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ARTICLE

Assessing the Environmental Impacts of Alluvial Gold Mining in Betare-Oya, Cameroon (2021–2025): An Integrated Remote Sensing and Ground-Truthing Approach

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ABSTRACT

Alluvial gold mining in Betare-Oya, Cameroon, poses a significant environmental threat, leading to deforestation, land degradation, and water pollution. This study investigates the spatiotemporal environmental impacts of alluvial gold mining in Betare-Oya, East Cameroon, over the period 2021 to 2025 by integrating remote sensing techniques with field-based observations. Sentinel-2 satellite imageries were analyzed using key indices: Bare Soil Index (BSI), Normalized Difference Vegetation Index (NDVI), and Land Use/Land Cover (LULC) to detect land degradation, vegetation loss, and changes in surface conditions. Key results include a substantial increase in bare soil (BSI rising from 19.20% in 2021 to 38.23% in 2024), a decline in dense vegetation (NDVI decreasing from 46.13% in 2021 to 42.34% in 2024), and a conversion of forested areas to mining zones (LULC showing a decrease in dense vegetation from 38.27% in 2021 to 30.69% in 2024, and an increase in bare land from 32.22% to 45.48%). Change detection analysis revealed that

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the most significant changes are from dense vegetation to bare land and mine sites. Field observations corroborated these findings, highlighting deforestation, soil erosion, and water pollution. While these results demonstrate a strong correlation between mining and environmental degradation, limitations in temporal resolution, spatial resolution, and the scope of ground-truthing necessitate further investigation. Future research should focus on quantifying the specific impacts of artisanal versus semi-mechanized mining, assessing water quality parameters, and evaluating the long-term ecological consequences. This study underscores the urgent need for improved regulation and sustainable management of mining operations to mitigate the negative environmental impacts in Betare-Oya and similar regions.

Keywords: Alluvial Gold Mining; Remote Sensing; Field Observation; NDVI; BSI; LULC; Environmental Impact; Betare-Oya

1. Introduction

Mining has been a significant economic activity worldwide, contributing to industrial development, employment, and revenue generation [1]. However, its environmental and socio-economic impacts have raised major concerns, particularly in developing countries [2]. Among various forms of mining, alluvial gold mining is one of the most prevalent in tropical regions, especially in Africa, where semi-mechanized and artisanal small-scale miners extract gold from riverbeds and floodplains [3]. In Cameroon, the East Region particularly Betare-Oya has become a hotspot for such activities due to its rich gold endowment [4]. Despite its economic contributions, alluvial gold mining is increasingly recognized for its adverse environmental impacts, including deforestation, land degradation, river siltation, and water pollution [5]. These environmental issues are exacerbated by weak regulatory enforcement, the informal nature of most operations, and the lack of sustainable mining practices. The mining process typically involves removing overburden and sediment layers to access alluvial gold, often resulting in the stripping of vegetation and topsoil. This disrupts local ecosystems and alters land cover, contributing to long-term environmental degradation [6].

The introduction of remote sensing technology has transformed the monitoring and assessment of environmental changes caused by mining [7,8]. It offers timely and accurate data, enabling the analysis of spatial and temporal patterns of land degradation. Studies have demonstrated the effectiveness of satellite imagery in detecting land use and land cover (LULC) changes in mining areas [9]. In addition Multispectral and thermal imaging for spatiotemporal analysis of mining impacts have widely been used in monitoring vegetation health over time [10].

Several studies have utilized remote sensing to map LULC changes resulting from alluvial gold mining activities in Betare-Oya. For example, research employing Landsat imagery from 1987 to 2017 revealed significant environmental transformations, such as increased human settlements and expanded artisanal mining at the expense of vegetation cover [11]. Another study using Sentinel-2 imagery from 2018 to 2022 by [12] highlighted the expansion of mining activities and their impact on local ecosystems. These findings underscore the critical need for continuous monitoring and the development of rehabilitation measures to mitigate environmental degradation.

A deeper understanding of the environmental impacts of alluvial gold mining requires situating the study within broader frameworks of landscape fragmentation and post-mining land reclamation, both of which are central to environmental and applied landscape ecology. Landscape fragmentation refers to the breaking up of continuous, functioning ecosystems into smaller, isolated patches due to anthropogenic disturbances such as mining, logging, urbanization, and road construction [13,14]. This process disrupts ecological connectivity, reduces habitat quality, and leads to biodiversity loss, microclimatic shifts, and hydrological changes [15]. In mining regions, these effects are exacerbated by the physical transformation of terrain through excavation, creation of spoil heaps, bare land exposure, and the removal of native vegetation. Metrics such as patch density, edge contrast, and landscape shape index have been widely used to assess the degree of fragmentation in such altered environments [16,17].

In Eastern Europe, decades of open cast mining have produced complex post-industrial landscapes characterized by fragmented forests and abandoned spoil heaps. Studies in Romania's Jiu Valley [18], Poland's Upper Silesian basin [19], and Slovakia's Nováky region [20] have documented severe land degradation and ecological disconnection. Although restoration efforts, including land reshaping, reforestation, and soil stabilization have been undertaken, challenges persist due to soil infertility, contamination, and socio-economic transitions in post-mining towns [21,22].

In Asia, large-scale coal and gold mining in countries like China, India, and Indonesia has led to accelerated landscape fragmentation and ecological stress. Open cast mining in Inner Mongolia has fragmented grasslands, reduced species richness, and caused irreversible topsoil loss [23]. In India's Jharkhand and Odisha regions, mining has devastated tribal lands, with NDVI analyses showing consistent vegetation loss over time [24]. In Indonesia's Kalimantan, uncontrolled mining along riverbanks has resulted in forest loss, pollution, and erosion, with poor post-mining reclamation [25].

In North America, stricter environmental laws have supported more advanced reclamation practices, especially in the United States and Canada. For example, the Surface Mining Control and Reclamation Act (SMCRA) of 1977 in the U.S. mandates that mining companies restore the land to pre-mining conditions. Studies in Appalachia show that while reclamation has improved over time, ecological recovery is still partial, forest regrowth is often replaced with grasslands or invasive species, and hydrological systems remain altered [26,27]. In Canada's Alberta oil sands, efforts include soil reconstruction and wetland re-creation, but challenges persist with tailings pond rehabilitation and biodiversity reinstatement [28].

In South America, especially in the Amazon basin of Brazil, Peru, and Colombia, alluvial gold mining has caused intense forest fragmentation and riverine pollution. Remote sensing studies have shown alarming rates of forest loss due to informal mining [29]. In Madre de Dios, Peru, mining has fragmented habitats critical for endemic species, leading to persistent ecological degradation [30]. Although governments have launched initiatives like reforestation and illegal mining control, socio-economic pressures and weak enforcement often impede success [31].

In Africa, artisanal and small-scale gold mining (ASGM) is widespread, particularly in Ghana, DR Congo, Uganda, the Central African Republic, Mali, Zambia, Tanzania, Cameroon etc. Studies in Ghana's Western Region have shown extensive land fragmentation using NDVI and LULC analyses, with poor site rehabilitation following gold extraction [32,33]. In DR Congo and Uganda, mercury contamination and uncontrolled excavation have left lasting ecological and public health impacts [34].

Although anecdotal evidence and short-term assessments of environmental damage exist, there is a notable lack of systematic, spatiotemporal analyses that document how these environmental changes evolve over time. Remote sensing offers a valuable tool to fill this gap by enabling the consistent monitoring of environmental parameters across large and often inaccessible areas. By using satellite-derived indices such as the Bare Soil Index (BSI) and the Normalized Difference Vegetation Index (NDVI), researchers can assess changes in land cover, vegetation health, and surface disturbance. Land Use/Land Cover (LULC) classification and change detection techniques further enhance our understanding of landscape dynamics over time [9].

This study integrates satellite remote sensing with field-based observations and Google Earth Pro imagery to evaluate the spatiotemporal impacts of alluvial gold mining in Betaré-Oya from 2021 to 2025. The combined approach allows for a more comprehensive and accurate assessment of environmental change, providing spatial evidence that is critical for effective land management and policy-making. Remote sensing data from Sentinel-2 were used to calculate key indices and classify land cover types, while ground-truthing during the January–March 2025 field investigation helped validate and interpret the satellite-based findings.

The research was guided by the following objectives. The main objective was to assess the spatiotemporal environmental impacts of alluvial gold mining in Betaré-Oya, Cameroon, from 2021 to 2025 by integrating remote sensing techniques and field observations. Specifically, the study aimed to: (1) assess the degree of land degradation using the Bare Soil Index and field-validated observations; (2) determine changes in vegetation health using the NDVI; (3) monitor LULC dynamics and detect spatial changes in mining-affected areas; (4) corroborate satellite-based findings with field observations and Google Earth Pro imagery; and (5) provide spatial data to support future environmental monitoring and sustainable land management initiatives.

This study is significant for several reasons. First, it provides a replicable methodological framework for integrating satellite imagery with ground-based observations in mining-affected regions. Second, it delivers empirical data on the extent and progression of environmental degradation caused by gold mining in Betaré-Oya. Third, the insights generated can inform local and national stakeholders including government agencies, environmental NGOs, and community organizations about priority areas for intervention. Finally, the study contributes to the broader academic literature on artisanal mining and environmental sustainability in Central Africa.

1.1. Study Area Description

Betare-Oya is a key alluvial gold mining area located in the East Region of Cameroon, It is situated at approximately latitude 14°1'0.643"E and longitude 5°42'48.587"N in the Lom-et-Djerem Division of Cameroon's East Region (**Figure 1**). It is bordered by Ngoura, Belabo, and Garoua-Boulaï and lies along the Lom River, a major water source that is heavily impacted by gold mining activities [35]. The population of Betare-Oya is diverse, with the Gbaya, Beti, and Baka ethnic groups being predominant. The Gbaya people, who are primarily agriculturalists and traders, form the largest community. The region also hosts migrant workers from other parts of Cameroon and neighboring countries who engage in artisanal mining [36]. Betare-Oya experiences a tropical humid climate with two major seasons. Rainy Season: Extends from March to October, with peak rainfall occurring in July and September. Annual precipitation ranges between 1,500–2,000 mm [37]. Dry Season: Runs from November to February, characterized by hot temperatures (28°C–35°C) and reduced river flow. The natural vegetation of Betare-Oya consists of dense semi-deciduous forests. The main vegetation types include: Gallery forests along rivers and wetlands; Savannah woodlands in degraded mining zones; Farmland and secondary forests due to shifting cultivation [38].

