it facilitates benchmarking across sites (Becerra *et al.*, 2019) and detects seasonal trends (e.g., dry vs. wet season, $p < 0.05$, ANOVA, 2021-2024 series);
- **Decision-support for territorial planning**: high-resolution exposure maps (100 m) integrate socio-environmental vulnerabilities into spatial decision-making tools (Geneletti, 2011).

These dimensions can be used to evaluate the impact of the strategic environmental plan on current air quality conditions. However, limitations must be acknowledged. Aggregation effects may obscure short-term pollution peaks (up to +40% deviation), necessitating the integration of continuous monitoring systems [3]. Moreover, optimal use of the AQI requires transparency in pollutant weighting schemes, participatory validation of indicators with local communities (UNECE, 2018), and context-specific calibration of thresholds, particularly in artisanal zones.

Despite the inherent complexity of the Kedougou region, characterized by the presence of numerous mining sites that potentially emit air pollutants, this study demonstrates that integrating AQI into SEA frameworks provides substantial benefits. It enhances risk prioritization through spatialized exposure data [21] [30], supports multi-scalar planning [49] [50], and improves the transparency of environmental information shared with communities. **Table 8** shows recommendations for integrating AQI into environmental governance in a mining context. More fundamentally, the AQI is a key driver for reorienting SEA toward a more territorialized, participatory, and anticipatory approach, consistent with international environmental governance standards and grounded in the socio-environmental realities of eastern Senegal. Ultimately, the integration of air quality into SEA is not merely a technical upgrade—it is an ethical imperative for promoting environmental balance and social justice Söderman Therivel Dalal [22] [51] [52].

The successful implementation of these recommendations depends on the creation of enabling conditions, including sustainable financing mechanisms for equipment, capacity-building, and institutional coordination, the standardization of methodologies and pollutant thresholds, aligned with health-based evidence, improved inter-agency coordination across authority bodies, *i.e.,* ministries (environment, health, mining, territorial planning) and the integration of air quality indicators into national development and health surveillance strategies.

These structural reforms are therefore needed to take into consideration the lived realities of mining communities and to achieve the Sustainable Development

Table 8. Recommendations for integrating air quality into environmental governance in mining context.

Recommendations	Description
Institutionalizing the AQI in environmental regulation	• Integrate AQI as a mandatory cross-cutting indicator in all ESIAs, following air quality guidelines (WHO, NS 05-062). • Ensure legal alignment with applicable regional frameworks—such as the UEMOA environmental directives (UEMOA, 2018)—and evolving international guidelines, including forthcoming European standards on responsible mining practices (e.g., anticipated EU Directive on critical raw materials and environmental due diligence, 2024). • Explicitly include other pollutants including $PM_{2.5}$, VOCs (BTEX) in baseline and monitoring protocols, especially in artisanal and peri-urban mining zones.
Enhancing technical and spatial monitoring capacities	• Deploy low-cost, georeferenced air quality monitoring stations, particularly in vulnerable artisanal communities and strategic industrial corridors. • Develop territorialized environmental maps combining AQI data, land use, social vulnerability indices, and cumulative exposure models. • Promote continuous data collection protocols integrated into national early warning systems and SEA platforms.
Embedding air quality into participatory environmental governance	• Establish community-based environmental monitoring committees with open access to validated AQI data and participatory interpretation tools. • Institutionalize the systematic integration of AQI into SEA, not as an add-on but as a core diagnostic and planning instrument. • Promote a differentiated regulatory approach that adjusts thresholds based on proximity, exposure intensity, and social vulnerability.
Mobilizing scientific and civil society actors	• Encourage partnerships between universities, research centers, non-governmental organizations (NGOs), and local authorities to co-produce air quality data and generate public environmental awareness. • Support training programs and citizen science initiatives focused on air pollution monitoring, data analysis, and environmental justice. • Establish multi-actor knowledge platforms to bridge the gap between data generation, decision-making, and community empowerment.

Goals (SDG 3—Good Health, SDG 11—Sustainable Cities, SDG 13—Climate Action). Other chemical compounds such as volatile organic compounds (VOCs, including BTEX compounds), potentially emitted during open combustion or chemical processes in artisanal contexts were not systematically measured in this study due to technical limitations. Their integration into future studies is strongly recommended, in line with the expanded guidelines from [19] [30], to ensure a more comprehensive assessment of atmospheric health risks.

