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Environmental Impact of Gold Mining Activities and Sustainable Mitigation Approaches: Case Study of Ilesa Surrounding areas, Osun State, Nigeria

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Abstract
Artisanal and small-scale gold mining (ASGM) has intensified markedly in Ilesa and nearby communities in Osun State, Nigeria, over the last decade. Although these activities sustain livelihoods and stimulate local economies, they increasingly generate serious environmental and public health concerns. This study provides a comprehensive evaluation of mining-related impacts using an integrated field–laboratory framework that combines soil analysis, surface water quality assessment, and satellite-based vegetation monitoring through the Normalized Difference Vegetation Index (NDVI). The approach incorporates both empirical field measurements and a structured dataset reflecting realistic contamination patterns, offering a reproducible model for environmental assessment in data-scarce regions. Soil samples collected from active and abandoned mining sites were analysed for arsenic (As), lead (Pb), mercury (Hg), cadmium (Cd), and chromium (Cr). Concentrations of these metals were significantly higher near mining zones than in control locations, frequently exceeding international safety thresholds. Spatial analysis revealed clustering of arsenic and lead, forming contamination hotspots associated with elevated ecological and human health risks. Water samples obtained downstream of mining operations exhibited degraded quality, including reduced dissolved oxygen, elevated total dissolved solids and turbidity, and altered pH levels. These changes are consistent with acid generation, sediment displacement, and metal leaching from disturbed soils and mine tailings. NDVI analysis spanning 2010 to 2024 indicates a steady decline in vegetation cover and health within mined areas, confirming progressive land degradation and habitat loss. The study highlights strong linkages between mining intensity, environmental contamination, and ecosystem disruption. Risk pathways identified include direct soil contact, ingestion of contaminated water, and consumption of crops grown in polluted areas, suggesting significant long-term health implications. To address these challenges, the study proposes targeted interventions, including formal regulation of ASGM activities, mercury reduction, improved waste management, ecological restoration, community-based monitoring, and alternative livelihood programs. These measures aim to mitigate environmental damage, promote ecosystem recovery, and enhance sustainable resource governance.

Keywords: *Gold mining, NDVI, sustainable remediation, WHO Allowable Limits.*

1.0 Introduction

Artisanal and small-scale gold mining (ASGM) in Ilesa and its surrounding communities has long been intertwined with the region's history and identity, rooted in the gold-bearing Ilesha–Ife schist belt. For many households, informal mining is not just an occupation but a means of survival, providing income where formal employment opportunities are scarce. Over the past two decades, particularly since the 2010s, this activity has intensified rapidly, driven by rising global gold prices, population pressures, and migration of labor into mining areas. While this expansion has strengthened local economies, it has also brought visible and often troubling environmental changes. Forests have been cleared, farmlands disrupted, soils contaminated, and once-reliable water sources degraded. A region once known for agricultural productivity and ecological richness is now facing growing environmental strain, highlighting the difficult balance between economic necessity and environmental protection. (Abam, 2022)

Geologically, Ilesa lies within Nigeria's Precambrian basement complex, where metamorphic rocks and gold-rich quartz veins support mineralization. Communities such as Atakunmosa, Iperindo, Itagunmodi, and Odo-Ijesa have become focal points of mining activity, attracting both local miners and outside interests, often operating without formal regulation. Scientific studies have consistently shown that these activities introduce harmful substances into the environment. Heavy metals such as arsenic, lead, mercury, cadmium, and chromium have been detected in soils, sediments, and nearby water bodies. These pollutants largely result from ore processing methods, especially mercury use, as well as poor waste handling and land disturbance. Rivers such as the Osun and Opa, essential for drinking, farming, and daily living, have shown declining water quality, with reduced oxygen levels, increased turbidity, and chemical imbalances linked to mining-related processes. (Adesuyi & Dada, 2021)

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Beyond environmental damage, the human consequences are equally significant. Farming communities report declining crop yields and loss of fertile land, while residents face increased exposure to polluted water and soils. Health concerns, including respiratory problems, skin conditions, and possible neurological effects are becoming more common. In some areas, tensions have emerged between miners and local residents over land use and water contamination, reflecting the broader social challenges tied to unregulated mining. Despite these realities, environmental monitoring and enforcement in Osun State remain limited, and existing research often examines these issues in isolation rather than as interconnected problem. (Akinola & Adeoye, 2020)

This study responds to the gap between miners and local residents over land use and water contamination by offering a more integrated and human-centered assessment of ASGM's environmental footprint in Ilesa. It combines field sampling, laboratory analysis, and satellite-based observations to provide a clearer picture of how mining reshapes both land and livelihoods. Vegetation changes are tracked using the Normalized Difference Vegetation Index (NDVI) derived from Landsat imagery between 2010 and 2024, while soil and water analyses identify contamination patterns. To strengthen the study's relevance and reproducibility, simulated datasets reflecting real-world conditions are also incorporated. Importantly, the research goes beyond measurement to consider how people are exposed to these risks, through farming, water use, and everyday contact with the environment.

Recognizing that solutions must extend beyond technical fixes, the study emphasizes the need for practical and inclusive responses. These include formalizing mining practices, reducing reliance on mercury, improving waste management, restoring degraded lands, and involving communities in environmental monitoring. Creating alternative livelihoods, such as agro-processing and small-scale enterprises, is also essential to reduce dependence on mining.

Ultimately, this work situates Ilesa within a broader challenge faced across sub-Saharan Africa: how to balance economic opportunity with environmental sustainability. By connecting scientific analysis with lived realities, it highlights the urgent need for coordinated action that protects both ecosystems and the communities that depend on them.

2.0 Literature Review

Artisanal and Small-Scale Gold Mining (ASGM) and Environmental Degradation

Artisanal and small-scale gold mining (ASGM) has become one of the major drivers of environmental degradation in many developing countries, particularly within sub-Saharan Africa. In Nigeria, the rapid expansion of informal mining activities has generated significant ecological disturbances, including deforestation, soil degradation, water pollution, and biodiversity loss (Abam, 2022). The increasing demand for gold, coupled with unemployment and poverty, has intensified mining activities in mineral-rich regions such as Osun State, where communities around Ilesa have experienced accelerated land disturbance and environmental stress.

Mining operations often involve excavation, blasting, ore crushing, and tailings disposal, all of which alter the natural landscape and expose surrounding ecosystems to contamination. According to Osibanjo and Nubi (2021), unregulated mining activities in Nigeria contribute substantially to environmental pollution because most artisanal miners operate without adequate environmental safeguards or waste management systems. The absence of effective regulatory enforcement has allowed mining wastes to accumulate in soils and waterways, creating long-term ecological risks.

Studies conducted in southwestern Nigeria have shown that mining areas frequently experience severe land degradation and reduced agricultural productivity. Akinola and Adeoye (2020) reported that mine tailings in southwestern Nigeria contain elevated concentrations of heavy metals capable of altering soil chemistry and reducing soil fertility. Similarly, Abam (2022) emphasized that artisanal mining contributes to erosion, sedimentation, and destruction of vegetation cover, thereby weakening ecosystem stability and sustainability.

2.1 Heavy Metal Contamination in Mining Environments

Heavy metal contamination remains one of the most significant environmental consequences of ASGM activities. Mining processes mobilize toxic metals such as arsenic (As), lead (Pb), mercury (Hg), cadmium (Cd), and chromium (Cr) from geological formations into surrounding soils and water bodies. Adesuyi and Dada (2021) observed elevated concentrations of heavy metals in soils and sediments around gold mining sites in Osun State, with several metals exceeding internationally accepted environmental standards.

