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Full Length Research Paper

Assessment of soil quality in mining areas: Cross-analysis of environmental impact assessment (EIA) and field data in Kedougou, Senegal

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Soil contamination remains a critical yet often underestimated challenge in environmental impact assessments (EIAs) of mining projects in West Africa. This study assessed soil quality across 37 industrial and artisanal gold mining sites in the Kédougou region of Senegal. A Mining Soil Quality Index (MSQI) was developed, integrating heavy metal concentrations (As, Pb, Hg, etc.) with international and regional reference thresholds. Combined with a strategic land-use and vulnerability zoning framework, the analysis revealed widespread contamination, with nearly half (45%) of artisanal sites categorized as high-risk zones. The evaluation also exposed major inconsistencies in EIA datasets, including outdated baseline measurements, poor comparability across reports, and a lack of methodological standardization. These findings underscore the urgent need to institutionalize systematic soil monitoring programs, adopt harmonized assessment frameworks across West Africa, and integrate soil quality into Strategic Environmental Assessment (SEA) processes.

Key words: Soil contamination, strategic zoning by land use (QSMA), artisanal mining, environmental impact assessments, land degradation, environmental governance.

INTRODUCTION

Mining remains a cornerstone of economic development in West Africa, yet it generates severe and persistent environmental degradation, particularly through soil contamination by heavy metals. While air and water

impacts are routinely considered in Environmental Impact Assessments (EIAs), soil quality remains critically underrepresented despite its fundamental role in ecosystem services, agricultural productivity, food

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security, and public health.

This gap is especially acute in Senegal's Kédougou region, where the rapid expansion of both industrial and artisanal gold mining has resulted in widespread pedological pollution, with limited monitoring and inadequate mitigation measures. Current EIAs in the region suffer from three interrelated limitations: (1) inconsistent soil sampling protocols, (2) lack of alignment with international standards such as the Food and Agriculture Organization (FAO) and the World Health Organization (WHO) guidelines, and (3) neglect of cumulative and long-term impacts. These weaknesses undermine environmental governance and directly compromise the health and livelihoods of local communities relying on contaminated lands for subsistence agriculture.

Previous studies in comparable mining contexts (Gbané et al., 2021; Chen et al., 2020; Schreck et al., 2022; Wittoh, 2020) have documented heavy metal contamination, but none have systematically bridged the divide between empirical field evidence and EIA reporting practices across an entire mining region.

This study makes three key contributions to address these challenges. First, it introduces an innovative Mining Soil Quality Index (MSQI) that integrates weighted heavy metal concentrations with land-use vulnerability zoning (QSMA). Second, it provides the first comprehensive cross-analysis of EIA reports (2006 to 2023) and field data (2021 to 2024) across 37 industrial and artisanal mining sites in Kédougou. Third, it demonstrates how strategic environmental assessment (SEA) frameworks could be strengthened to include soil quality as a central pillar of mining governance, consistent with Sustainable Development Goal (SDG) 15 (Life on Land).

The findings of this study reveal alarming contamination levels, particularly in artisanal mining zones where mercury concentrations exceed WHO thresholds by up to fifteen-fold. The study also highlights significant discrepancies between EIA reports and field realities, with only 22% of projects maintaining updated soil quality data. These results underscore the urgent need for policy reforms that institutionalize standardized soil monitoring and promote adoption of the MSQI–QSMA framework across West African mining regions.

MATERIALS AND METHODS

Theoretical and normative framework

Soil quality is defined as the capacity of soil to sustain ecological, agricultural, and sanitary functions while maintaining ecosystem productivity and resilience (FAO, 2015). In mining contexts, this quality is often compromised by metallic and organic pollutants released during extraction, ore processing, and waste disposal (Alloway, 2013). Such contaminants disrupt soil functions, reduce fertility, and compromise ecosystem services, including water filtration and greenhouse gas regulation.

Heavy metals represent the most critical threat, notably arsenic (As), lead (Pb), mercury (Hg), nickel (Ni), chromium (Cr), copper (Cu), and zinc (Zn). These metals are dangerous due to their:

- 1) Toxicity: Even at trace levels, Hg and As are highly toxic, causing neurological disorders, cancers, and genetic anomalies (WHO, 2007; Canadian Council of Ministers of the Environment [CCME], 2007).
- 2) Mobility: Pb and Hg are easily mobilized in soils and can migrate to groundwater and rivers, amplifying contamination risks.
- 3) Bioaccumulation: These metals accumulate in organisms and magnify through food chains, with mercury notably reaching hazardous levels in fish consumed by local populations (Gbané et al., 2021).
- 4) Persistence: Heavy metals remain in soils for decades to centuries, complicating remediation and threatening future generations.

Mercury, in particular, poses a severe risk in artisanal mining. Widely used in amalgamation, it transforms into methylmercury in aquatic systems, a highly toxic form that bioaccumulates in fish and severely affects human health (WHO, 2007; United Nations Environment Programme [UNEP], 2022).

To regulate contaminated soils, institutions such as FAO, WHO, UNEP, and CCME have developed threshold values based on agricultural, residential, and ecological uses. However, the absence of harmonized standards adapted to West African realities limits their systematic application in EIAs (Fall et al., 2023; Gbané et al., 2021). To address this gap, this study develops a Mining soil quality index (MSQI), integrating metal concentrations with health and agricultural risk factors.