5. Conclusions

This study presents the first long-term, temporal and spatial analysis of air quality in the Kedougou mining region, combining a critical review of ESIAs with independent field measurements collected between 2021 and 2024. The air quality

(AQI) has been evaluated across industrial, semi-industrial, and artisanal mining zones. Higher concentrations especially for PM_{10} and $PM_{2.5}$ were observed in the active mining corridors during the dry season when both WHO and NS05-062 limits were exceeded, likely due to the influence of industrial activities (extraction, crushing, and transport, etc.). During the wet season, heavy and frequent precipitations lead to lower PM concentrations, suggesting the use of wetting-type dust suppressants for air quality management during mining operations. Significant disparities in pollutant exposure were observed in the region, with worser air quality generally observed in artisanal mining zones (AQI > 100) compared to industrial zones (AQI of 51 - 100).

The cross-analysis exposes a persistent underestimation of air quality risks within existing environmental assessment systems and highlights structurally unjust and differentiated exposure patterns. Artisanal zones, often omitted from formal monitoring and ESIAs, concentrate the highest levels of concern. These findings underscore deep shortcomings in regulatory transparency, pollutant coverage, and institutional responsiveness to vulnerable populations.

Beyond this diagnosis, the study confirms the potential of the AQI as a lever for spatialized environmental governance. It allows for the production of synthetic, comparable, and decision-oriented indicators that support inter-site benchmarking and hotspot identification. As such, AQI serves a three-dimensional function: environmental assessment, comparative monitoring, and territorial decision-support. Ultimately, the integration of the AQI into SEA frameworks is not merely a technical enhancement. It is an ethical and governance imperative—anchored in environmental justice and aligned with the goals of equity, transparency, and sustainable development in resource-intensive regions like Kedougou.

To address these challenges, a deep reform of environmental assessment practices in mining contexts is required. This should necessarily go through extending the air quality network covering industrial (mining), urban and rural areas, the deployment of real-time continuous monitoring systems, methodological harmonization including other air pollutants (e.g., VOCs, metals), and the active involvement of local communities in data collection, alert systems, and environmental decision-making.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Appendix 1. Pollutant weighting logic for Air Quality Index (AQI) calculation.

Pollutant	Weight (w_i)	Justification	Source
$PM_{2.5}$	0.35	Highest health impact; deep lung penetration; WHO 2021	WHO (2021)
PM10	0.25	Respiratory irritant; common in mining; EPA 2016	EPA (2016)
NO_2	0.15	Toxic for respiratory tract; short-term exposure; WHO 2021	WHO (2021)
SO_2	0.1	Acid rain contributor; mucous membrane irritant; WHO 2021	WHO (2021)
CO	0.1	Neurological effects at high concentrations; EPA 2016	EPA (2016)
O_3	0.05	Secondary pollutant; respiratory effects; WHO 2021	WHO (2021)