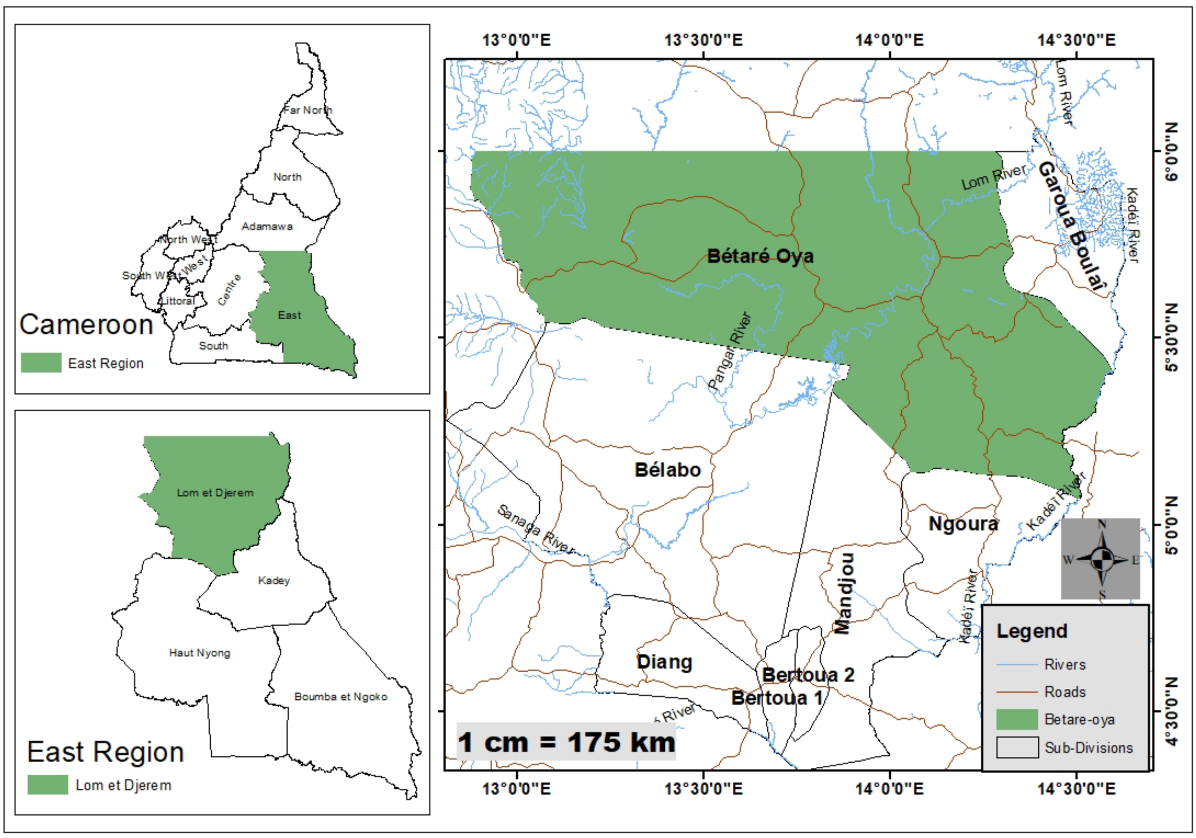


Figure 1. Location Map of study area.

2. Materials and Methods

The study integrates quantitative methods (satellite image analysis and spectral indices computation) and qualitative methods (field base assessment and expert consultations).

2.1. Quantitative Methods (Remote Sensing Techniques)

Sentinel-2 Level-2 (surface reflectance) imagery were acquired for the Betare-Oya region for the years 2021, 2023, and 2024. The selection of imagery as seen on **Table 1** prioritize dates within the dry season (November - March) to minimize cloud cover and vegetation influence on spectral indices computation (Bare soil Index- BSI, Normalized Difference Vegetation Index- NDVI) and Image Analysis for Land Used Land Cover Change (LULC) Detection. The images were downloaded from the Copernicus Open Dataspace System (formerly Sentinels Scientific Data Hub). The workflow as shown in **Figure 2** involves image acquisition/download, preprocessing i.e. subset region of interest and image enhancement using SNAP (Sentinel Application Platform), spectral indices computation and spatial analysis using ArcGIS 10.8.

Image Selection Criteria:

- Images with less than 10% cloud cover over the study area were preferred.
- The Level-2 product provides atmospherically corrected surface reflectance values, reducing the need for additional atmospheric correction procedures.
- The imagery covers the entire Betare-Oya study area.

Table 1. Characteristics of downloaded Sentinel images.

Year	Satellite	Date of image	Time	Phonological cycle
2021	Sentinel-2 Level 2	09/12/2021	09:22:59	Dry Season
2023	Sentinel-2 Level 2	14/12/2023	09:24:01	Dry Season
2024	Sentinel-2 Level 2	23/12/2024	09:23:19	Dry Season

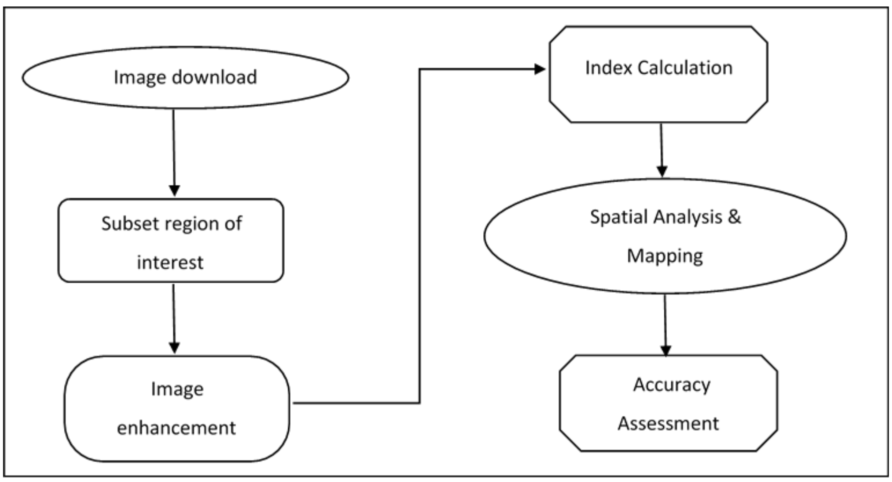


Figure 2. Flowchart for BSI and NDVI.

2.1.1. Bare Soil Index (BSI) Computation

The BSI is calculated using the following formula, which utilizes the red, blue, shortwave infrared (SWIR1), and near-infrared (NIR) bands of the Sentinel-2 imagery:

BSI = ((SWIR1 + Red) - (NIR + Blue)) / ((SWIR1 + Red) + (NIR + Blue))

Where:

SWIR1: Shortwave Infrared 1 (Sentinel-2 Band 11)

Red band (Sentinel-2 Band 4)

NIR: Near-Infrared band (Sentinel-2 Band 8)

Blue: Blue band (Sentinel-2 Band 2)

The BSI was calculated using the Raster Calculator tool in ArcGIS 10.8. The band designations were carefully matched to the corresponding Sentinel-2 bands in the preprocessed imagery. BSI values range from -1 to +1. Higher BSI values typically indicate a greater proportion of bare soil.

The BSI values were classified into different categories as:

- Bare Soil (actively mined areas or abandoned mine site)
- Dry grass (disturbed areas, partially revegetated areas)
- Sparse Vegetation (naturally bare areas, areas with minimal mining impact)
- Dense Vegetation

Ground truth data were used as a reference for accuracy assessment.

2.1.2. Normalized Difference Vegetation Index (NDVI) Computation

NDVI is calculated as**: NDVI = (NIR - Red) / (NIR + Red)**

Where:

NIR = Near-Infrared band (Sentinel-2 Band 8)

Red = Red band (Sentinel-2 Band 4)

SNAP and ArcGIS 10.8 were used for image preprocessing and spectral indices computation respectively. The Geotiff preprocessed raster images for 2021, 2023, and 2024 from SNAP were imported into the ArcGIS 10.8 for spatial analysis and spectral indices computation. Using the raster calculator, the NDVI values were obtained for each Year. The images were then classify into meaningful categories (Dense Vegetation, Moderate Vegetation, Sparse Vegetation, Bare Soil and water). The NDVI values and classifications were compared with satellite images from Google earth pro to assess the accuracy of the remote sensing analysis.

2.1.3. Land Use Land Cover (LULC) change detection

After Subsetting the area of interest and pre-processing the image in SNAP, image enhancement was done using ENVI 5.3 to improve the appearance of the image to assist in visual interpretation and analysis. These enhancement functions included contrast, stretching to increase the tonal distinction between features, and spatial filtering to enhance or suppress specific spatial patterns in the image. Also, different colour composites (4–3–2, 8–4–3 and 4–8–3, 5–4–3 bands, for RGB channels) were used to enhance the identification of features so as to select training set or classification signatures for use.

Training sets were selected for every image (2021, 2023 and 2024) in ArcGIS 10.8 (ArcMAP). Sample polygons were created based on visual interpretation of the image to recognize the Land Use/Land Cover feature classes. Every spectral analogous sub-area was demarcated with a specified class name using a training set.

After selecting the training sets, they were satisfactorily reviewed. Supervised classification was done using the maximum likelihood classification method (MLC) which is the most common efficient technique for evaluating the standard Land use/ land cover classifications. By the classification, six (6) Land Use and Land cover (LULC) types were recognized: Dense vegetation, Sparse Vegetation, Water, Settlement, Bare land and mine sites. Due to similarities in the reflectance of certain classes, the algorithm may experience confusion while classifying the land cover classes and as such may refer to one class as another. This was adjusted by post-classification where mistaken classes were reclassified into the actual classes. Pixels to be sampled were selected randomly and transferred to Google earth pro, by creating kml file in ArcGIS 10.8. Sample points were interpreted on Google earth Pro, the interpretation compared to the classification results, and corrected accordingly.