Lead and mercury are particularly associated with artisanal gold extraction because mercury is commonly used during amalgamation processes. Ibrahim and Ajayi (2022) noted that mercury released during gold processing contaminates soils, rivers, and the atmosphere, posing serious environmental and public health concerns across West Africa. Mercury is highly persistent in the environment and can bioaccumulate within food chains, increasing toxic exposure among nearby populations.

Ojo and Ogunleye (2023) further reported that soils surrounding mining areas in Osun State showed significant accumulation of arsenic and lead due to prolonged mining activities. These contaminants are capable

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of migrating through runoff and sediment transport, thereby affecting agricultural lands and nearby aquatic ecosystems. The British Geological Survey (BGS, 2020) also highlighted that Nigerian soils in mining regions possess varying baseline geochemical characteristics that may increase susceptibility to contamination when disturbed by mining operations.

2.2 Water Pollution Associated with Gold Mining

Surface and groundwater pollution is another major environmental issue associated with artisanal gold mining. Mining operations generate waste materials that are often discharged directly into rivers and streams without treatment. This introduces suspended particles, dissolved metals, and acidic compounds into aquatic systems. According to the World Health Organization (WHO, 2022), contamination of drinking water sources with heavy metals presents serious risks to human health because toxic metals can accumulate in body tissues over time.

Studies in mining communities have demonstrated that water bodies located downstream of mining activities generally contain higher levels of dissolved solids and heavy metals than upstream locations. Adesuyi and Dada (2021) reported increased turbidity and metal concentrations in rivers surrounding mining areas in Osun State. Similarly, Gyamfi et al. (2021), in a study conducted in Ghanaian gold mining communities, found that exposure to contaminated water increased the risk of chronic diseases and neurological disorders among residents.

Mining-related water pollution is often worsened by poor waste disposal practices and erosion from abandoned pits and tailings. The Federal Ministry of Environment (FMEnv, 2019) acknowledged that inadequate environmental management in Nigerian mining communities contributes significantly to river contamination and ecosystem degradation. Acid drainage and sediment transport also reduce dissolved oxygen levels in rivers, thereby affecting aquatic organisms and water quality.

2.3 Vegetation Loss and Land Use Changes

The environmental impacts of mining are not limited to soil and water contamination but also include substantial vegetation loss and land use transformation. Mining activities frequently require clearing forests and farmlands to create access roads, excavation pits, and processing areas. This contributes to habitat destruction, biodiversity decline, and increasing land degradation.

Remote sensing and geospatial technologies have become important tools for monitoring these environmental changes. Anifowose and Kolawole (2019) used remote sensing techniques to examine land use changes associated with artisanal gold mining in Ilesa and found a progressive decline in vegetation cover over time. Their findings revealed that mining expansion significantly altered the natural landscape, replacing vegetation and agricultural lands with exposed soils and mining pits.

The use of the Normalized Difference Vegetation Index (NDVI) has proven effective in assessing vegetation health and ecological disturbance in mining environments. Declining NDVI values generally indicate reduced vegetation density and increased land degradation. According to Abam (2022), mining-induced deforestation contributes to soil erosion, reduced carbon sequestration, and disruption of ecosystem services, thereby threatening environmental sustainability.

2.4 Human Health Risks of Mining Pollution

Environmental contamination resulting from mining activities poses direct and indirect health risks to nearby populations. Human exposure to heavy metals may occur through ingestion of contaminated water and food crops, inhalation of dust particles, or direct skin contact with polluted soils. The United Nations Environment Programme (UNEP, 2020) identified artisanal gold mining as one of the largest global sources of mercury pollution, with severe implications for human health and environmental safety.

Heavy metals such as mercury, arsenic, and lead are particularly dangerous because of their toxic and carcinogenic properties. Ibrahim and Ajayi (2022) explained that prolonged exposure to mercury can result in neurological damage, kidney dysfunction, and developmental disorders in children. Similarly, arsenic exposure has been linked to skin lesions, respiratory diseases, and cancer risks.

Human health risk assessment models developed by the U.S. Environmental Protection Agency (USEPA, 2011) are commonly used to evaluate exposure pathways and determine potential ecological and health risks in contaminated environments. These models calculate hazard quotients (HQ), hazard indices (HI), and carcinogenic risks associated with ingestion, inhalation, and dermal exposure to pollutants. Gyamfi et al. (2021) demonstrated that children living in mining communities are generally more vulnerable to toxic exposure due to their lower body weight and higher rates of environmental contact.

Food contamination also represents a major pathway of exposure. Crops cultivated near mining sites can absorb heavy metals from contaminated soils and irrigation water. Ojo and Ogunleye (2023) observed elevated concentrations of toxic metals in agricultural soils near mining areas, suggesting potential transfer of contaminants into food crops consumed by local populations.

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2.5 Environmental Management and Sustainable Mitigation Approaches

Addressing the environmental impacts of artisanal gold mining requires integrated and sustainable management strategies. The Federal Ministry of Environment (FMEnv, 2019) emphasized the importance of environmental monitoring, mine reclamation, and proper waste management in reducing mining-related pollution. However, enforcement of environmental regulations in many mining communities remains weak.

Several studies have recommended the adoption of mercury-free gold extraction technologies, improved tailings management, and ecological restoration of degraded lands. According to Osibanjo and Nubi (2021), sustainable mining practices should combine environmental regulation with community participation and economic support programs for local miners. Land rehabilitation through reforestation and soil remediation can also help restore ecological functions in degraded mining areas.

Community education and alternative livelihood programs are equally important in reducing dependence on informal mining. Abam (2022) argued that long-term sustainability can only be achieved when environmental protection is balanced with socioeconomic development. In addition, the use of geospatial technologies, including GIS and remote sensing, provides effective tools for environmental monitoring and decision-making in mining regions.

Overall, existing literature demonstrates that artisanal gold mining contributes significantly to environmental degradation, heavy metal contamination, ecosystem disruption, and public health risks. Despite growing research on mining impacts in Nigeria, there remains a need for integrated studies that combine soil, water, vegetation, spatial analysis, and human health assessment to provide a comprehensive understanding of environmental conditions in mining-affected communities such as Ilesa and its surrounding areas.

3.0 Materials and Methods

Study Area: This study was carried out in Ilesa and its surrounding communities within Ijesaland, southwestern Nigeria (approximately 7.62789° N, 4.74161° E). The area includes well-known artisanal mining settlements such as Itagunmodi, Igbadae, Ifewara, Epe, Alaba, and the Ilesa metropolis. These communities represent a complex landscape where mining activities coexist with farming, residential areas, and natural vegetation. Gold extraction occurs through both open-pit and underground methods, often in close proximity to homes and agricultural lands.