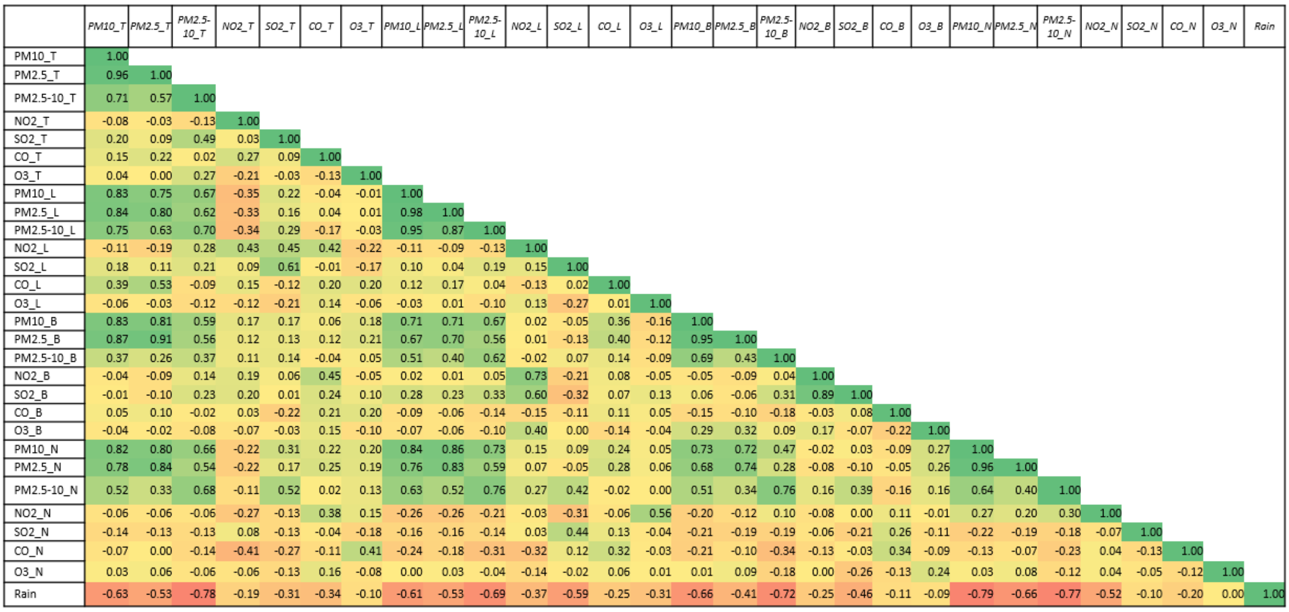
Appendix 2. Epidemiological summary—respiratory health and AQI exposure normalized (with percentage).

Village/Site	Average AQI	Estimated Respiratory Incidence Rate (per 1000)	Source of Data	Most Common Symptoms
Tambanoumouya	135	240	Field interviews + Health post reports	Chronic cough, shortness of breath
Kerekonko	145	265	Field interviews + NGO survey, 2023	Asthma, bronchitis, wheezing
Khossanto	128	210	Local health post, 2022	Chronic rhinitis, phlegm
PMC-Mako	85	125	Hospital records, 2021	Occasional cough, mild respiratory discomfort
Boto	60	90	Community survey, 2023	Minor irritation, no hospitalization

Appendix 3. Statistical summary—seasonal comparison of AQI.

Test	Statistic	p-value	Interpretation
ANOVA	37.46	<0.001	Significant difference between seasons
Wilcoxon signed-rank	0.0	0.018	Significant seasonal effect

Appendix 4. Pearson correlation coefficients between air pollutants measured at the sampling sites Tambanoumouya (T), Linguekhoto, (L) Buffer zone (B) and Niemenike (N).