With the classification of images of the individual years, a post-classification approach of subtracting the classification maps, 2023 – 2021 and 2024 – 2021 was applied. Quantitative area data of the overall land cover changes as well as the gains and losses in each category between for each LULC change detection were compiled. (See the work flow in **Figure 3**)

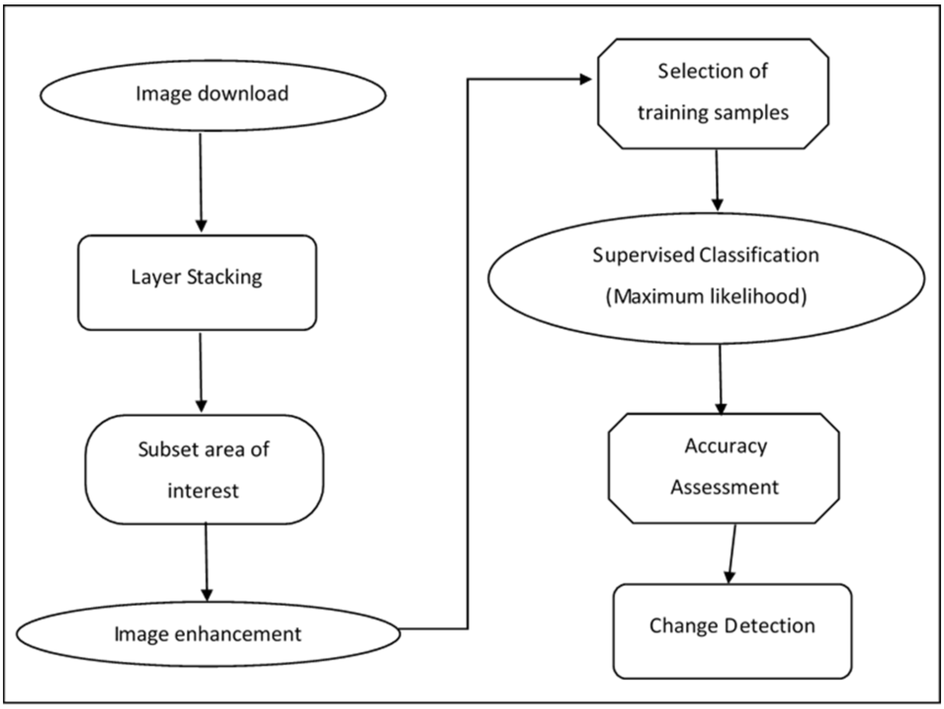


Figure 3. Flowchart for LULC change detection.

2.2. Qualitative Methods (Field-based observation and Google earth pro image appraisal)

A field visit was conducted between January and March 2025 to assess the extent of environmental degradation caused by alluvial gold mining. The assessment focused on active mining areas, abandoned mine sites, and general land degradation patterns. During the field visit, active and abandoned mine sites were identified and documented. Key observations included:

- Identification of active artisanal and semi-mechanized mining operations.
- Assessment of land degradation, deforestation, and soil erosion in affected areas.
- Visual examination of water bodies for signs of sedimentation and pollution.
- Inspection of abandoned mine sites to determine the extent of environmental impact.

A Garmin GPSMAP 64s was used to record the geographic coordinates of mining sites. GPS data collection was essential for spatial mapping and integration with satellite imagery. The collected data included:

- Locations of active mining pits and excavated areas.
- Coordinates of abandoned mine sites.
- Mapping of areas with visible land degradation and deforestation.

A Google pixel 6 smartphone with a high-resolution camera was used to capture photographic evidence of mining activities, abandoned sites, and environmental degradation. These images were used for validation of remote sensing analysis.

Semi-structured interviews were conducted with local residents, miners, and community leaders to gather qualitative information on mining activities and their environmental impacts. The discussions covered:

- Changes in land use and environmental conditions over time.
- Perceptions of the impact of mining on water quality and vegetation.
- Community perspectives on abandoned mine sites

To supplement field observations, Google Earth Pro was used to observe high-resolution satellite images of selected mining-affected areas for the year 2023. The imagery provided a detailed view of abandoned mine sites and land degradation. The selection of 2023 was to evaluate rehabilitation efforts with recent field observation.

3. Results and Discussion

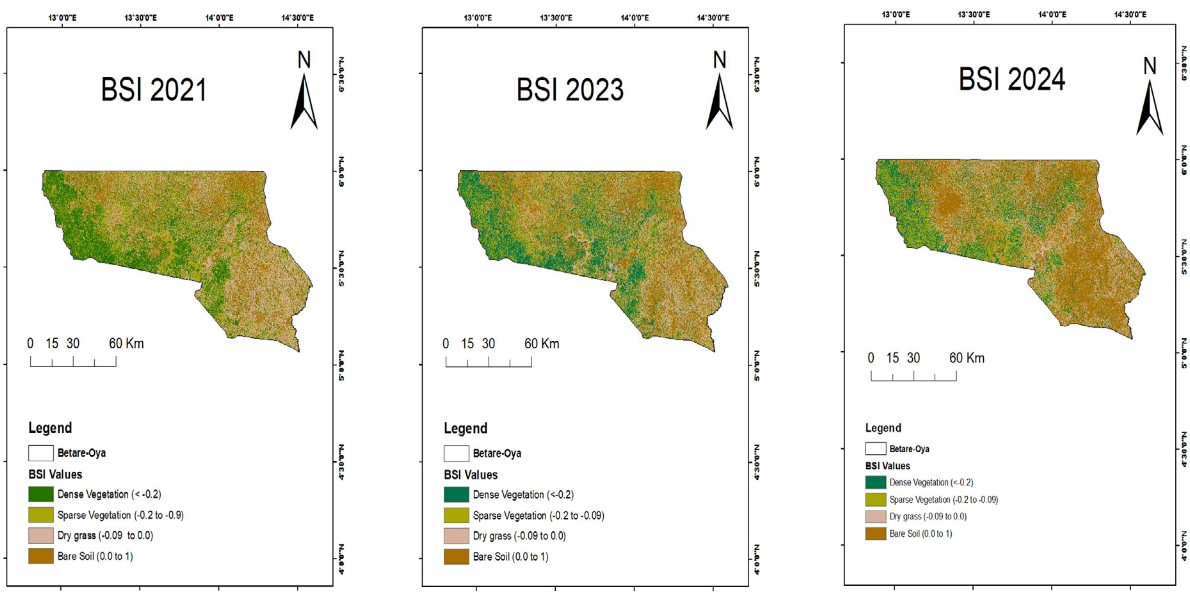
3.1. Remote Sensing techniques (Spectral indices Computation and Spatial Analysis)

The extent of land degradation was analysed using remote sensing techniques, including Bare Soil Index (BSI), Normalized Difference Vegetation Index (NDVI) and Land Use Land Cover (LULC) change detection.

3.1.1. Bare Soil Index (BSI)

The long-term ecological consequences of alluvial gold mining in the Betare-Oya region are potentially severe. Deforestation can lead to habitat loss, biodiversity decline, and reduced carbon sequestration. Soil erosion can degrade soil fertility and reduce agricultural productivity. The fragmentation of landscapes can also have significant ecological consequences. As mining activities expand, previously contiguous forests are broken up into smaller, isolated patches, which can reduce gene flow, increase the risk of extinction for certain species, and disrupt ecological processes

The BSI maps (**Figure 4**) illustrate the spatial distribution of bare soil across the Betare-Oya region for the years 2021, 2023, and 2024. In 2021, the BSI map shows a relatively low proportion of bare soil, with most areas classified as dense vegetation, sparse vegetation, or dry grass. However, by 2023, a noticeable increase in bare soil is evident, particularly in areas near active and abandoned mining sites. This trend continues in 2024, with further expansion of bare soil areas and a corresponding decrease in vegetation cover. The spatial patterns of BSI change appear to be strongly correlated with the locations of mining activities, suggesting a direct link between mining and land degradation.



(a) (b) (c)

Figure 4. Bare Soil Index (BSI) map for Betare-Oya: **(a)** BSI for 2021; **(b)** BSI for 2023; **(c)** BSI for 2024.

The BSI statistics (**Table 2**) provide a quantitative assessment of bare soil changes. The area of bare soil increased from 19.20% in 2021 to 38.23% in 2024, representing a significant increase in land degradation. Conversely, the area of dense vegetation decreased from 25.21% in 2021 to 15.37% in 2024, indicating a substantial loss of vegetation cover. The areas classified as sparse vegetation and dry grass also showed fluctuations, suggesting a dynamic response of vegetation to mining-related disturbances. The BSI trend from 2021 to 2024 (**Figure 5**) visually summarizes the changes in bare soil extent over time. The graph shows a consistent increase in the percentage of bare soil and a decrease in the percentage of dense vegetation. This trend suggests that mining activities are having a negative impact on land cover in the Betare-Oya region.

Table 2. Table Statistics for BSI.

Index	Class Name	Area (hectares)	Percentage (%)
BSI 2021	Dense Vegetation	283285.26	25.21
	Sparse Vegetation	307170.9	27.34
	Dry grass	317425.64	28.25
	Bare Soil	215701.32	19.20
BSI 2023	Dense Vegetation	245231.05	21.83
	Sparse Vegetation	330714.56	29.43
	Dry grass	261889.88	23.31
	Bare Soil	285747.14	25.43
BSI 2024	Dense Vegetation	172727.72	15.37
	Sparse Vegetation	268090.67	23.86
	Dry grass	253227.35	22.54
	Bare Soil	429539.52	38.23