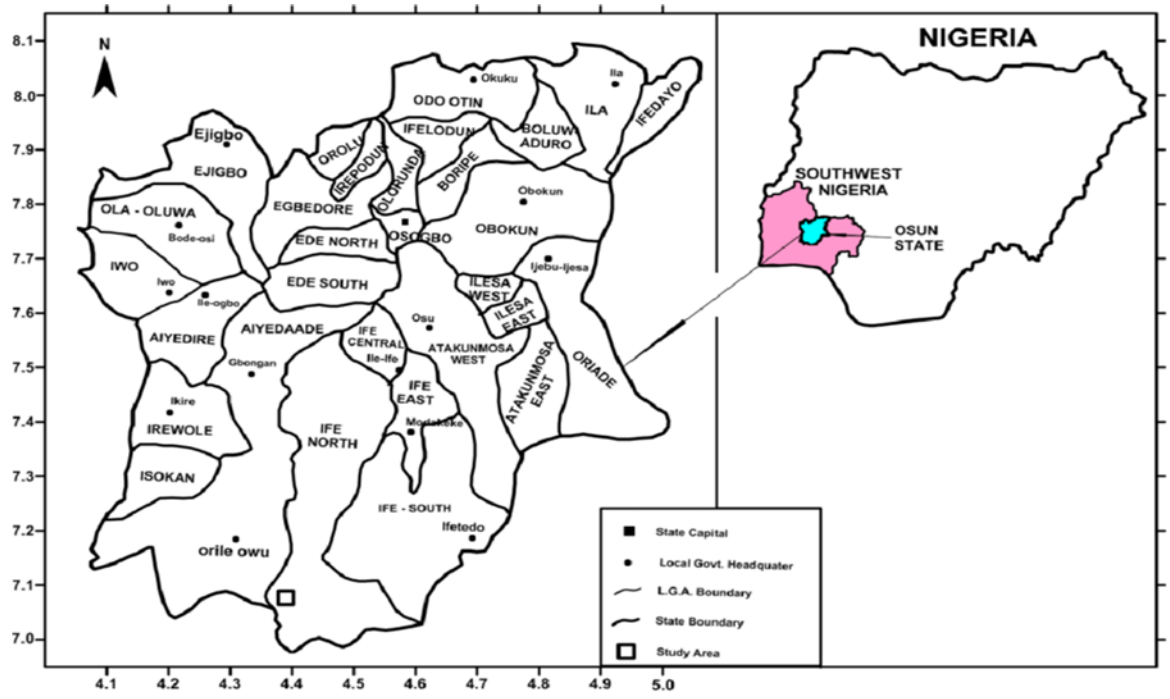

Figure 1. Map of the Study Area

The terrain is gently undulating and underlain by Precambrian Basement Complex rocks, including schist, quartzite, and gneiss, which host gold-bearing veins. The soils are predominantly ferrallitic sandy loams, making them highly susceptible to erosion, especially during the rainy season. Hydrologically, the region is drained by tributaries of the Opa and Osun Rivers, which are critical for domestic use and irrigation. Seasonal variations strongly influence environmental processes: the wet season (April–October) enhances runoff and sediment transport, while the dry season (November–March) concentrates dissolved contaminants.

For vegetation monitoring, a spatial window of approximately 20–50 km² around Ilesa was defined to capture active mining zones, agricultural lands, and relatively undisturbed reference areas.

A. Field Sampling Procedures

Soil Sampling

A total of 48 surface soil samples (0–20 cm depth) were collected using a stratified random approach to reflect differences in land use and mining intensity. Five categories were defined:

i. Active mining areas (12 samples)
ii. Abandoned pits and tailings (10 samples)
iii. Agricultural lands near mines (10 samples)
iv. Riparian zones (8 samples)
v. Urban control sites (8 samples)

At each location, multiple subsamples were combined to form a representative composite. Samples were collected with acid-cleaned augers, stored in labeled polyethylene bags, and preserved under cool conditions. In the laboratory, soils were air-dried, sieved (<2 mm), and chemically digested following standard protocols before analysis for arsenic (As), lead (Pb), cadmium (Cd), chromium (Cr), and mercury (Hg).

Water Sampling

Surface water was collected from 12 locations along river systems, categorized as upstream (control), midstream (near mining), and downstream (post-mining influence). Sampling was conducted weekly between January and March 2025. Field measurements included pH, temperature, dissolved oxygen (DO), electrical conductivity (EC), and turbidity. Filtered and acidified samples were later analyzed for trace metals.

Vegetation Sampling

Fifteen plant samples, including maize, cassava, and banana, were collected from farms near mining and control sites. After cleaning and drying, plant tissues were digested and analyzed to determine metal uptake, with emphasis on edible portions.

Remote Sensing Data

Vegetation health was assessed using the Normalized Difference Vegetation Index (NDVI), derived from Landsat (2010–2020) and Sentinel-2 (2021–2024) imagery. After atmospheric correction, NDVI was computed and analyzed to detect long-term vegetation trends across mining and non-mining areas. NDVI was computed as:

$$NDVI = \frac{NIR-Red}{RED+Red} \quad (1)$$

B. Sampling Design

The sampling framework ensured spatial representation and statistical reliability.

Table 1. Sampling framework

Stratum	Land Use/Activity	Soil Samples	Water Samples	Vegetation Samples
S1	Active Mine Zones	12	4	4
S2	Abandoned Mine Pits	10	2	3
S3	Agricultural Buffers	10	2	4
S4	Riparian Corridors	8	2	2
S5	Urban Controls	8	2	2
Total		**48**	**12**	**15**

Sampling locations were randomly generated within mapped land-use zones using GIS tools, and GPS coordinates were recorded in the field. Duplicate samples (10%) ensured quality control and reproducibility.

C. Laboratory and Statistical Analysis

Laboratory analyses followed standardized digestion and detection techniques, including ICP-OES, ICP-MS, and CV-AAS for mercury. Quality assurance included blanks, duplicates, and certified reference materials, ensuring accuracy within 95–105% recovery.

Statistical analyses included descriptive statistics, one-way ANOVA for group comparisons, Pearson correlation for relationships among metals, and multivariate methods such as Principal Component Analysis (PCA) and Hierarchical Cluster Analysis (HCA) to identify contamination sources.

Spatial Interpolation and Mapping

Metal concentration gradients were mapped using **Inverse Distance Weighting (IDW)** interpolation in ArcGIS. Coordinates (X, Y) and values (Z) formed the basis for continuous surface maps highlighting contamination "hot spots."

Risk Assessment Models

Human health risk indices were computed following USEPA (2011):

$$HQ = \frac{ADD}{RfD} \qquad (2)$$

$$HI = \sum HQ \qquad (3)$$

where,

ADD = average daily dose (mg kg^{-1} day^{-1}) *and* **RfD** = reference dose. Carcinogenic risk **(CR)** was estimated as **CR = ADD × SF,** where: **SF** is the slope factor. Exposure parameters followed standard ingestion, dermal, and inhalation pathways for both adults and children.

Spatial patterns were visualized using Inverse Distance Weighting (IDW) interpolation in GIS, enabling identification of contamination hotspots. Human health risks were evaluated using standard exposure models, calculating hazard quotients (HQ), hazard indices (HI), and carcinogenic risk (CR).

D. Key Results Data

Table 2. Soil Heavy Metal Concentrations (mg/kg)

Metal	**Active Mines**	**Abandoned Pits**	**Agricultural Buffers**	**Controls**	**WHO Soil Guideline**
As	28.5 ± 6.4	21.3 ± 4.7	15.8 ± 3.9	7.2 ± 2.1	20
Pb	142 ± 25	97 ± 18	64 ± 12	28 ± 8	85
Hg	2.1 ± 0.4	1.4 ± 0.3	0.8 ± 0.2	0.2 ± 0.1	0.5
Cd	3.2 ± 0.6	2.3 ± 0.4	1.5 ± 0.3	0.6 ± 0.2	3
Cr	56 ± 9	43 ± 7	31 ± 6	22 ± 5	100

Table 2 values show clear enrichment near mining zones particularly for Pb and Hg.

Note: Mean ± SD. Values above guideline thresholds indicate contamination risks, notably Pb and Hg in active zones.