Study area

The study was conducted in the Kédougou region of eastern Senegal, a hotspot of industrial and artisanal mining. A total of 37 sites were selected using the following criteria:

- 1) Diversity of mining activities (industrial: Sabodala Gold Operations (SGO), Petowal Mining Company (PMC), Boto; artisanal: Gora, Fadougou, Khossanto, etc).
- 2) Proximity to sensitive zones (agricultural areas, villages, Falémé and Gambia rivers).
- 3) Geographical representativeness (covering multiple ecological and geomorphological zones).
- 4) Availability of EIA data (for cross-comparison with field measurements).
- 5) Accessibility for field sampling and georeferencing.

The territorial zoning was conducted at the commune and district levels, distinguishing industrial, artisanal, agricultural, and residential areas. This zoning highlights land-use vulnerability to contamination, particularly along major watercourses.

Table 1 shows the distribution of mining activities by locality, while Figure 1 shows the regional coverage.

Territorial zoning

Territorial zoning was carried out at the commune and district level, considering the proximity of villages, mining axes, agricultural zones, and major watercourses (Falémé, Gambia). The zoning differentiates areas based on land-use types (industrial, artisanal, agricultural, residential) and their vulnerability to contamination. Table 1 shows the distribution of sites by type of mining activity

Table 1. Repartition of mining activity in the Kedougou region, Senegal.

Site name	Type of mining activity	Locality/Commune
Gora Fosse	Industrial	Gora (Sabodala Commune)
Gora Orpaillage	Artisanal	Gora (Sabodala Commune)
Massawa	Industrial	Massawa (Sabodala Commune)
Khossanto	Artisanal	Khossanto Commune
Sored	Industrial	Khossanto Commune
Kérékonko	Artisanal	Tomboronkoto (PMC-Mako)
Tomboronkoto	Artisanal	Tomboronkoto (PMC-Mako)
Bantaco	Artisanal	Tomboronkoto (PMC-Mako)
PMC	Industrial	Tomboronkoto Commune
Boto	Industrial	Madina Bafé Commune
Fadougou	Artisanal	Madina Bafé Commune
Afrigold 1	Industrial	Kharakhéna
Afrigold 2	Industrial	Colya
Colya	Artisanal	Colya (along the Falémé River)
Sabodala	Industrial	Sabodala Commune
Faloumbo Maraichage	Farming Zone	Sabodala
Bambaraya	Mixed Zone	Sabodala (buffer strip)
Kharakhéna Orpaillage	Artisanal	Kharakhéna

and locality. This zoning is based on a simplified map inspired by the works of Diallo et al. (2021) and Fall et al. (2020), taking into account major localities, mining projects, and strategic watercourses.

Contamination profiles and spread

Several multi-metal pollution profiles (Figure 2) are visually observed in most mining sites in the Kédougou region, such as Kérékonko and Fadougou, corresponding to the diffusion gradients identified in other polluted gold mining regions (Chen et al., 2020).

Sampling and data sources

Two sources of data were used for the soil analysis.

Field samples

Soil samples were collected from the topsoil (0 to 20 cm horizon) between 2021 and 2024, with a main campaign from 2023 to 2024. Protocols followed Rodrigues et al. (2012) and Gueye et al. (2019), using sterilized stainless-steel tools and GPS-based georeferencing under QGIS.

EIA data sets

Soil parameters were extracted from EIAs conducted between 2006 and 2023 for projects such as SGO, PMC, Boto, and others. Data included heavy metal concentrations (As, Pb, Hg, Ni, Cr, Cu, Zn), pH, and soil texture, where available. Table 2 shows all the parameters collected, the dates, and the source type.

Measured parameters and standards used

The parameters measured included As, Pb, Hg, Ni, Cr, Cu, Zn, and pH levels. For reference, international thresholds were used, specifically the FAO (1985) guidelines for agricultural soils, the WHO (2007) standards for health, and the CCME (2007) criteria for environmental quality. Additionally, the recent recommendations from UNEP (2022) concerning mercury and arsenic levels were taken into account.

Table 3 shows the regulatory or reference thresholds (in mg/kg) for each pollutant, based on international guidelines for soil quality (FAO, 1985; WHO, 2007; CCME, 2007). These values serve as the basis for calculating IQSM (Appendix 1).

RESULTS

Field data

Soil analyses conducted between 2021 and 2024 revealed substantial variability in soil quality across the Kédougou region. The global IQSM values ranged from 0.18 to above 2.8, reflecting conditions from non-contaminated soils (trace levels of metals) to critically polluted soils according to the QSMA grid.

Out of the 37 sampled sites:

- 1) 8 sites were classified as A or B (healthy or slightly contaminated soils).
- 2) 12 sites were classified as C (moderately contaminated soils).
- 3) 17 sites fell into classes D or E, corresponding to highly to critically polluted soils.