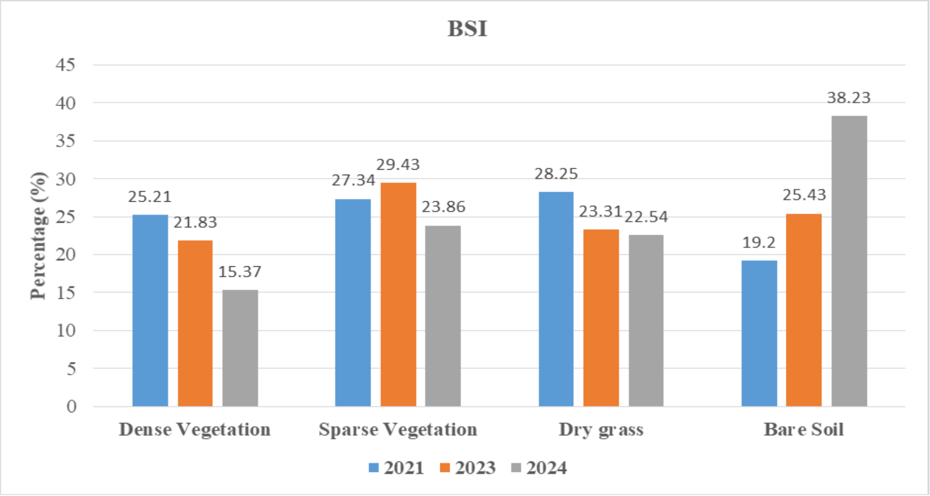
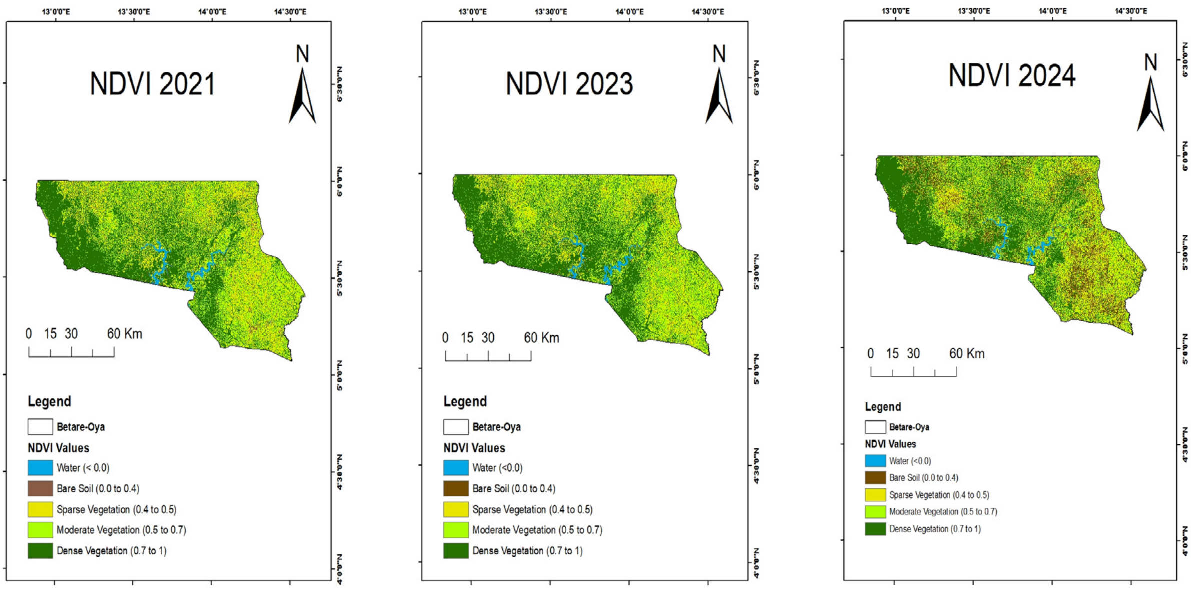


Figure 5. BSI trend from 2021 to 2024.

3.1.2. Normalized Difference Vegetation Index (NDVI)

The NDVI maps (**Figure 6**) provide a visual representation of vegetation health across the Betare-Oya region. In 2021, the maps show a relatively high proportion of dense vegetation, particularly in the northern and western parts of the study area. However, by 2023, a noticeable decline in dense vegetation is evident, with a corresponding increase in areas classified as sparse vegetation and bare soil. This trend continues in 2024, with further fragmentation of dense vegetation patches and expansion of degraded areas. The NDVI statistics (**Table 3**) provide a quantitative assessment of vegetation health changes. The area of dense vegetation decreased from 46.13% to 42.34% in 2024, representing a significant loss of vegetation cover. Conversely, the area of bare soil increased from 1.82% in 2021 to 12.55% in 2024, indicating a substantial increase in land degradation. The areas classified as sparse vegetation and moderate vegetation also showed fluctuations, suggesting a dynamic response of vegetation to mining-related disturbances.



(a) (b) (c)

Figure 6. Normalized Difference Vegetation Index (NDVI) map for Betare-Oya: **(a)** NDVI for 2021; **(b)** NDVI for 2023; **(c)** NDVI for 2024.

Table 3. Table Statistics for NDVI.

Index	Class Name	Area (hectares)	Percentage (%)
NDVI 2021	Water	18130.72	1.61
	Bare soil	20446.78	1.82
	Sparse vegetation	271631.71	24.18
	Moderate Vegetation	295101.27	26.26
	Dense Vegetation	518272.64	46.13
NDVI 2023	Water	17737.16	1.58
	Bare soil	76917.32	6.85
	Sparse vegetation	293233.83	26.10
	Moderate Vegetation	307388.95	27.36
	Dense Vegetation	428295.24	38.12
NDVI 2024	Water	16025.19	1.43
	Bare soil	140979.14	12.55
	Sparse vegetation	248247.3	22.09
	Moderate Vegetation	242560.41	21.59
	Dense Vegetation	475773.22	42.34

The NDVI trend from 2021 to 2024 (**Figure 7**) visually summarizes the changes in vegetation health over time. The graph shows a consistent increase in the percentage of bare soil.

The NDVI maps and statistics reveal a clear trend of declining vegetation health in the Betare-Oya region from 2021 to 2024. The decrease in dense vegetation and the increase in bare soil indicate that mining activities are having a significant impact on vegetation cover. The fragmentation of dense vegetation patches suggests that mining activities are disrupting the connectivity of ecosystems and reducing the resilience of vegetation to disturbances. The observed decline in vegetation health is likely due to a combination of factors associated with mining activities, including deforestation, topsoil removal, soil compaction, and soil contamination. Deforestation directly reduces vegetation cover, while topsoil removal and soil compaction hinder natural regeneration. Soil contamination from heavy metals and other pollutants can also inhibit plant growth and survival. The findings are consistent with previous studies that have used NDVI to assess vegetation health in mining-affected areas. For example, [17] found that NDVI values decreased in areas affected by mining activities, indicating a decline in vegetation health. The study also supports the findings of [18], who found that NDVI values were negatively correlated with soil degradation in mining areas.

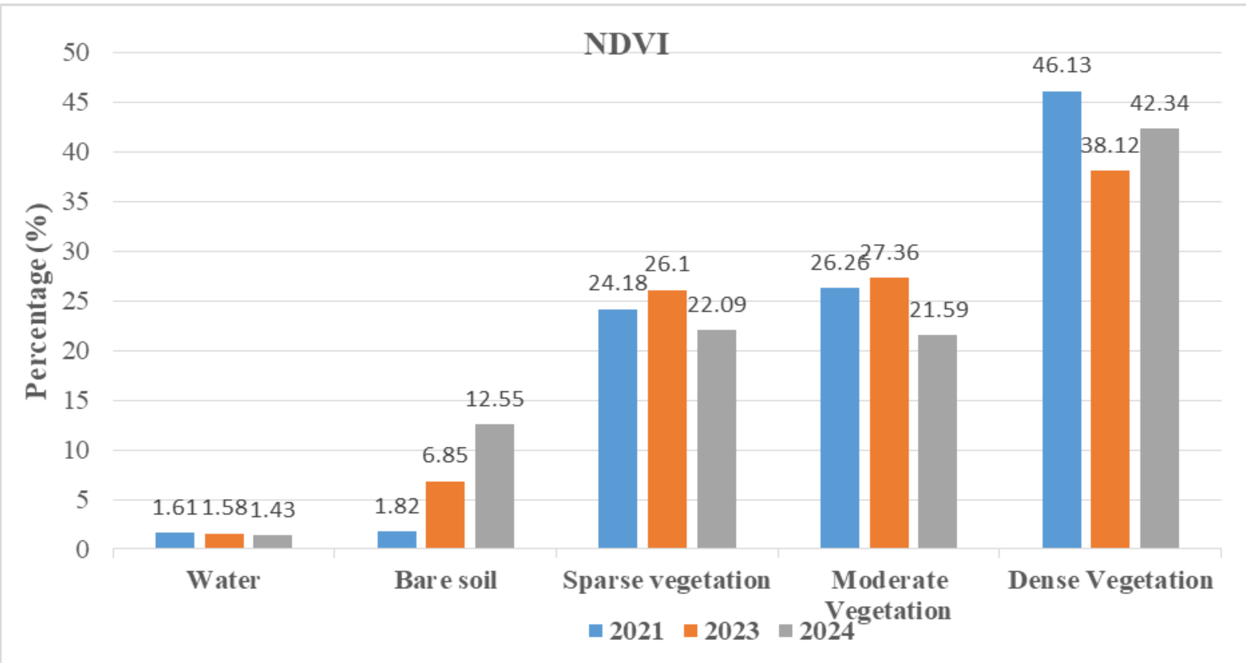
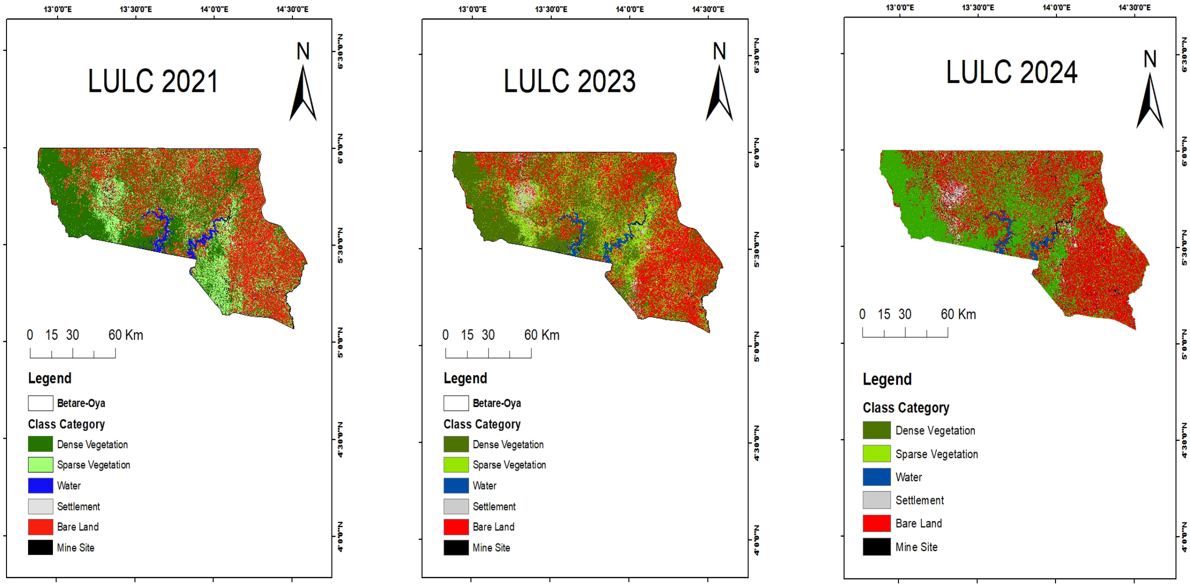


Figure 7. NDVI trend from 2021 to 2024.