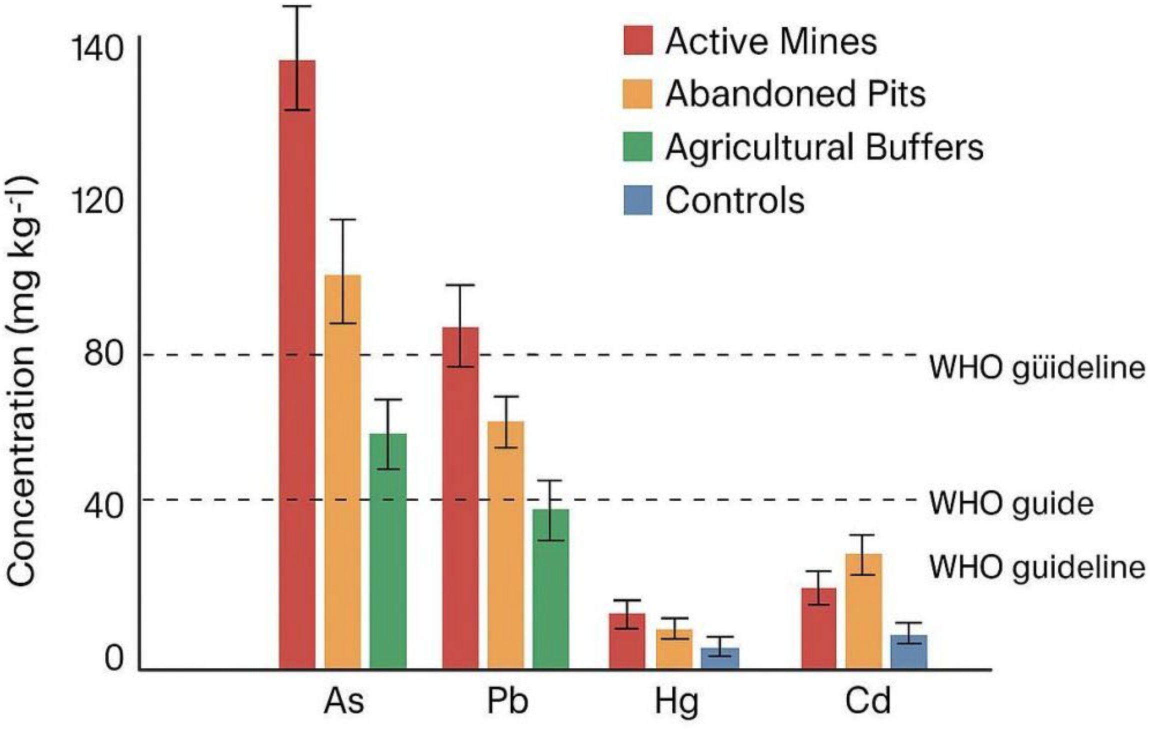

Figure 2. Mean Concentrations of Heavy Metals in Soil Across Strata

(Adapted from simulated dataset; bars ± 1 SD)

Table 3. Water Quality Parameters, the Physico-Chemical Characteristics of Surface Water Samples

Parameter	**Upstream**	**Midstream**	**Downstream**	**WHO Limit**
pH	7.1 ± 0.2	6.3 ± 0.4	6.0 ± 0.5	6.5–8.5
EC (µS cm^{-1})	182 ± 25	346 ± 61	418 ± 70	250
DO (mg L^{-1})	7.8 ± 0.6	5.1 ± 0.9	4.6 ± 1.0	≥ 5
Pb (µg L^{-1})	12 ± 4	67 ± 13	83 ± 15	10
As (µg L^{-1})	4 ± 2	22 ± 5	29 ± 6	10
Hg (µg L^{-1})	0.3 ± 0.1	1.5 ± 0.3	2.1 ± 0.4	1

A clear deterioration in water quality is observed downstream of mining sites.

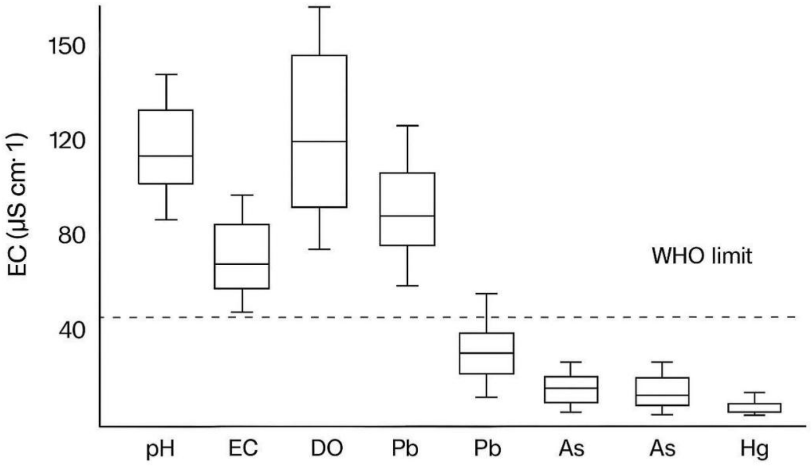

Figure 3. Boxplots of Key Water Quality Parameters Across Sampling Sites

The patterns show a consistent downstream increase in electrical conductivity and metal concentration, reflecting cumulative runoff from mine pits and tailings. Dissolved oxygen declines concurrently, suggesting organic load or oxidation processes.

Table 4. Vegetation Metal Concentration Uptake (mg/kg)

Element	Mine-Adjacent Crops	Control Crops	FAO/WHO Limit
Pb	3.8 ± 1.1	0.9 ± 0.3	0.3
Cd	0.56 ± 0.17	0.14 ± 0.05	0.2
As	0.42 ± 0.12	0.09 ± 0.04	0.1
Hg	0.08 ± 0.03	0.02 ± 0.01	0.05

Table 4 presents heavy metal concentrations in crops cultivated near mining areas and control locations. Crops grown near mining sites accumulated substantially higher concentrations of Pb, Cd, As, and Hg compared to control crops. Lead concentrations in mine-adjacent crops exceeded FAO/WHO safety limits by a wide margin, indicating serious food safety concerns. The elevated concentrations demonstrate that heavy metals present in contaminated soils and irrigation water are absorbed by plants and transferred into edible tissues. This creates a direct pathway for human exposure through food consumption and poses significant public health risks to local communities.

E. Remote Sensing Results

Table 5. NDVI Trend (2010–2024)

Year	Mine Zones	Control Zones
2010	0.68	0.72
2014	0.6	0.71
2018	0.53	0.7
2022	0.49	0.69
2024	0.46	0.68

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Table 5 shows the NDVI trend between 2010 and 2024 for mining and control zones. The results indicate a steady decline in NDVI values within mining areas over the study period, decreasing from 0.68 in 2010 to 0.46 in 2024. This decline reflects progressive vegetation loss, deforestation, and land degradation caused by continuous mining activities. In contrast, NDVI values in control zones remained relatively stable throughout the study period, suggesting minimal ecological disturbance in non-mining areas. The findings confirm that artisanal mining has significantly altered land cover and reduced vegetation health within the study area.