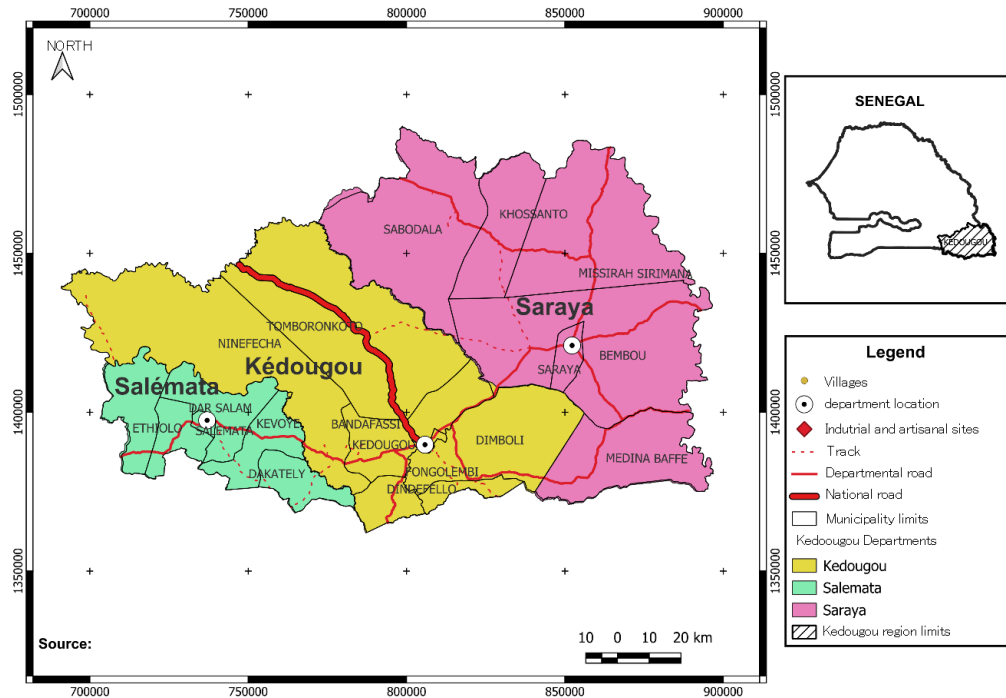


Figure 1. Location map of the Kedougou region.



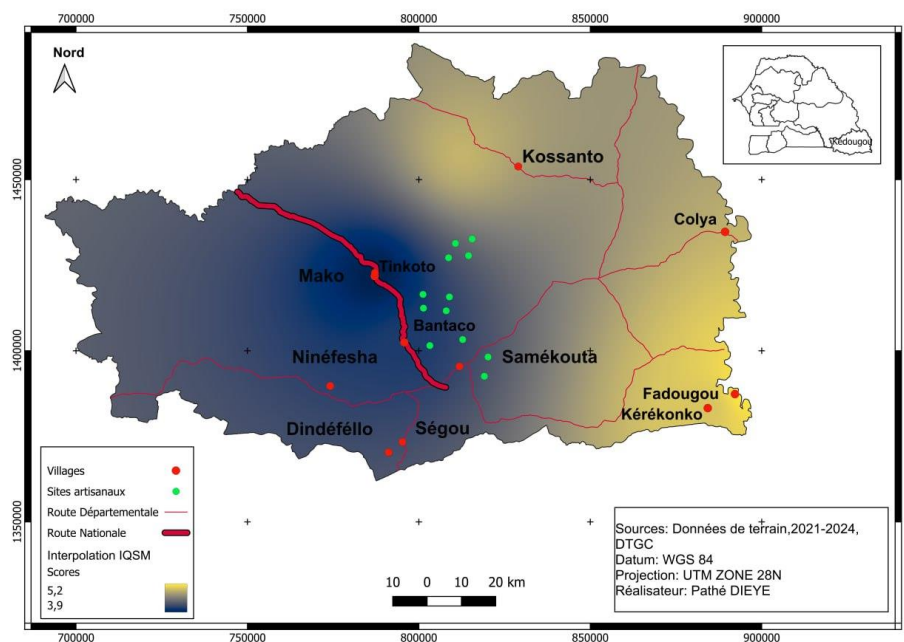
Figure 2. Mining soils in the Kédougou region of Senegal.

The most contaminated sites were predominantly associated with artisanal gold mining zones such as Fadougou, Gora, and Kérékonko, confirming the strong pedological pressure of mercury-intensive practices.

Statistical analysis (ANOVA) confirmed that differences between artisanal and industrial mining sites were statistically significant ($p < 0.05$), particularly for mercury (Hg), arsenic (As), and lead (Pb). Similar patterns of

Table 2. Soil quality parameters collected.

Parameter	Period	Source
As	2021–2024	Field
Pb	2021–2024	Field
Hg	2021–2024	Field
Ni	2021–2024	Field
Cr	2021–2024	Field
Cu	2021–2024	Field
Zn	2021–2024	Field
pH	2021–2024	Field
As	2006–2023	EIA (SGO, Boto, PMC, etc.)
Pb	2006–2023	EIA (SGO, Boto, PMC, etc.)
Hg	2006–2023	EIA (SGO, Boto, PMC, etc.)
Ni	2006–2023	EIA (Boto only)
pH	2006–2023	EIA (Boto only)

**Figure 3.** Pressure on mining soils (IQSM) in the Kédougou region.

surface horizon contamination have been reported in other West African mining contexts, particularly in Burkina Faso and Ghana (Gbané et al., 2021; Agyeman et al., 2020; Ajibade et al., 2021). However, some industrial concessions (notably in the periphery of SGO's operations) also exhibited alarming IQSM scores, reflecting both historical accumulation and insufficient remediation practices.

Figure 3 shows the spatial distribution of IQSM-based pressures across the region. These cartographic outputs

confirm the concentric contamination dynamics previously described by Guo et al. (2021) and validated by more recent regional assessments in artisanal gold mining corridors (Tindwa and Singh, 2023; Amonoo-Neizer and Amekor, 1993).