3.1.3. Land Use Land Cover (LULC) Change Detection

LULC maps (**Figure 8**) provide a visual representation of land use and land cover across the Betare-Oya region. In 2021, the maps show a relatively high proportion of dense vegetation, particularly in the northern and western parts of the study area. However, by 2023, a noticeable decrease in dense vegetation is evident, with a corresponding increase in areas classified as bare land and mine sites. This trend continues in 2024, with further fragmentation of dense vegetation patches and expansion of degraded areas.



(a) (b) (c)

Figure 8. Land Use Land Cover (LULC) map for Betare-Oya: **(a)** LULC for 2021; **(b)** LULC for 2023; **(c)** LULC for 2024.

The LULC statistics (**Table 4**) provide a quantitative assessment of LULC changes. The area of dense vegetation decreased from 38.27% in 2021 to 30.69% in 2024, representing a significant loss of vegetation cover. Conversely, the area of bare land increased from 32.22% in 2021 to 45.48% in 2024, indicating a substantial increase in land degradation. The area of mine site also increased from 2.69% in 2021 to 4.76% in 2024, further confirming the expansion of mining activities (**Figure 9**).

Table 4. Table Statistics for LULC.

Index	Class Name	Area (hectares)	Percentage (%)
LULC 2021	Dense Vegetation	430001.36	38.27
	Sparse Vegetation	240000.67	21.36
	Water	20019.3	1.78
	Settlement	41378.37	3.68
	Bare Land	362011.39	32.22
	Mine Site	30202.77	2.69
LULC 2023	Dense Vegetation	410022.55	36.49
	Sparse Vegetation	220067.55	19.59
	Water	23871.62	2.12
	Settlement	45058.37	4.01
	Bare Land	389065.83	34.63
	Mine Site	35545.71	3.16
LULC 2024	Dense Vegetation	344844.74	30.69
	Sparse Vegetation	151026.71	13.44
	Water	15046.81	1.34
	Settlement	48103.41	4.28
	Bare Land	511034.88	45.48
	Mine Site	53528.71	4.76

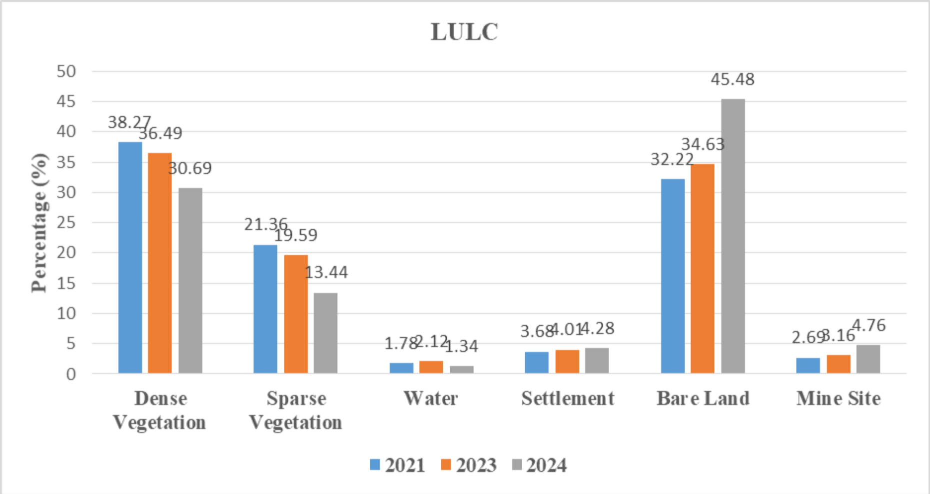


Figure 9. LULC trend from 2021 to 2024.

The LULC change detection maps (**Figure 10** and **Figure 11**) show the areas that have changed from one LULC class to another. The change detection analysis reveals that the most significant changes are from dense vegetation to bare land and mine site, indicating that mining activities are driving deforestation and land degradation.

LULC change detection histogram (**Figure 12** and **Figure 13**) provides a quantitative summary of the LULC changes. The histogram confirms that the most significant changes are from dense vegetation to bare land and mine site.

The LULC maps, statistics, and change detection analysis reveal a clear trend of changing LULC in the Betare-Oya region from 2021 to 2024 (**Table 5** and **Table** 6). The decrease in dense vegetation and the increase in bare land and mine site indicate that mining activities are having a significant impact on LULC.

Table 5. LULC change detection table statistics from 2021 to 2023.

LULC 2021	LULC 2023	Change Detection Category	Area (hectares)	Percentage (%)
Dense Vegetation	Dense Vegetation	Dense Vegetation to Dense Vegetation	264946.11	23.58
Dense Vegetation	Sparse vegetation	Dense Vegetation to Sparse vegetation	89388.71	7.96
Sparse Vegetation	Sparse Vegetation	Sparse Vegetation to Sparse Vegetation	132434.81	11.79
Bare land	Settlement	Bare land to Settlement	7552.7	0.67
Bare land	Sparse Vegetation	Bare land to Sparse Vegetation	366.63	0.03
Mine site	Dense Vegetation	Mine site to Dense Vegetation	10.08	0.00
Mine site	Sparse Vegetation	Mine site to Sparse Vegetation	3444.49	0.31
Bare land	Bare land	Bare land to Bare land	307752.74	27.39
Mine site	Settlement	Mine site to Settlement	8451.47	0.75
Sparse Vegetation	Dense Vegetation	Sparse Vegetation to Dense Vegetation	15826.11	1.41

Table 5. *Cont.*

LULC 2021	LULC 2023	Change Detection Category	Area (hectares)	Percentage (%)
Bare land	Dense Vegetation	Bare land to Dense Vegetation	912.11	0.08
Bare land	Mine site	Bare land to Mine site	12395.36	1.10
Sparse Vegetation	Bare land	Sparse Vegetation to Bare land	58369.24	5.20
Sparse Vegetation	Settlement	Sparse Vegetation to Settlement	23061.19	2.05
Mine site	Bare land	Mine site to Bare land	7318.35	0.65
Mine site	Mine site	Mine site to Mine site	8058.55	0.72
Dense Vegetation	Settlement	Dense Vegetation to Settlement	3440.8	0.31
Sparse Vegetation	Mine site	Sparse Vegetation to Mine site	31580.6	2.81
Dense Vegetation	Bare land	Dense Vegetation to Bare land	50420.79	4.49
Dense Vegetation	Mine site	Dense Vegetation to Mine site	51032.81	4.54
Settlement	Dense Vegetation	Settlement to Dense Vegetation	209.57	0.02
Settlement	Sparse Vegetation	Settlement to Sparse Vegetation	920.77	0.08
Settlement	Settlement	Settlement to Settlement	2861.83	0.25
Settlement	Bare land	Settlement to Bare land	185.81	0.02
Settlement	Mine site	Settlement to Mine site	5.56	0.00
Water	Mine site	Water to Mine site	2245.68	0.20
Water	Water	Water to Water	17746.19	1.58
Mine site	Water	Mine site to Water	13417.81	1.19
Water	Settlement	Water to Settlement	9.17	0.00
Dense Vegetation	Water	Dense Vegetation to Water	0.82	0.00
Water	Bare land	Water to Bare land	5.34	0.00
Water	Sparse Vegetation	Water to Sparse Vegetation	1.32	0.00
Sparse Vegetation	Water	Sparse Vegetation to Water	1.22	0.00
Bare land	Water	Bare land to Water	9150.32	0.81
Settlement	Water	Settlement to Water	3.94	0.00
Water	Dense Vegetation	Water to Dense Vegetation	0.26	0.00

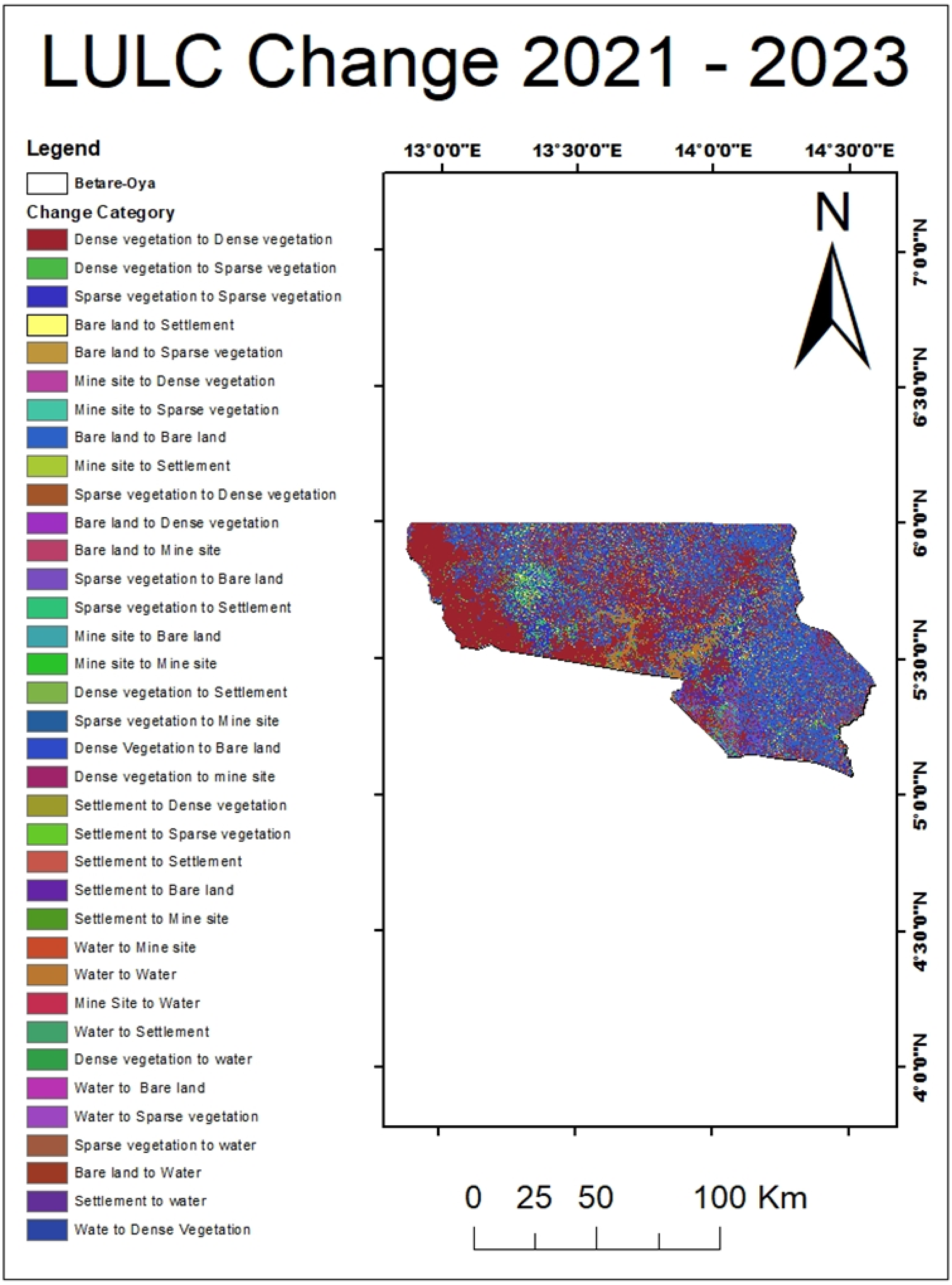


Figure 10. LULC change detection map from 2021 to 2023.