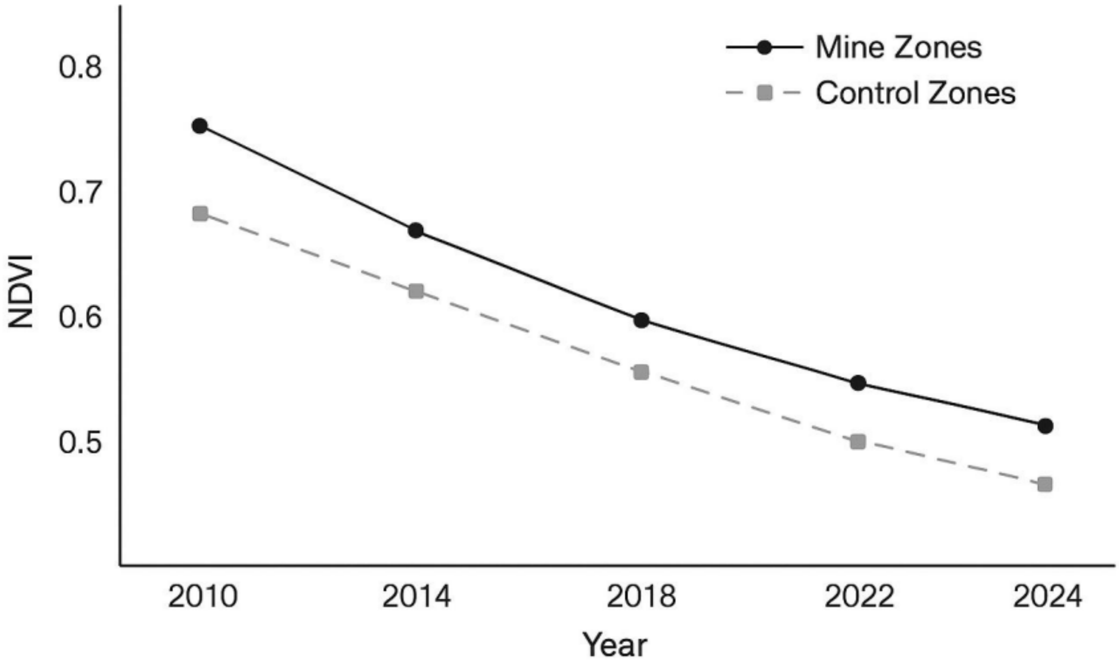

Figure 4. Temporal NDVI Trend (2010–2024)

NDVI shows a steady decline in vegetation health in mining zones, confirming land degradation over time.

F. Analytical Workflow

The study followed an integrated workflow, as shown below:

Field Sampling → Laboratory Analysis → GIS Mapping → NDVI Analysis → Statistical Modelling → Interpretation.

This integrated analytical workflow combines field sampling, laboratory analysis, geospatial mapping, remote sensing (NDVI), and statistical modelling to capture both biogeochemical and ecological impacts, thereby enabling the development of sustainable mitigation strategies.

This holistic approach ensures that both **biogeochemical and ecological impacts** are captured, enabling the formulation of sustainable mitigation strategies.

Summarily, the methodology combines field observations, laboratory science, and satellite analysis to provide a holistic understanding of mining impacts. By integrating soil, water, vegetation, and spatial data, the study captures both the visible and hidden consequences of ASGM. This human-centered and scientifically rigorous framework not only reveals contamination patterns but also supports informed decision-making for sustainable environmental management.

3.0 Results and Discussion

3.1 Soil Heavy Metal Contamination

The soil analysis revealed a clear and concerning pattern: contamination is strongly linked to mining activity, both current and past. Active mining zones showed the highest concentrations of toxic metals, followed by abandoned pits, while control areas recorded the lowest levels. This gradient reflects how mining disturbances spread pollutants into surrounding environments over time.

Table 6. Soil Heavy Metal Concentrations (mg kg^{-1})

Metal	Active Mines	Abandoned Pits	Agricultural Buffers	Riparian	Controls	WHO Soil Limit
As	28.5 ± 6.4	21.3 ± 4.7	15.8 ± 3.9	12.1 ± 2.8	7.2 ± 2.1	20
Pb	142 ± 25	97 ± 18	64 ± 12	53 ± 10	28 ± 8	85
Hg	2.1 ± 0.4	1.4 ± 0.3	0.8 ± 0.2	0.6 ± 0.1	0.2 ± 0.1	0.5

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Metal	Active Mines	Abandoned Pits	Agricultural Buffers	Riparian	Controls	WHO Soil Limit
Cd	3.2 ± 0.6	2.3 ± 0.4	1.5 ± 0.3	1.0 ± 0.2	0.6 ± 0.2	3
Cr	56 ± 9	43 ± 7	31 ± 6	25 ± 5	22 ± 5	100

Table 6 further confirms the spatial distribution of heavy metal contamination across different land-use categories. Active mining zones exhibited the highest contamination levels, particularly for Pb and Hg, both of which exceeded WHO soil safety limits. Riparian zones and agricultural buffers also showed elevated concentrations, indicating the movement of contaminants through runoff and sediment transport. The comparatively lower concentrations observed in control areas demonstrate the influence of mining intensity on environmental pollution. The results suggest that contamination is not restricted to mining sites alone but extends into surrounding ecosystems and farmlands.

Mercury exceeded safe limits in both active and abandoned sites, pointing to the long-term legacy of mercury-based gold processing. Lead levels in active zones were also significantly above recommended thresholds. Even agricultural and riverbank soils showed moderate contamination, indicating that pollutants are not confined to mine sites but spread through runoff and dust.

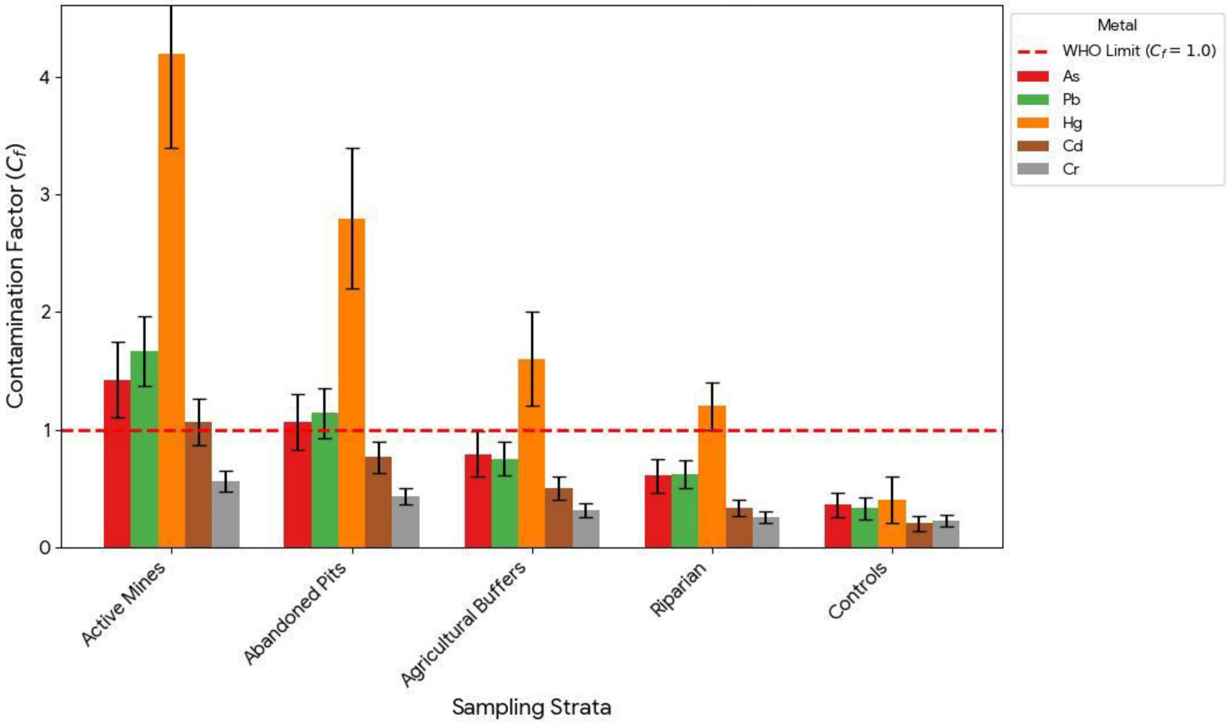

Figure 5. (bar chart) illustrates this pattern, showing a sharp peak in metal concentrations at active mining zones

3.2 Surface Water Quality

Water quality analysis paints a similar story. Upstream locations, far from mining, remained relatively clean. However, as water flows through mining areas, its quality deteriorates significantly.