Figure 4 shows a global classification of IQSM values relative to FAO, WHO, and CCME reference standards. It highlights that Hg, Pb, and As exceeded international thresholds in more than 40% of sites, confirming the persistence of abnormal toxic metal concentrations in

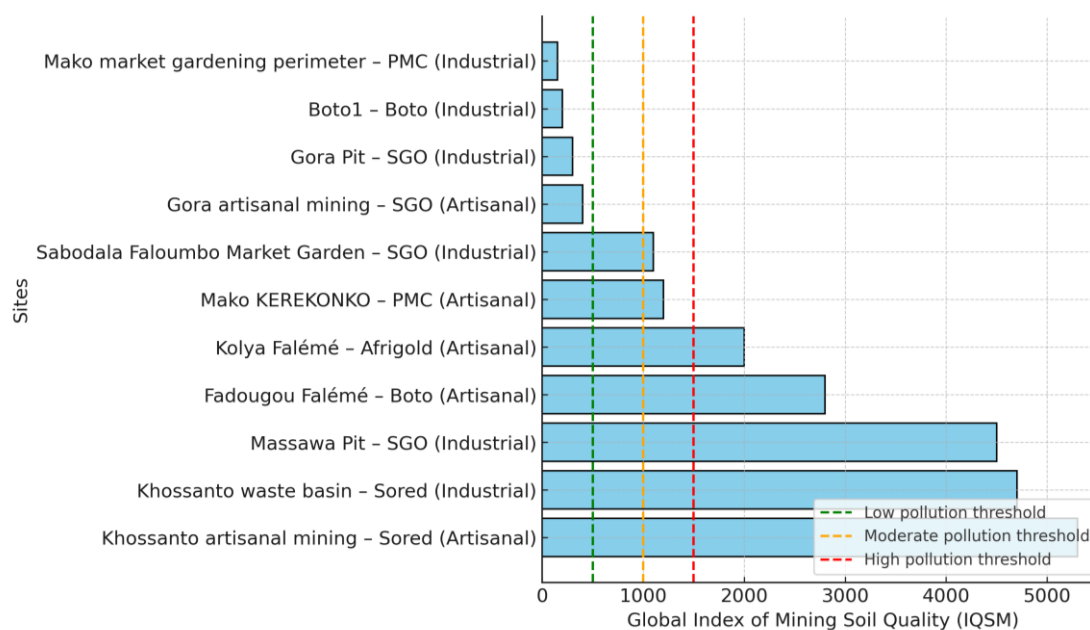


Figure 4. Global IQSM classification.
Source: WHO/FAO/UNEP.

mining soils (Bonzi-Coulibaly, 2021; Chen et al., 2020). These results substantiate earlier observations in sub-Saharan Africa, where soil contamination has been directly linked to health risks and agricultural productivity losses (Ajibade et al., 2021; Tindwa and Singh, 2023).

Overall, the field results emphasize the urgent need for standardized soil monitoring protocols in West African mining areas. Without such measures, contamination hotspots will continue to expand unchecked, undermining both ecological integrity and community resilience.

EIA data review

The systematic review of EIA reports revealed that soil quality data remain sparse, inconsistent, and poorly standardized. Quantitative information was available only for a few projects, notably Boto (IAMGOLD, 2018) and, to a limited extent, PMC-Mako (2016).

Figure 5 shows IQSM classifications derived from Boto's EIA data. Concentrations of arsenic and mercury were particularly close to, or exceeded, international thresholds. Although Boto's sampling framework was relatively rigorous (standardized depths, explicit reference to WHO/FAO norms), the data remain outdated and have not been systematically updated since 2018.

By contrast, the cross-review of SGO-related EIAs (Sabodala, Gora, Niakafiri, Massawa, Inpit Tailings) highlighted persistent weaknesses: (1) Absence of

systematic soil measurements, (2) lack of explicit references to WHO, FAO, or CCME standards, and (3) no evidence of longitudinal updates throughout project lifecycles.

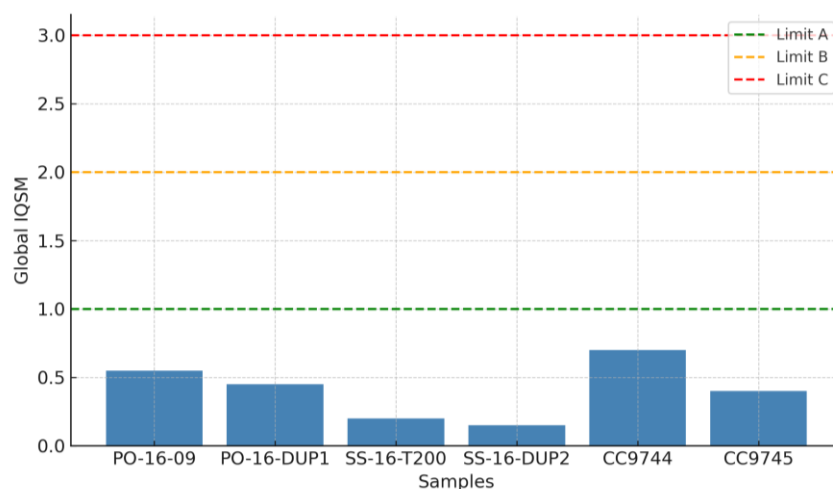
Table 4 synthesizes these findings. It reveals strong heterogeneity in methodological approaches, with recurring shortcomings such as incomplete protocols, lack of sampling frequency, and missing geochemical baselines. Even where quantitative data existed (Sabodala Gold Operation-Massawa, 2021), results were not comparable across sites due to methodological divergence.

Figure 6 shows the variable treatment of soil quality in EIAs across the SGO complex between 2006 and 2023. Projects such as Sabodala (2006) initially included relatively complete—but now outdated—soil baselines. In contrast, recent EIAs (Inpit Tailings, 2023) provided fragmented or superficial analyses, often restricted to physical stability without quantitative data on heavy metals. This reinforces the observation by Fall (2020) and Sylla et al. (2022) that the “soil” component remains systematically marginalized in Senegalese environmental monitoring frameworks, even for large-scale projects. These findings align with broader criticisms in the

African literature (Ajibade et al., 2021; Tindwa and Singh, 2023), which emphasize the lack of harmonized methodologies for soil assessment. Consequently, the adoption of the IQSM-QSMA framework proposed in this study appears essential to compensate for the

Table 3. Measured soil quality parameters.