	PM10_T	PM2.5_T	PM2.5-10_T	NO2_T	SO2_T	CO_T	O3_T	PM10_L	PM2.5_L	PM2.5-10_L	NO2_L	SO2_L	CO_L	O3_L	PM10_B	PM2.5_B	PM2.5-10_B	NO2_B	SO2_B	CO_B	O3_B	PM10_N	PM2.5_N	PM2.5-10_N	NO2_N	SO2_N	CO_N	O3_N	Rain
PM10_T	1.00																												
PM2.5_T	0.96	1.00																											
PM2.5-10_T	0.71	0.57	1.00																										
NO2_T	-0.08	-0.03	-0.13	1.00																									
SO2_T	0.20	0.09	0.49	0.03	1.00																								
CO_T	0.15	0.22	0.02	0.27	0.09	1.00																							
O3_T	0.04	0.00	0.27	-0.21	-0.03	-0.13	1.00																						
PM10_L	0.83	0.75	0.67	-0.35	0.22	-0.04	-0.01	1.00																					
PM2.5_L	0.84	0.80	0.62	-0.33	0.16	0.04	0.01	0.98	1.00																				
PM2.5-10_L	0.75	0.63	0.70	-0.34	0.29	-0.17	-0.03	0.95	0.87	1.00																			
NO2_L	-0.11	-0.19	0.28	0.43	0.45	0.42	-0.22	-0.11	-0.09	-0.13	1.00																		
SO2_L	0.18	0.11	0.21	0.09	0.61	-0.01	-0.17	0.10	0.04	0.19	0.15	1.00																	
CO_L	0.39	0.53	-0.09	0.15	-0.12	0.20	0.20	0.12	0.17	0.04	-0.13	0.02	1.00																
O3_L	-0.06	-0.03	-0.12	-0.12	-0.21	0.14	-0.06	-0.03	0.01	-0.10	0.13	-0.27	0.01	1.00															
PM10_B	0.83	0.81	0.59	0.17	0.17	0.06	0.18	0.71	0.71	0.67	0.02	-0.05	0.36	-0.16	1.00														
PM2.5_B	0.87	0.91	0.56	0.12	0.13	0.12	0.21	0.67	0.70	0.56	0.01	-0.13	0.40	-0.12	0.95	1.00													
PM2.5-10_B	0.37	0.26	0.37	0.11	0.14	-0.04	0.05	0.51	0.40	0.62	-0.02	0.07	0.14	-0.09	0.69	0.43	1.00												
NO2_B	-0.04	-0.09	0.14	0.19	0.06	0.45	-0.05	0.02	0.01	0.05	0.73	-0.21	0.08	-0.05	-0.05	-0.09	0.04	1.00											
SO2_B	-0.01	-0.10	0.23	0.20	0.01	0.24	0.10	0.28	0.23	0.33	0.60	-0.32	0.07	0.13	0.06	-0.06	0.31	0.89	1.00										
CO_B	0.05	0.10	-0.02	0.03	-0.22	0.21	0.20	-0.09	-0.06	-0.14	-0.15	-0.11	0.11	0.05	-0.15	-0.10	-0.18	-0.03	0.08	1.00									
O3_B	-0.04	-0.02	-0.08	-0.07	-0.03	0.15	-0.10	-0.07	-0.06	-0.10	0.40	0.00	-0.14	-0.04	0.29	0.32	0.09	0.17	-0.07	-0.22	1.00								
PM10_N	0.82	0.80	0.66	-0.22	0.31	0.22	0.20	0.84	0.86	0.73	0.15	0.09	0.24	0.05	0.73	0.72	0.47	-0.02	0.03	-0.09	0.27	1.00							
PM2.5_N	0.78	0.84	0.54	-0.22	0.17	0.25	0.19	0.76	0.83	0.59	0.07	-0.05	0.28	0.06	0.68	0.74	0.28	-0.08	-0.10	-0.05	0.26	0.96	1.00						
PM2.5-10_N	0.52	0.33	0.68	-0.11	0.52	0.02	0.13	0.63	0.52	0.76	0.27	0.42	-0.02	0.00	0.51	0.34	0.76	0.16	0.39	-0.16	0.16	0.64	0.40	1.00					
NO2_N	-0.06	-0.06	-0.06	-0.27	-0.13	0.38	0.15	-0.26	-0.26	-0.21	-0.03	-0.31	-0.06	0.56	-0.20	-0.12	0.10	-0.08	0.00	0.11	-0.01	0.27	0.20	0.30	1.00				
SO2_N	-0.14	-0.13	-0.13	0.08	-0.13	-0.04	-0.18	-0.16	-0.16	-0.14	0.03	0.44	0.13	-0.04	-0.21	-0.19	-0.19	-0.06	-0.21	0.26	-0.11	-0.22	-0.19	-0.18	-0.07	1.00			
CO_N	-0.07	0.00	-0.14	-0.41	-0.27	-0.11	0.41	-0.24	-0.18	-0.31	-0.32	0.12	0.32	-0.03	-0.21	-0.10	-0.34	-0.13	-0.03	0.34	-0.09	-0.13	-0.07	-0.23	0.04	-0.13	1.00		
O3_N	0.03	0.06	-0.06	-0.06	-0.13	0.16	-0.08	0.00	0.03	-0.04	-0.14	-0.02	0.06	0.01	0.01	0.09	-0.18	0.00	-0.26	-0.13	0.24	0.03	0.08	-0.12	0.04	-0.05	-0.12	1.00	
Rain	-0.63	-0.53	-0.78	-0.19	-0.31	-0.34	-0.10	-0.61	-0.53	-0.69	-0.37	-0.59	-0.25	-0.31	-0.66	-0.41	-0.72	-0.25	-0.46	-0.11	-0.09	-0.79	-0.66	-0.77	-0.52	-0.10	-0.20	0.00	1.00