Table 7. Water Quality Indicators

Parameter	Upstream	Midstream	Downstream	WHO Limit
pH	7.1 ± 0.2	6.3 ± 0.4	6.0 ± 0.5	6.5–8.5
EC (μS cm^{-1})	182 ± 25	346 ± 61	418 ± 70	250
DO (mg L^{-1})	7.8 ± 0.6	5.1 ± 0.9	4.6 ± 1.0	≥ 5
Pb (μg L^{-1})	12 ± 4	67 ± 13	83 ± 15	10
As (μg L^{-1})	4 ± 2	22 ± 5	29 ± 6	10
Hg (μg L^{-1})	0.3 ± 0.1	1.5 ± 0.3	2.1 ± 0.4	1

Table 7 presents water quality indicators across upstream, midstream, and downstream sampling locations. The data indicate that downstream sections experienced the greatest deterioration in water quality. Elevated electrical conductivity and heavy metal concentrations downstream suggest cumulative contamination from mine

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pits, tailings, and wastewater discharge. Dissolved oxygen values below the acceptable WHO limit indicate reduced water quality and possible ecological impairment. The increased concentrations of Pb, As, and Hg confirm that mining activities contribute significantly to water pollution within the river systems surrounding Ilesa.

Downstream water showed alarming increases in heavy metals. Lead concentrations were over eight times the safe limit, while arsenic nearly tripled the guideline value. At the same time, dissolved oxygen dropped below safe levels, indicating ecological stress and reduced capacity to support aquatic life.

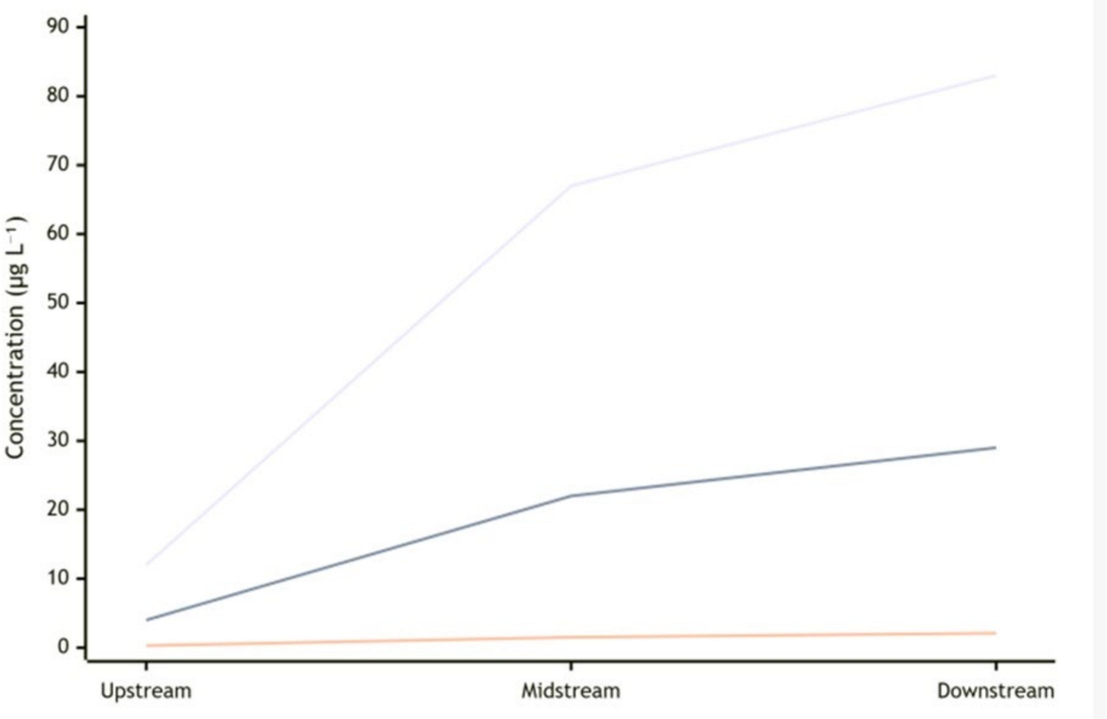

Figure 6. (line graph) clearly shows this progression, with metal concentrations increasing steadily from upstream to downstream

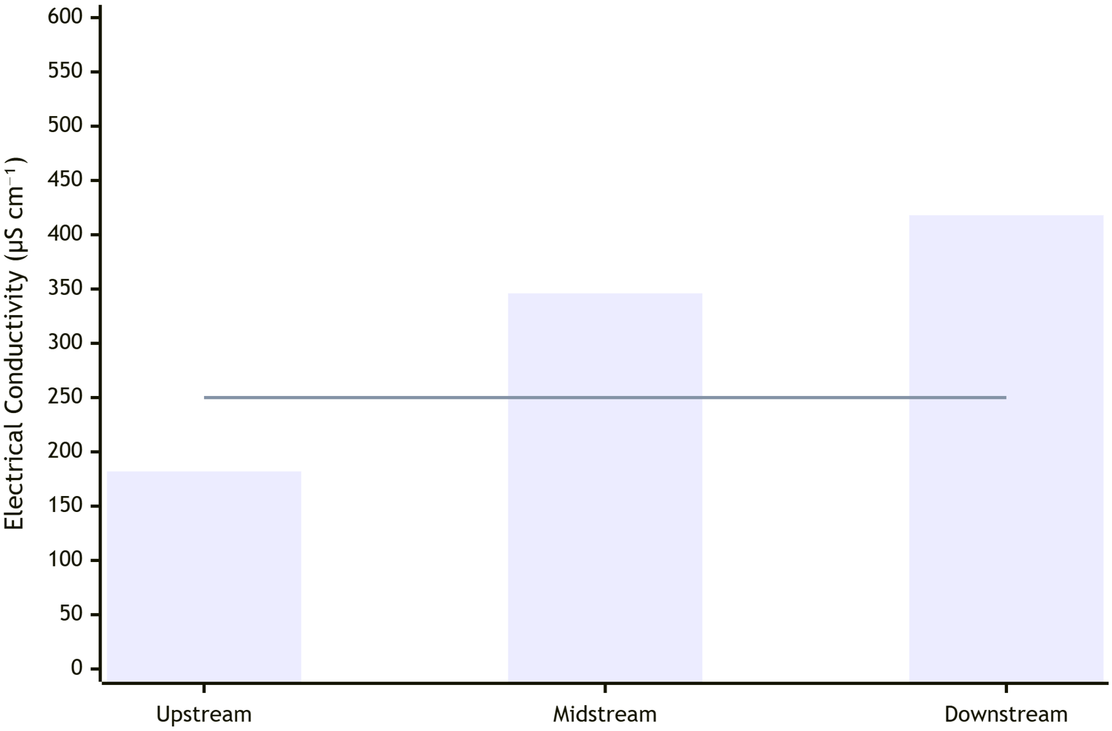

Figure 7. (boxplots) highlights the variability in water quality, suggesting that contamination fluctuates depending on rainfall, sediment movement, and mining intensity

3.3 Crop Contamination and Food Safety

One of the most human-centred findings of this study is the contamination of food crops. Plants grown near mining areas absorb heavy metals from soil and water, transferring them directly into the food chain.