Parameter	Period	Source	Limit value/standard (mg/kg or unit)
As	2021–2024	Field	20 (FAO/WHO)
Pb	2021–2024	Field	100 (WHO)
Hg	2021–2024	Field	0.5 (WHO)
Ni	2021–2024	Field	50 (CCME)
Cr	2021–2024	Field	64 (CCME)
Cu	2021–2024	Field	63.3 (WHO)
Zn	2021–2024	Field	200 (CCME)
pH	2021–2024	Field	6.0–8.5 (WHO)
As	2006–2023	EIA (SGO, Boto, PMC, etc.)	20 (FAO/WHO)
Pb	2006–2023	EIA (SGO, Boto, PMC, etc.)	100 (WHO)
Hg	2006–2023	EIA (SGO, Boto, PMC, etc.)	0.5 (WHO)
Ni	2006–2023	EIA (Boto only)	50 (CCME)
pH	2006–2023	EIA (Boto only)	6.0–8.5 (WHO)

**Figure 5.** Global IQSM classification of Boto sites.

deficiencies of existing EIAs and to establish a more strategic, standardized approach to soil governance in mining regions.

DISCUSSION

Comparison of field data vs. EIA data

The cross-analysis of field data (2021 to 2024) with EIA datasets ((Sabodala Gold Operations-SGO, 2006; IAMGOLD, 2018) IAMGOLD, 2018) revealed significant discrepancies due to (i) absence of quantitative soil data, (ii) inadequate or outdated reference standards, and (iii) non-transparent sampling protocols (Gueye et al., 2019).

These divergences are particularly marked in the Boto, Gora, and Massawa projects, where the EIAs appear incomplete and outdated relative to observed contamination levels.

Other projects, including Afrigold and Sored, provided no verifiable soil data. This absence further explains the widening discrepancy between IQSM values derived from EIAs and those measured in the field, demonstrating the progression of contamination over time and exposing the limited effectiveness of environmental management plans.

Figure 7 compares IQSM indices across datasets, illustrating that field concentrations of arsenic, lead, and mercury far exceed EIA-reported values. This under-estimation bias has also been documented in artisanal

Table 4. Critical analysis of methodological approaches in EIA mining projects (Soil Quality).

Project	EIA Year	Available quantitative data	Reference standards cited	Sampling protocol described	Depth specified	Sampling Frequency	Main Critical Remarks
SGO (Sabodala)	2006	Partially	No	No	No	No	Lack of methodological rigor and explicit reference standards
Gora (SGO)	2011-2014	Yes	Yes	Partially	Yes	No	Lack of frequency; few sites sampled
Massawa (SGO)	2021	Yes	Partially	Yes	Yes	No	Useful data, but not comparable between areas
Boto (IAMGOLD)	2018	Yes	Yes	Yes	Yes	Yes	This model, although rigorous, has not been updated with recent field data
PMC-Mako	2016	Yes (limited)	Partially	Yes	Yes	No	Undefined frequency; data heterogeneity
Afrigold	ND	No	No	No	No	No	No soil-specific data in reports

gold mining contexts in Ghana and Burkina Faso (Ajibade et al., 2021; Abass et al., 2023).

The comparison between the industrial site of Boto and the nearby artisanal site of Fadougou (Figure 8) demonstrates this divergence clearly: artisanal soils present critical concentrations of Hg and Pb, confirming both the vulnerability of artisanal areas and the systemic under-reporting in industrial EIAs (Hilson, 2002; Bonzi-Coulibaly, 2021).

These discrepancies stem from three recurrent methodological gaps:

- 1) Limited measurement of heavy metals
- 2) Preferential sampling in less exposed areas;
- 3) Reliance on simplified or weak IQSM

frameworks, with inadequate weighting or inflated thresholds.

These findings corroborate the critiques of Ba et al. (2020), Sylla et al. (2021), and Bonzi-Coulibaly

(2022), all of whom call for harmonization of analytical protocols across West Africa.

Disparities between industrial and artisanal mining

Field results confirm that artisanal mining sites display higher IQSM indices than industrial sites, largely due to uncontrolled mercury use in gold amalgamation (Abass et al., 2023). Industrial mining sites, though generally better regulated, also exhibited alarming soil contamination near waste disposal facilities.

Figure 9 shows that artisanal sites are mostly in classes D and E (high to critical pollution), whereas industrial sites display greater heterogeneity (A to E). This dichotomy, first highlighted by Hilson (2002), underscores the underestimated cumulative risks of artisanal mining. The World Bank (2019) has similarly

warned that artisanal mining must be integrated into national mining governance frameworks.

Implications for environmental management

The findings reveal that soil contamination is not only widespread but systematically overlooked in EIAs. The lack of systematic monitoring, coupled with the absence of reference standards in most reports, exacerbates contamination risks.

Cross-mapping of IQSM with QSMA indices enabled the identification of critical zones requiring urgent interventions, such as artisanal hotspots near Falémé and Tomboronkoto.