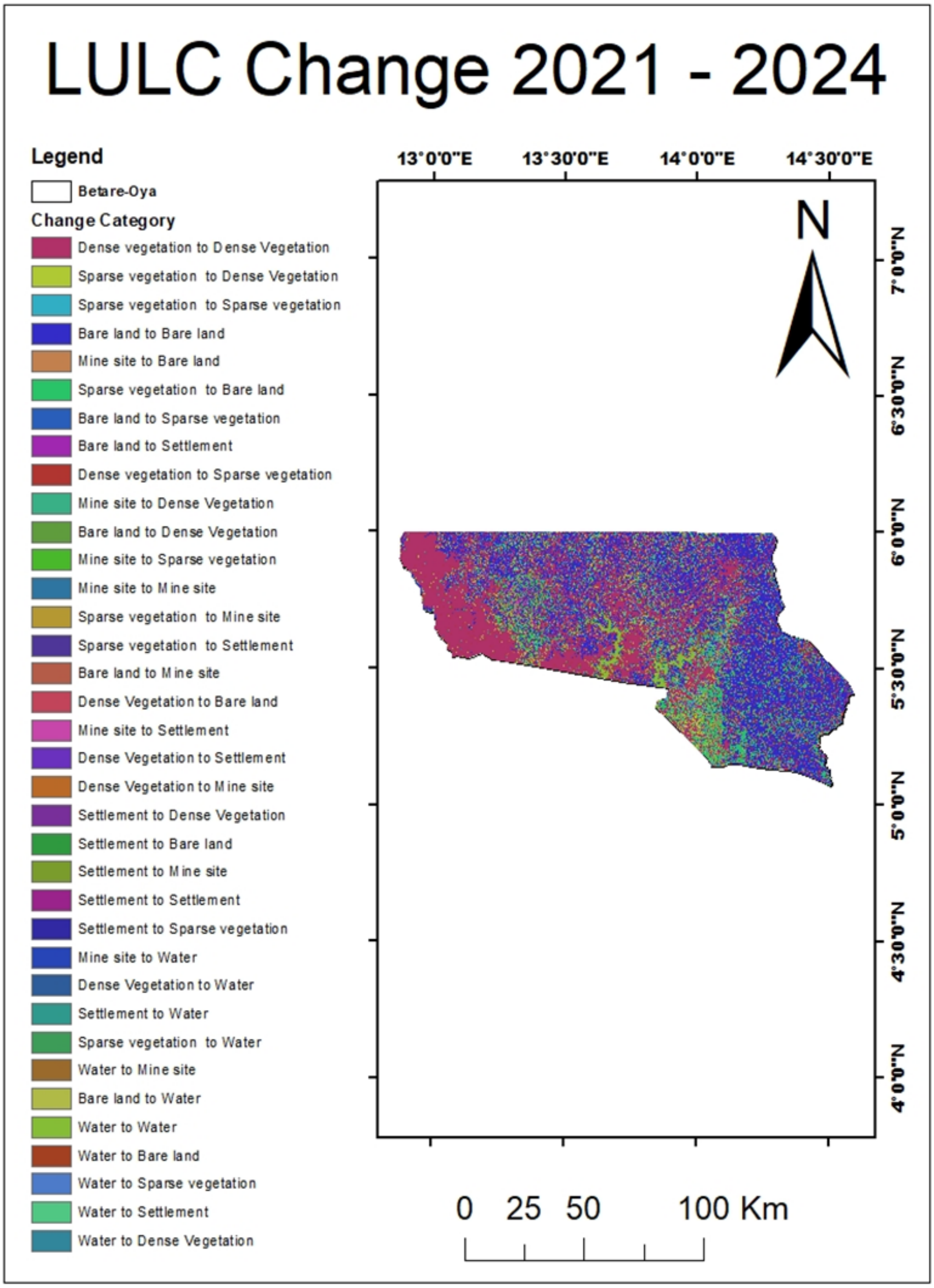


Figure 11. LULC Change detection from 2021 to 2024.

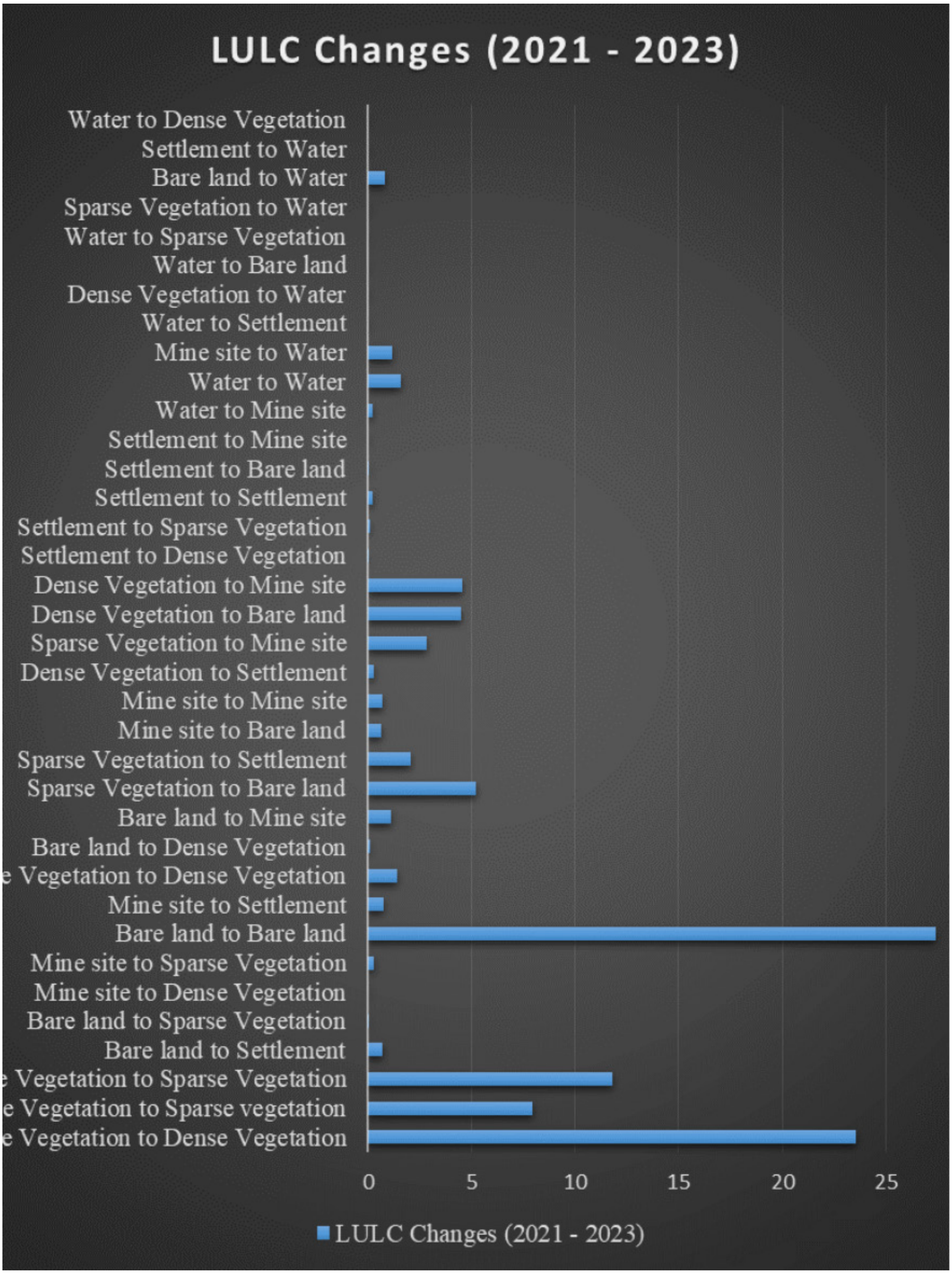


Figure 12. LULC Change detection histogram from 2021 to 2023.

Table 6. LULC change detection table statistics from 2021 to 2024.