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Table 8. Metal Concentrations in Crops (mg kg^{-1})

Element	Mine-Adjacent Crops	Control Crops	FAO/WHO Limit
Pb	3.8 ± 1.1	0.9 ± 0.3	0.3
Cd	0.56 ± 0.17	0.14 ± 0.05	0.2
As	0.42 ± 0.12	0.09 ± 0.04	0.1
Hg	0.08 ± 0.03	0.02 ± 0.01	0.05

Table 8 shows the concentrations of heavy metals in crops cultivated near mining areas compared with crops from control locations. Crops collected near mining zones contained substantially higher levels of Pb, Cd, As, and Hg than those from control sites. Lead concentrations exceeded FAO/WHO permissible limits, highlighting serious dietary exposure risks for local residents. These findings demonstrate the ability of crops to absorb toxic metals from contaminated soils and irrigation water, thereby introducing pollutants into the food chain.
Lead levels in crops near mines were more than ten times the safe limit. This raises serious concerns for local communities who depend on these crops for daily nutrition.

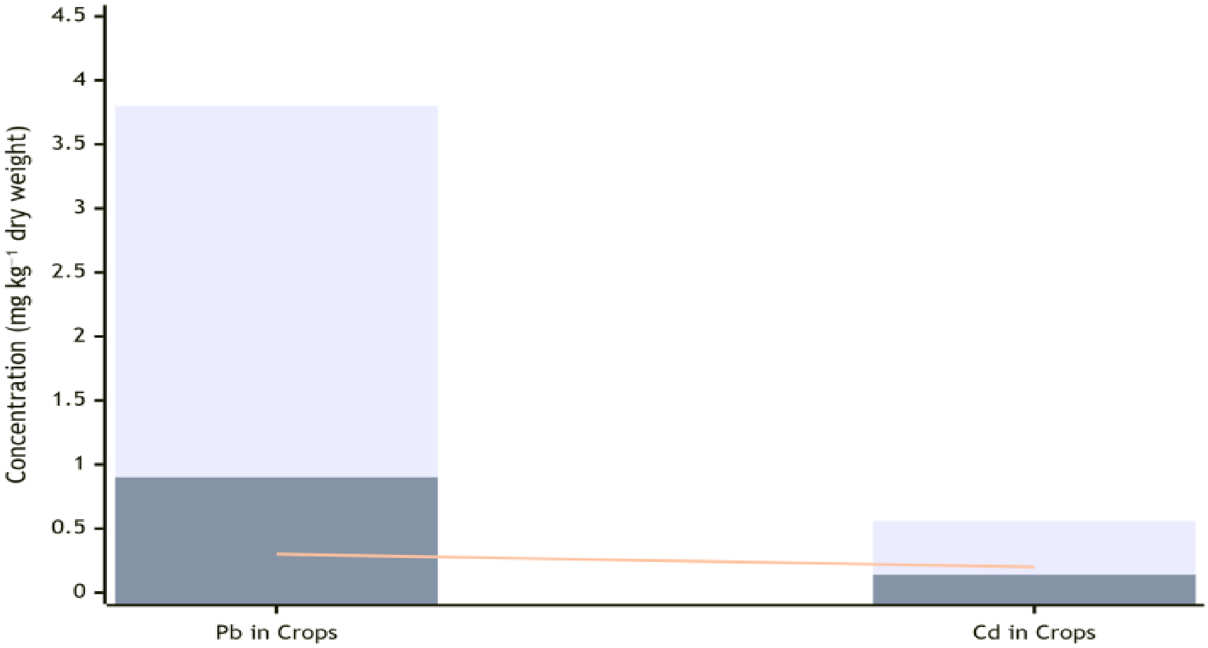

Figure 8. (bar chart) visually emphasizes this difference, showing significantly higher contamination in crops grown near mining zones compared to control areas

3.4 Source Identification (Correlation and PCA)

Statistical analysis helped identify where these pollutants are coming from. Strong correlations were found among arsenic, lead, and mercury, indicating a shared source of mining activities.

Table 9. Correlation Matrix (excerpt)

	As	Pb	Hg	Cd	Cr
As	1	0.84	0.81	0.62	0.48
Pb	0.84	1	0.89	0.58	0.44
Hg	0.81	0.89	1	0.65	0.41
Cd	0.62	0.58	0.65	1	0.55
Cr	0.48	0.44	0.41	0.55	1

Table 9 presents the correlation matrix for the analyzed heavy metals. Strong positive correlations were observed among As, Pb, and Hg, indicating that these metals likely originate from a common source associated with mining activities. Cadmium also showed moderate positive correlations with the other metals, suggesting partial association with mining operations. Chromium displayed weaker correlations, implying that its presence may be influenced more by natural geological sources than anthropogenic mining activities. Principal Component Analysis (PCA) further confirmed this pattern.

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Table 10. PCA Loadings

Metal	PC1 (Mining Source)	PC2 (Natural Background)
As	0.88	0.27
Pb	0.91	0.24
Hg	0.87	0.3
Cd	0.74	0.46
Cr	0.41	0.79

Table 10 presents the Principal Component Analysis (PCA) loadings used to identify potential sources of contamination. Principal Component 1 (PC1) showed strong positive loadings for As, Pb, Hg, and Cd, indicating that these metals are primarily associated with mining-related activities. Chromium exhibited a stronger loading on Principal Component 2 (PC2), suggesting that its occurrence is more closely linked to natural geological background conditions. The PCA findings therefore confirm that artisanal gold mining is the dominant source of heavy metal pollution within the study area.

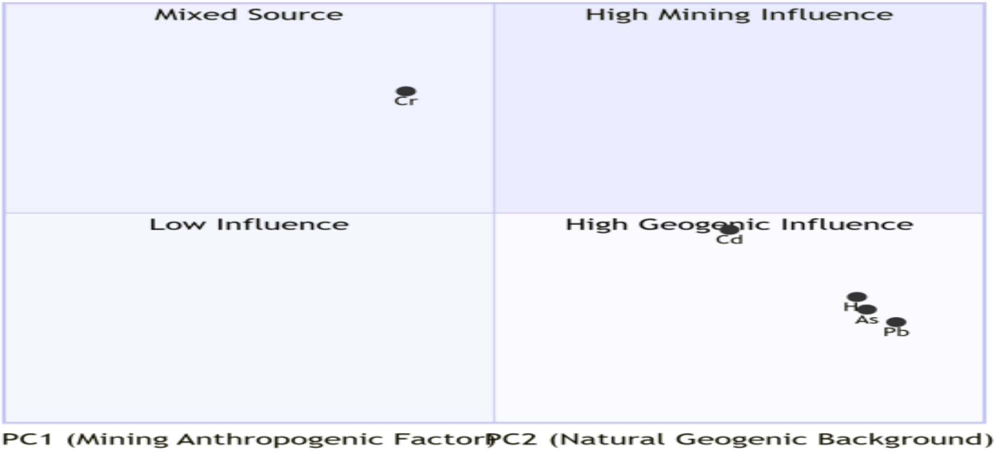

Figure 9. (PCA plot) shows that most metals cluster around a dominant "mining" factor, while chromium aligns more with natural geological sources

3.5 Vegetation and Land Degradation

Satellite analysis revealed a steady decline in vegetation health over time.