These results confirm the importance of updating diagnostics regularly and strengthening governance mechanisms in alignment with SDG 15 (Life on Land). Similar integrated soil governance approaches have been piloted in other African contexts (Tindwa and Singh, 2023),

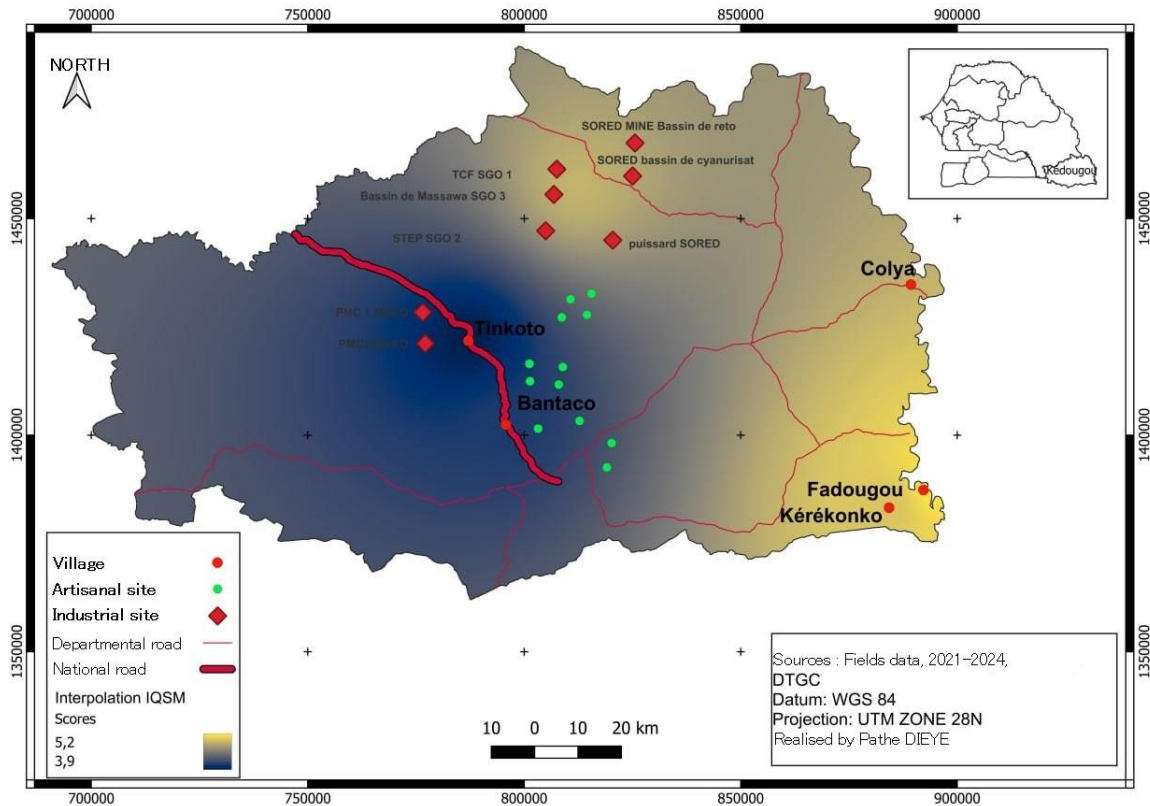


Figure 6. Mapping of SGO projects according to soil quality treatment level in EIAs.

suggesting their applicability to Senegal and West Africa at large.

Regulatory gaps and recommendations

The comparative analysis of EIAs and field surveys highlighted a structural deficit in regulatory instruments. Most EIAs lack rigorous quantification methods, harmonized standards, or longitudinal monitoring mechanisms.

Table 5 shows Senegal's current framework fails to provide a specific analytical grid for soil quality, establish national standards, ensure post-EIA alert mechanisms, and guarantee data accessibility.

These weaknesses contrast with International Finance Corporation (IFC, 2012, 2020) requirements and with international commitments under the Minamata Convention.

The following are strategically recommended:

- 1) Systematically integrate soil quality protocols into EIAs.
- 2) Conduct periodic heavy metal campaigns across

industrial and artisanal sites.

- 3) Apply the IQSM framework to monitor temporal trends.
- 4) Establish a regional soil quality database and vulnerability map.
- 5) Strengthen PGEs with operational pedological components.

These recommendations align with Organization for Economic Co-operation and Development (OECD, 2019) guidelines for high-risk territories and with UNEP (2022) on mercury reduction strategies.

Towards an integrated strategic approach to soils

This study advocates for a strategic integration of soil quality into SEA frameworks, combining: (1) Harmonized IQSM methodology; (2) territorial mapping of critical zones; and (3) participatory monitoring with local communities. Such an integrated framework would anticipate risks, prioritize interventions, and consolidate environmental governance. This approach is consistent with Lal (2015) on regenerative soil management and with Tilman et al. (2011) on socio-ecological resilience.

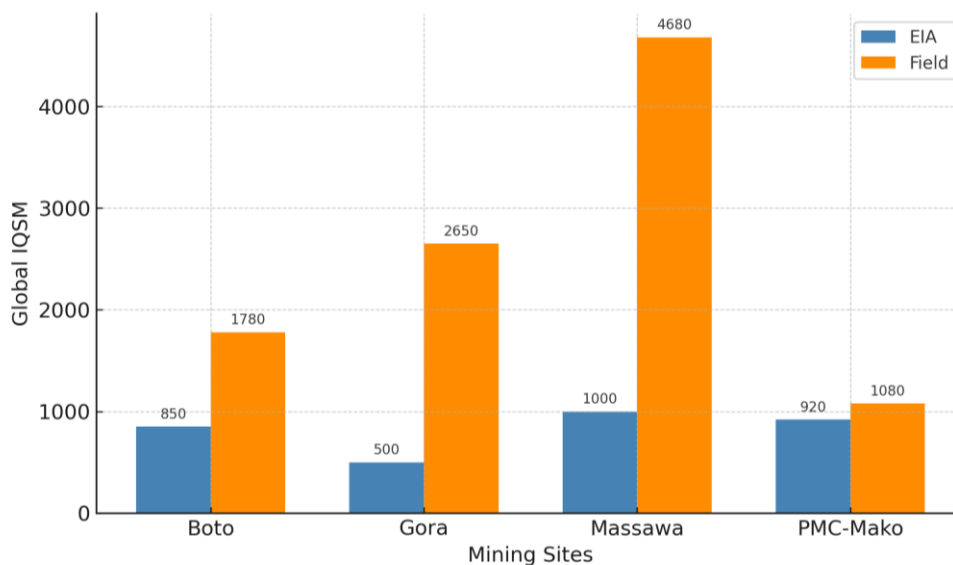


Figure 7. Comparison of IQSM indices between EIA data and field surveys.