LULC 2021	LULC 2024	Change Detection Category	Area (Hectares)	Percentage (%)
Dense vegetation	Dense Vegetation	Dense vegetation to Dense Vegetation	240467.49	21.40
Sparse vegetation	Dense Vegetation	Sparse vegetation to Dense Vegetation	2115.56	0.19
Sparse vegetation	Sparse vegetation	Sparse vegetation to Sparse vegetation	42851.73	3.81
Bare land	Bare land	Bare land to Bare land	367991.46	32.75
Mine site	Bare land	Mine site to Bare land	2567.37	0.23
Sparse vegetation	Bare land	Sparse vegetation to Bare land	117507.74	10.46
Bare land	Sparse vegetation	Bare land to Sparse vegetation	5112.37	0.46
Bare land	Settlement	Bare land to Settlement	7958.72	0.71
Dense vegetation	Sparse vegetation	Dense vegetation to Sparse vegetation	37054.61	3.30
Mine site	Dense Vegetation	Mine site to Dense Vegetation	2266.81	0.20
Bare land	Dense Vegetation	Bare land to Dense Vegetation	1580.31	0.14
Mine site	Sparse vegetation	Mine site to Sparse vegetation	1706.92	0.15
Mine site	Mine site	Mine site to Mine site	9260.55	0.82
Sparse vegetation	Mine site	Sparse vegetation to Mine site	94481.34	8.41
Sparse vegetation	Settlement	Sparse vegetation to Settlement	19315.93	1.72
Bare land	Mine site	Bare land to Mine site	15358.11	1.37
Dense Vegetation	Bare land	Dense Vegetation to Bare land	12240.12	1.09
Mine site	Settlement	Mine site to Settlement	5733.08	0.51
Dense Vegetation	Settlement	Dense Vegetation to Settlement	3463.52	0.31
Dense Vegetation	Mine site	Dense Vegetation to Mine site	74009.33	6.59
Settlement	Dense Vegetation	Settlement to Dense Vegetation	369.45	0.03
Settlement	Bare land	Settlement to Bare land	897.95	0.08
Settlement	Mine site	Settlement to Mine site	802.14	0.07
Settlement	Settlement	Settlement to Settlement	10147.86	0.90
Settlement	Sparse vegetation	Settlement to Sparse vegetation	198.95	0.02
Mine site	Water	Mine site to Water	64.07	0.01
Dense Vegetation	Water	Dense Vegetation to Water	7	0.00
Settlement	Water	Settlement to Water	1.13	0.00
Sparse vegetation	Water	Sparse vegetation to Water	4.53	0.00
Water	Mine site	Water to Mine site	11615.89	1.03
Bare land	Water	Bare land to Water	21111.74	1.88
Water	Water	Water to Water	14968.83	1.33
Water	Bare land	Water to Bare land	116.04	0.01
Water	Sparse vegetation	Water to Sparse vegetation	100.35	0.01
Water	Settlement	Water to Settlement	82.67	0.01
Water	Dense Vegetation	Water to Dense Vegetation	32.4	0.00

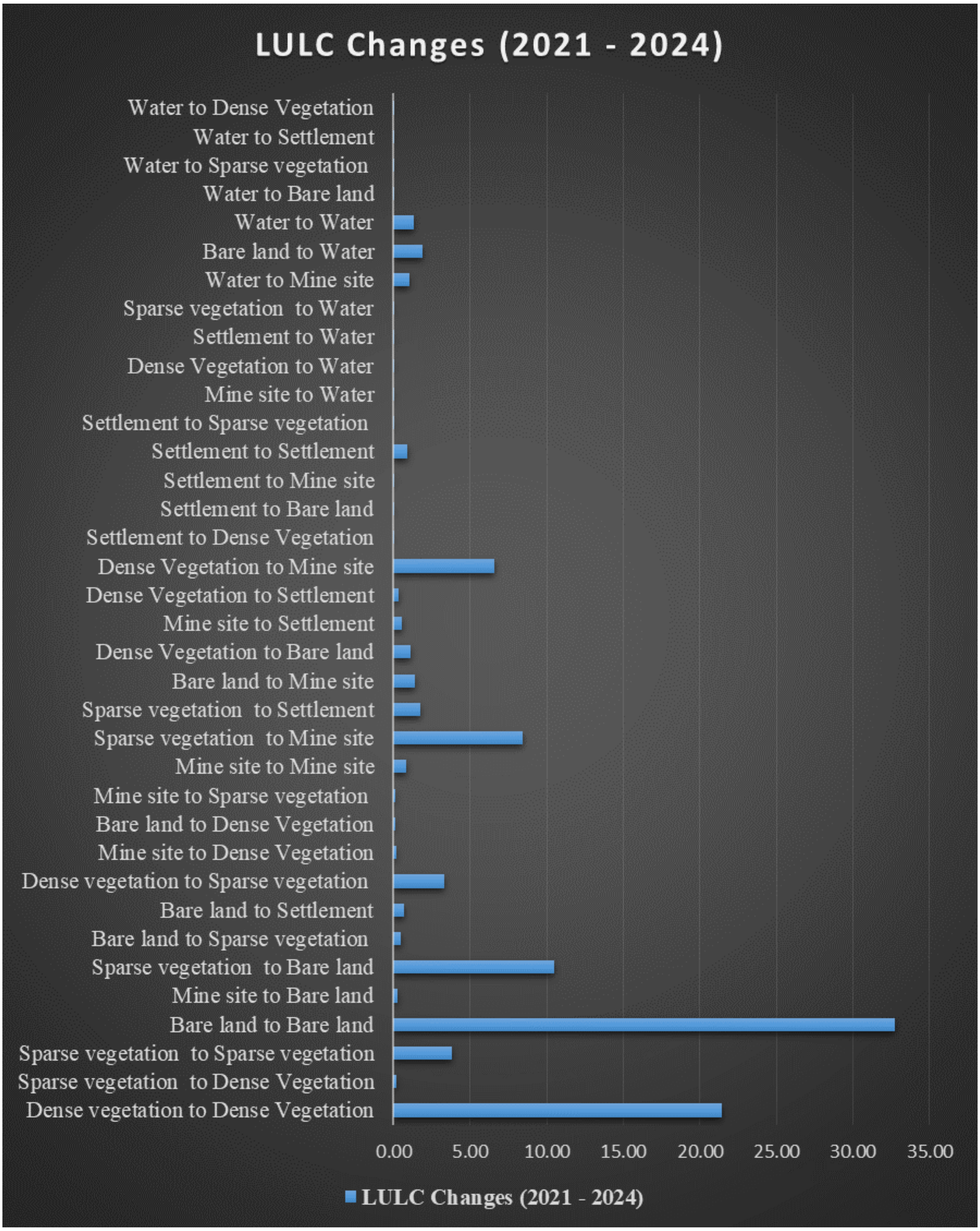


Figure 13. LULC Change detection histogram from 2021 to 2024.

The observed changes in LULC are directly related to mining activities. The clearing of forests to access alluvial gold deposits results in a decrease in dense vegetation and an increase in bare land and mine site. The expansion of mining activities also leads to an increase in settlement areas, as people migrate to the region in search of employment opportunities.

The findings are consistent with previous studies that have used LULC classification to assess environmental changes in mining-affected areas. For example, [11] found that mining activities were driving deforestation and land degradation in the Betare-Oya region. The study also supports the findings of [19], who found that mining activities were associated with increased levels of bare land and settlement areas.

The observed changes in LULC have significant implications for sustainable development in the Betare-Oya region. The loss of dense vegetation reduces the capacity of ecosystems to provide essential services, such as carbon sequestration, water regulation, and soil stabilization. The increase in bare land and mine site contributes to land degradation and reduces agricultural productivity. The expansion of settlement areas can lead to increased pressure on natural resources and social conflicts.

3.2. Field Evaluation and Google Earth Pro Image Appraisal

Alluvial gold mining in the Betare-Oya region is characterized by a mix of artisanal and semi-mechanized techniques. Artisanal miners typically work independently or in small groups, using rudimentary tools such as shovels, picks, and pans. They often target easily accessible deposits along riverbanks and floodplains. Semi-mechanized operations involve the use of small-scale machinery, such as water pumps, excavators, and washing plants, to process larger volumes of sediment. A key aspect of these mining practices is the removal of overburden (topsoil and vegetation) to access the gold-bearing gravels. This process often involves deforestation and the stripping of large areas of land. The extracted gravels are then washed and processed to separate the gold. In many cases, mercury is used to amalgamate the gold particles, which poses a significant environmental and health risk. The tailings (waste material) from the processing are often discharged directly into rivers or left in piles on the landscape, contributing to sedimentation and soil contamination.

The field visit conducted between January and March 2025 provided valuable ground-truth data and preliminary insights into the extent and nature of land degradation within the Betare-Oya alluvial gold mining district. Direct observations and photographic documentation from active and abandoned mine sites revealed a consistent pattern of extensive soil erosion and sedimentation impacting nearby water bodies, widespread deforestation and removal of topsoil, leaving barren landscapes, and the presence of large, unrehabilitated mining pits filled with stagnant water. These observations aligned with the findings of [14], who documented similar patterns of deforestation and soil erosion associated with gold mining in the Eastern Region of Cameroon. The field photographs captured during the visit vividly illustrate these impacts.

Figure 14(**a**) shows a photograph taken at a former mining site at kombo-koro, depicting a large, abandoned mining pit filled with turbid, stagnant water. The water's opaque, brownish color suggests a high concentration of suspended sediments and potential chemical contamination, consistent with the findings of [20], who reported elevated levels of mercury and other heavy metals in water samples from the Betare-Oya region. The surrounding landscape is devoid of vegetation, with exposed soil and eroded banks clearly visible. This lack of vegetation cover exacerbates soil erosion and hinders natural regeneration, highlighting the long-term environmental consequences of unregulated mining practices, where excavated areas are left unrehabilitated, leading to the accumulation of contaminated water and the loss of biodiversity. **Figure 14**(**b**) shows an active mining site at Timangaro, with heavy machinery excavating soil and a washing plant. The photograph reveals the scale of deforestation required to access alluvial gold deposits, with a significant area of previously forested land now cleared and disturbed. The presence of sediment plumes in nearby water bodies suggests ongoing soil erosion and sedimentation, further impacting water quality and aquatic habitats. This aligns with the findings of [11], who used Landsat imagery to document the expansion of artisanal mining at the expense of vegetation cover in the Betare-Oya region. **Figure 14**(**c**) depicts a section of the Lom River where the natural river course has been significantly altered due to mining activities. The photograph shows a large pile of excavated material deposited directly adjacent to the river, leading to increased sedimentation and turbidity. The altered river course can disrupt aquatic ecosystems and impact downstream water users, as noted by [21], who highlighted the excessive excavation of riverbanks leading to increased sedimentation and changes in river flow. **Figure 14**(**d**) shows a barren landscape in an abandoned mining area, characterized by scattered debris, minimal vegetation cover, and compacted soil. The photograph suggests a complete loss of topsoil and a lack of conditions suitable for natural regeneration. This aligns with the findings of [3], who emphasized the severe environmental degradation, including land degradation, deforestation, and biodiversity loss, resulting from artisanal and small-scale mining in Africa. **Figure 14**(**e**) shows a large excavation pit filled with standing water, likely rainwater mixed with sediment and potential contaminants. The photograph highlights the scale of disturbance caused by mining activities and the lack of rehabilitation efforts to restore the landscape. The standing water can serve as a breeding ground for mosquitoes and other disease vectors, posing a risk to public health, as discussed by [6], who highlighted the health risks associated with mercury and cyanide contamination in alluvial gold concentration. **Figure 14**(**f**) shows a deforested area with mining pits visible in the distance, illustrating the encroachment of mining activities into previously forested regions. The photograph highlights the direct link between gold mining and deforestation, which can have significant impacts on biodiversity, carbon sequestration, and climate change, as noted by [16], who documented extensive deforestation due to gold mining, agriculture, and logging in the Betare-Oya region. **Figure 14**(**g**) shows turbid water flowing through a stream near an active mining site. The photograph provides visual evidence of the direct impact of mining activities on water quality, with sediment runoff contributing to increased turbidity and potential contamination. This aligns with the findings of [22], who reported increased turbidity and elevated concentrations of heavy metals in surface water samples from mining-affected rivers. **Figure 14**(**h**), a photograph taken in an active mining area at Ngengue, provides a stark illustration of the severe soil erosion resulting from alluvial gold mining. The image reveals a deeply incised soil profile, exposing distinct soil horizons and highlighting the removal of the fertile topsoil layer. The vertical striations in the soil face indicate the presence of erosion gullies, formed by the concentrated flow of surface water. The presence of scattered rocks and debris further contributes to the instability of the landscape. This type of soil erosion can lead to the loss of valuable nutrients, reduced water infiltration, and increased sedimentation in nearby water bodies, as discussed by [23], who emphasized the use of remote sensing-derived indices to evaluate soil degradation and track soil erosion. The limited vegetation cover in the upper portion of the image suggests that natural regeneration is hindered by the degraded soil conditions. The presence of a small amount of vegetation is not enough to prevent further erosion. The photograph highlights the long-term consequences of mining activities on soil health and the challenges associated with restoring degraded landscapes, as emphasized by [24], who discussed the importance of soil remediation and sustainable land-use planning in effective reclamation and restoration strategies.