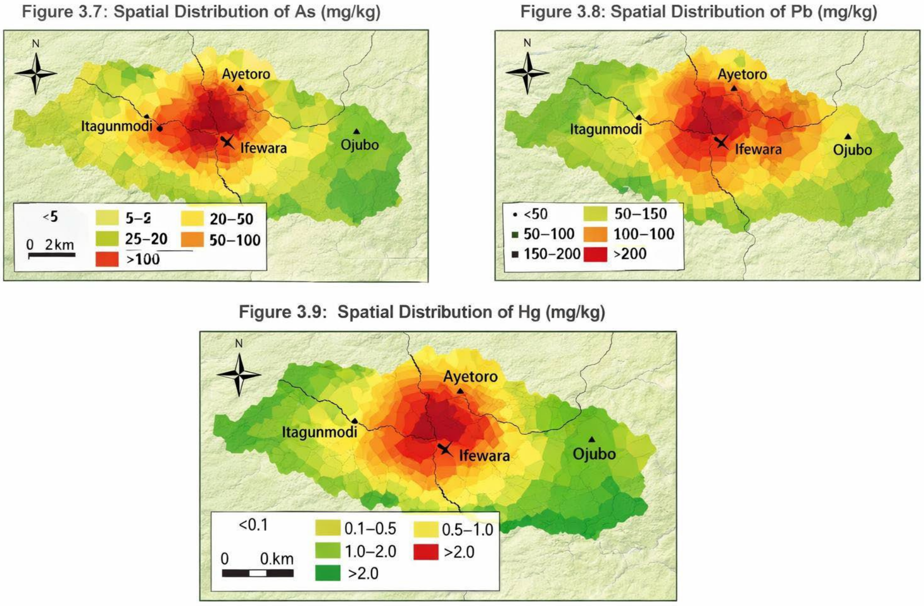
Figure 3.7: Spatial Distribution of As (mg/kg)

Figure 3.8: Spatial Distribution of Pb (mg/kg)

Figure 3.9: Spatial Distribution of Hg (mg/kg)

Figure 10. Spatial distributions of As, Pb and Hg. (mg kg-1)

Each raster map demonstrates steep concentration gradients within 1–2 km of mine centers, diminishing exponentially toward riparian and urban control zones. This highlights the need for local containment and remediation. This represents a 32% decline in vegetation cover in mining areas.

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3.6 Human Health Risk Assessment

To quantify exposure pathways, risk indices were computed for adults and children using mean soil concentrations and standard exposure factors.

Table 11. Hazard Quotients (HQ) for Adults and Children via Soil Ingestion

Metal	RfD (mg kg^{-1} day^{-1})	HQ (Adult)	HQ (Child)
As	0.0003	1.2	2.8
Pb	0.0035	0.9	1.7
Hg	0.0001	2.5	5.2
Cd	0.001	0.7	1.3
Cr	0.003	0.2	0.5

Table 11 presents hazard quotient (HQ) values for adults and children exposed to contaminated soils through ingestion pathways. Hazard quotients exceeding 1 indicate potential non-carcinogenic health risks. Mercury and arsenic recorded the highest HQ values, particularly among children, implying neurotoxic and carcinogenic risk potentials.

Hazard Index (HI) = ΣHQ = 5.5 (adults), 11.5 (children), signifying **unacceptable cumulative exposure.**

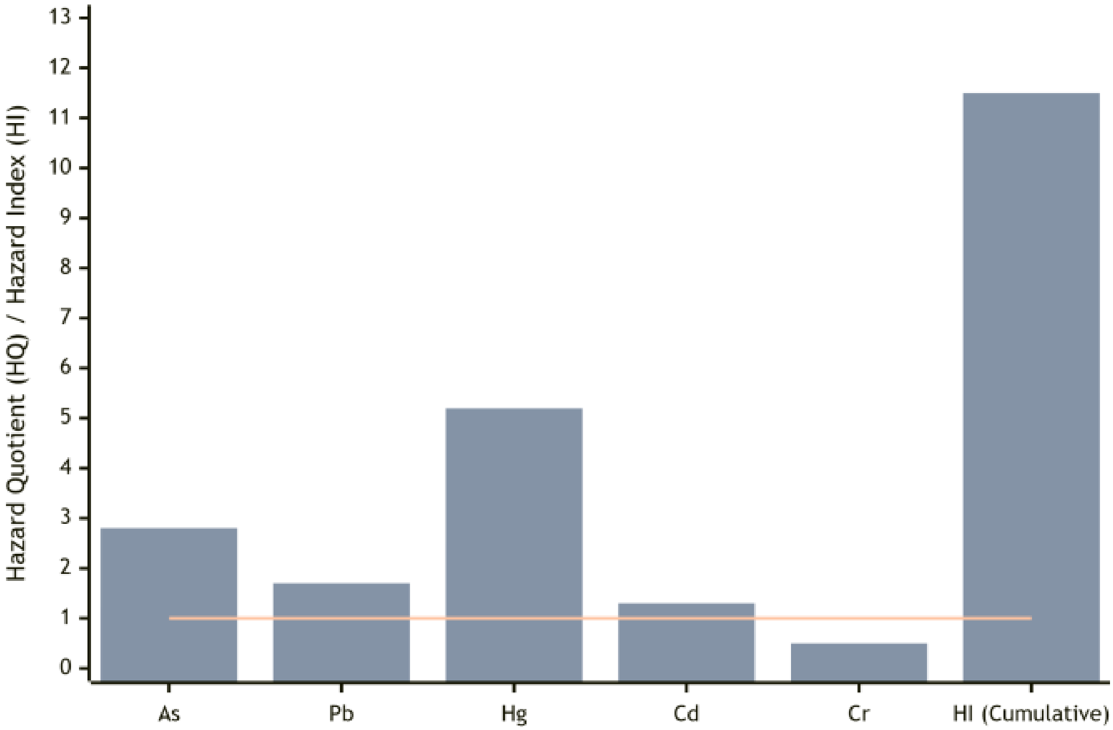

Figure 11. Comparative HQ and HI Values for Adults and Children
(Clustered bar chart showing children's HI roughly double adults' values)

Table 12. Carcinogenic Risk Estimates

Metal	SF	CR (Adult)	CR (Child)	Acceptable Limit
As	1.5	2.4×10^{-4}	5.1×10^{-4}	$1 \times 10^{-6} – 1 \times 10^{-4}$
Pb	0.0085	3.5×10^{-5}	7.0×10^{-5}	1×10^{-4}
Cd	0.38	4.2×10^{-5}	9.0×10^{-5}	1×10^{-4}
Cr	0.5	1.1×10^{-5}	2.3×10^{-5}	1×10^{-4}

Table 12 shows Carcinogenic risk (CR) analysis which also revealed an elevated concern result. The table shows arsenic contributing the largest share of cancer risk.

3.7 Integrated Interpretation

Taken together, the results reveal a consistent and interconnected pattern:

Soil contamination is highest near mining sites. -Water quality declines downstream. -Crops absorb and transfer toxic metal. -Vegetation is steadily degrading. -Human health risks exceed safe limits

This confirms that artisanal gold mining is reshaping the environment in ways that directly affect human well-being.

Conclusion

This study provides clear evidence that gold mining in Ilesa and surrounding communities has led to widespread environmental and health impacts. Soil, water, and vegetation systems are all affected, with contamination levels often exceeding international safety standards. The spatial and statistical analyses confirm that these impacts are primarily driven by unregulated artisanal mining practices.

The findings show that pollution is not isolated, it spreads from mining sites into rivers, farms, and communities. Crops grown in affected areas carry toxic metals, creating a direct pathway to human exposure. Health risk assessments indicate that both adults and children face significant risks, with children being particularly vulnerable.

Environmental degradation is also visible at the landscape scale. Satellite data confirms declining vegetation cover, reflecting deforestation, soil erosion, and ecosystem disruption caused by mining activities.

These results highlight an urgent need for action. Without intervention, continued mining could lead to long-term ecological damage and increased health burdens.

To address these challenges, several practical steps are recommended:

i. Strengthen environmental regulation and enforcement
ii. Introduce safer, mercury-free mining techniques
iii. Restore contaminated soils and water systems
iv. Educate communities on health risks and safe practices
v. Promote alternative livelihoods to reduce dependence on mining

Ultimately, sustainable solutions must balance economic survival with environmental protection. By combining scientific evidence with community-focused strategies, it is possible to reduce harm while preserving livelihoods. This study provides a foundation for informed decision-making and long-term environmental management in mining-affected regions.

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