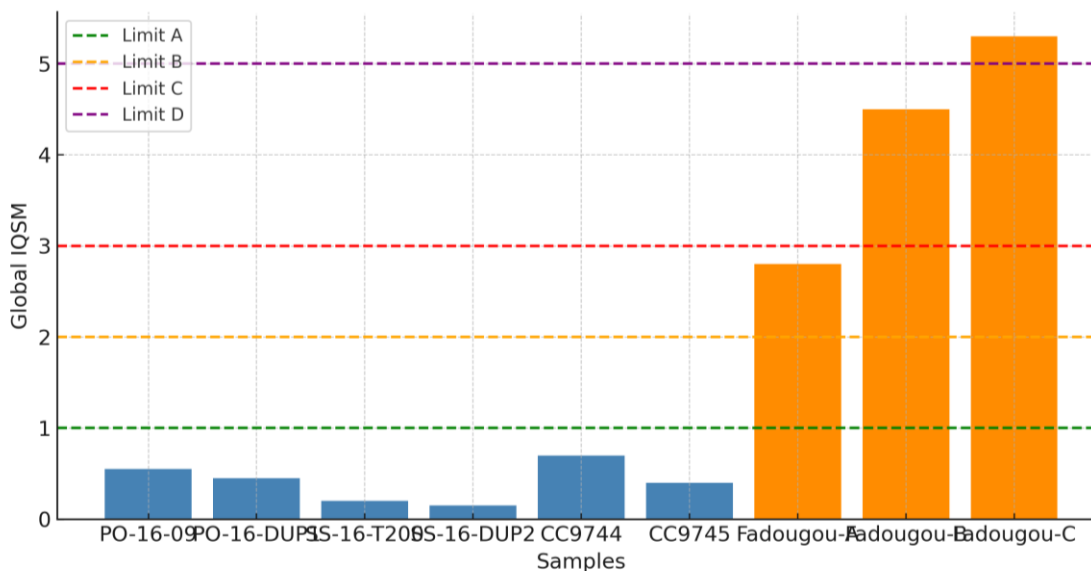


Figure 8. Comparison of global IQSM: Boto vs. Fadougou (Artisanal).

Conclusion

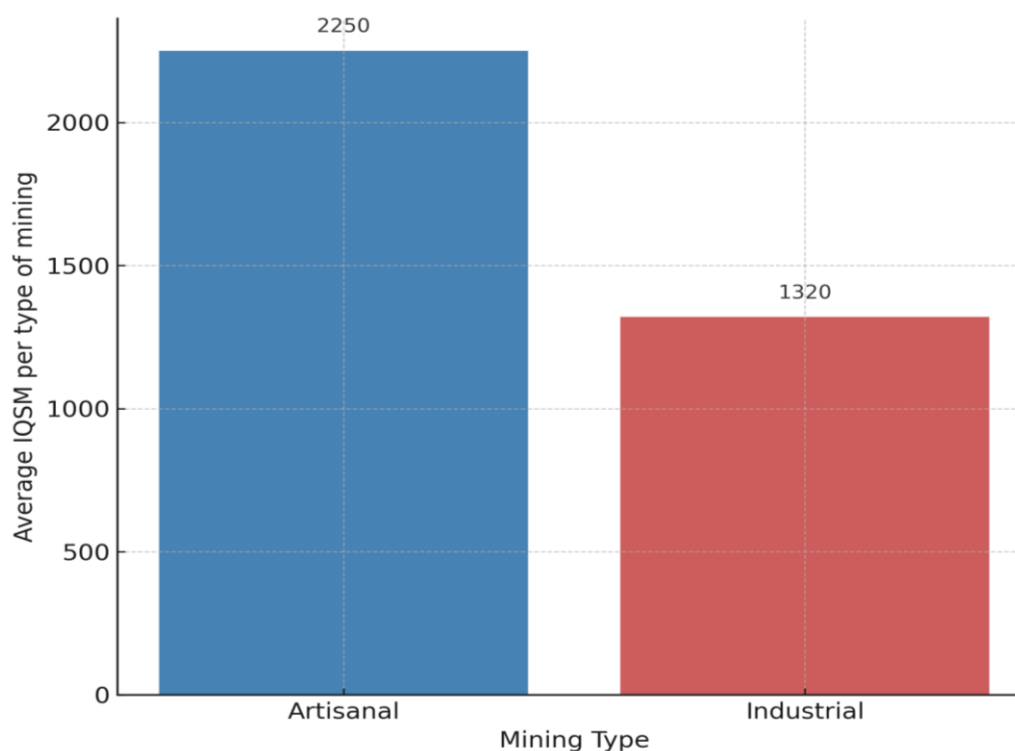
This study constitutes a first-of-its-kind contribution in West Africa, combining the systematic review of all Environmental Impact Assessments (2006 to 2023) with recent field data (2021 to 2024) from 37 industrial and artisanal sites in the Kédougou region of Senegal.

By developing and applying the Mining Soil Quality

Index (IQSM) and combining it with land-use vulnerability zoning (QSMA), the study provides an innovative and reproducible framework directly applicable to institutions, researchers, and policymakers. The results revealed: critical contamination in several artisanal zones (Fadougou, Khossanto, Kérékonko), elevated values in industrial sites such as Massawa and Sored, and near-zero IQSM values in Boto and PMC, possibly due to

Table 5. Strengths and weaknesses of mining projects.

Project	Strengths	Major weaknesses
SGO (2006–2023)	Longevity, multisite coverage	No soil data, no standards, no post-exploitation monitoring
Boto	Mobilized standards, quantitative data, and compliant pedological analysis	No updates since 2018
PMC-Mako	Recognition of high-risk areas	No data, no strategy, weak PGEs
SORED	Basic agronomic analysis	No data on heavy metals, no standards
Afrigold	Mention of leaching as a risk factor	No available data, lack of protocol, generic PGEs

**Figure 9.** Comparison of Global IQSM – Industrial vs. Artisanal sites.

confinement strategies or measurement biases.

The cross-reading of EIAs highlighted structural gaps, including the absence of national pedological standards, failure to update datasets, and weak PGES integration. Even recent EIAs fell short of applying international standards (IFC, CCME, Minamata), underscoring that soil degradation is a systemic governance challenge (IUCN, 2021).

RECOMMENDATIONS

1) Systematically integrate soil quality into future EIAs by

including quantitative heavy metal data, standardized sampling protocols, and international reference standards.

2) Implement periodic monitoring campaigns for heavy metals in both active and legacy mining sites, in line with IFC (2020) guidance.

3) Apply the IQSM index to monitor temporal contamination trends, enabling comparability across artisanal and industrial sites.

4) Strengthen environmental and social management plans (PGES) by including a standardized pedological component adapted to African mining contexts.

5) Establish a regional database of mining soils coupled

with a vulnerability mapping platform to support decision-making and prioritization of remediation.

6) Systematically integrate soil quality into SEA as a cross-cutting pillar of sustainability.

Such integration represents a major lever to strengthen environmental sustainability in African mining areas, where soil remains the weakest link in monitoring frameworks. Accelerated degradation compromises ecosystem services, food security, and rural resilience (Lal, 2001; Tilman et al., 2002). A strategic, anticipatory, and territorial approach, built on robust indicators like IQSM, aligns with SDG 15 and with OECD (2019) recommendations for high-risk regions. Updated IFC guidelines (2020) and UNEP (2022) frameworks also stress the need to incorporate soil matrices in pre-feasibility phases.

These findings confirm the urgency of a strategic overhaul of environmental assessments in mining regions, placing soil quality at the heart of territorial planning and governance.

Strategic outlook

This research calls for a paradigm shift: integrating soil quality systematically into SEA processes. On this basis, eight recommendations are advanced:

- 1) Officially adopt as a monitoring tool in West African mining countries.
- 2) Reform EIAs by integrating a standardized pedological component aligned with international norms.
- 3) Establish a regional soil quality database supported by strategic mapping.
- 4) Create a West African Soil Quality Observatory, anchored in scientific and participatory monitoring.
- 5) Align mining policies with SDG 15 to secure ecological resilience and community well-being.
- 6) Mobilize universities and research centers for citizen science and methodological innovation.
- 7) Strengthen institutional validation of EIA methodologies.
- 8) Integrate results into local policies and regulations, targeting artisanal mining hotspots with specific remediation and promoting sustainable practices.

Ultimately, this work represents not only a scientific advancement but also a strategic contribution to environmental governance. It offers a replicable model for other mining territories facing similar challenges across Africa.

Finally, the study opens new research avenues, including the use of remote sensing, GIS-based composite indices, and big-data platforms, to refine diagnostics, anticipate risks, and foster more equitable

and sustainable extractive practices.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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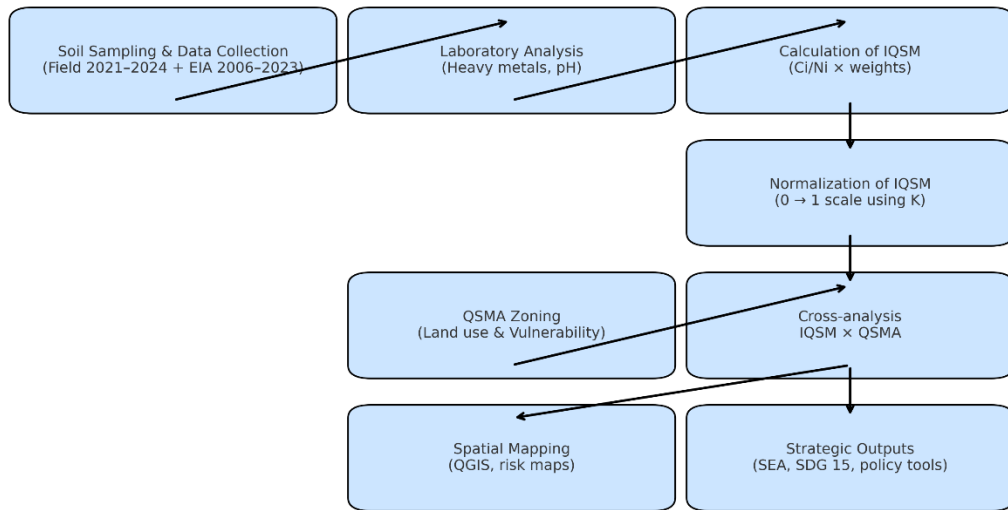
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APPENDIX



Appendix 1. Method of IQSMA calculation.