(a) **(b)** **(c)** **(d)**

Figure 14. *Cont*.

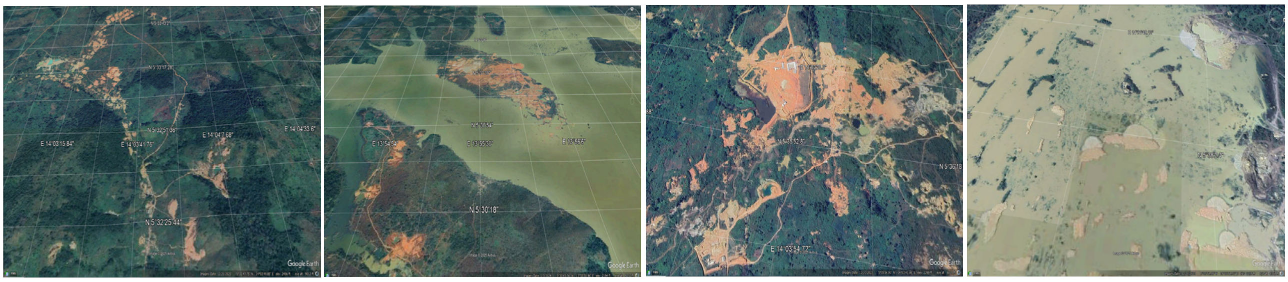
(e) **(f)** **(g)** **(h)**

Figure 14. Images taken onsite during field visit: **(a)** Abandoned Mining Pit with Turbid Water (Location: Kombo-koro); **(b)** Active Mining Site with Heavy Machinery (Location: Timangaro); **(c)** Altered River Course and Sediment Deposition (Location: Lom River); **(d)** Barren Landscape with Scattered Debris (Location: Nakayo); **(e)** Large Excavation Pit with Standing Water (Location: Mali village); **(f)** Deforested Area with Mining Pits in the Distance (Location: Bouli); **(g)** Turbid Water Flowing Through Mining-Affected Area (Location: Tributary of River Mari); **(h)** Exposed Soil Profile and Erosion Gullies (Location: Ngengue)

Interviews with local residents, miners, and community leaders further contextualized these physical observations. Residents consistently reported a decline in agricultural productivity due to soil degradation and water pollution. Miners acknowledged the environmental impacts of their activities but cited economic necessity as the primary driver. Community leaders expressed concerns about the long-term sustainability of mining and the need for effective rehabilitation strategies. One resident stated, "Before the mining, we could grow anything here. Now, the soil is dead, and the water is poisoned" This sentiment underscores the direct impact of mining activities on local livelihoods and the urgent need for sustainable mining practices and effective rehabilitation efforts.

To further contextualize the field observations and assess the spatial distribution and severity of land degradation across the study area, high-resolution Google Earth Pro imagery from 2023 was analyzed. The imagery confirmed the presence of numerous abandoned mine sites, often characterized by bare earth, altered drainage patterns, and a lack of vegetation cover. The imagery also revealed the expansion of active mining areas into previously forested regions, highlighting the ongoing deforestation associated with the industry

Figure 15(**a**) shows a Google Earth Pro image of a mining area characterized by a linear pattern of disturbance. The image reveals a series of interconnected mining pits and access roads extending through a previously forested area. The linear pattern suggests that mining activities are following a specific geological feature or river channel, as alluvial gold deposits are often concentrated along these features. The image also shows a clear contrast between the disturbed mining area and the surrounding intact forest, highlighting the impact of mining on the landscape. This pattern aligns with the findings of [11], who used Landsat imagery to document the expansion of artisanal mining at the expense of vegetation cover in the Betare-Oya region. **Figure 15**(**b**) shows a Google Earth Pro image of a mining area located directly adjacent to a water body. The image reveals extensive soil disturbance and sedimentation along the shoreline, indicating the direct impact of mining activities on water quality. The presence of bare earth and altered drainage patterns suggests that the natural hydrological processes have been disrupted. This proximity of mining activities to water bodies poses a significant threat to aquatic ecosystems and downstream water users, as discussed by [20], who reported elevated levels of mercury and other heavy metals in water samples from the Betare-Oya region. **Figure 15**(**c**) shows a Google Earth Pro image of a large-scale mining operation, characterized by extensive deforestation, large excavation pits, and processing facilities. The image reveals the scale of disturbance caused by mechanized mining activities and the significant impact on the landscape. The presence of processing facilities suggests that the mining operation is extracting and processing large quantities of ore, potentially leading to increased environmental impacts. This aligns with the findings of [3], who emphasized the severe environmental degradation, including land degradation, deforestation, and biodiversity loss, resulting from artisanal and small-scale mining in Africa. Also, the image reveals a landscape dominated by bare earth, with limited vegetation cover and altered drainage patterns. The photograph highlights the direct link between gold mining and deforestation, which can have significant impacts on biodiversity, carbon sequestration, and climate change, as noted by [16], who documented extensive deforestation due to gold mining, agriculture, and logging in the Betare-Oya region. **Figure 15**(**d**) shows a Google Earth Pro image of a mining area that appears to be flooded. The image reveals a landscape dominated by water, with scattered patches of bare earth and limited vegetation cover. The flooding may be due to the disruption of natural drainage in the mining area and can lead to the mobilization of sediments and contaminants, further impacting water quality and aquatic ecosystems, as discussed by [22], who reported increased turbidity and elevated concentrations of heavy metals in surface water samples from mining-affected rivers.



(a) **(b)** **(c)** **(d)**

Figure 15. Google earth pro images extracted on 2023: **(a)** Linear Mining Pattern (Location: N 5°33'43.2", E 14°03'15.84"); **(b)** Mining Area Adjacent to Water Body (Location: N 5°30'54", E 13°54'54"); **(c)** Large-Scale Mining Operation (Location: N 5°35'52.8", E 14°03'38.8"); **(d)** Flooded Mining Area (Location: N 5°38'2.4", E 14°16'45.92")

A comparison of Google Earth Pro imagery with the field photographs revealed a strong correlation between areas identified as severely degraded in the field and areas exhibiting extensive bare earth and altered topography in the satellite imagery. Furthermore, the imagery allowed for a broader spatial assessment of land degradation patterns, identifying areas that were inaccessible during the field visit. For example, Google Earth Pro imagery revealed a network of interconnected mining pits and drainage channels that were not fully apparent from ground-level observations, highlighting the cumulative impact of mining activities on the landscape.

The use of Google Earth Pro also allowed for a preliminary assessment of rehabilitation efforts. While some areas showed signs of natural revegetation, particularly along riverbanks, the majority of abandoned mine sites remained largely unrehabilitated. This is evident in the field photograph shown in **Figure 14**(**d**), which depicts a barren landscape with scattered debris and minimal vegetation cover. This suggests a limited implementation of effective mine closure and rehabilitation strategies, consistent with the findings of [25], who noted the lack of proper rehabilitation strategies in abandoned mining sites in the region.

The regulatory framework for mining in Cameroon is governed by the Mining Code, which sets out the rules and procedures for exploration, exploitation, and environmental management. However, the enforcement of these regulations is often weak, particularly in the artisanal and small-scale mining sector. This is due to a number of factors, including limited resources, corruption, and a lack of political will. The informal nature of the mining sector also makes it difficult to regulate. Many miners operate without formal permits or licenses, making it challenging to monitor their activities and enforce environmental regulations. In addition, the lack of transparency and accountability in the mining sector can create opportunities for corruption and illegal mining. Strengthening the policy and governance framework for mining is essential for promoting sustainable mining practices and protecting the environment

4. Socioeconomic drivers, community dependence and social impacts

Alluvial gold mining in Betaré-Oya is embedded within a complex socioeconomic landscape that shapes why, how and where mining activities expand. In many parts of the East Region, artisanal and semi-mechanized mining serve as primary or important supplementary livelihoods for rural households, driven by limited alternative income sources, seasonal agricultural cycles, and migration dynamics. Local and regional studies have highlighted that artisanal mining commonly provides immediate cash income in contexts characterized by low agricultural profitability, limited formal employment opportunities, and restricted access to credit and markets [4,36].

Understanding these drivers is essential because environmental degradation (deforestation, soil loss, sedimentation) is not only a biophysical problem but also a socio-economic one: interventions that ignore miners' livelihood imperatives are unlikely to be adopted or enforced. Many operators remain informal (unlicensed) or episodically licensed, limiting their exposure to environmental regulation while increasing the probability of ad-hoc and environmentally damaging practices such as excavation without progressive rehabilitation and the use of mercury for gold recovery [3,5]. Interviews conducted during the field campaign support this dynamic: miners cited economic necessity and lack of alternatives as the main reasons for continuing mining despite known environmental harms.

The social impacts of mining extend beyond income. Field respondents and local leaders reported diminished agricultural productivity (loss of cultivable land, reduced soil fertility), increased health concerns (water turbidity and suspected contamination), and shifts in local labor allocation that affect household food security and gender roles. The presence of abandoned pits and stagnant water also poses public-health risks (vector-borne diseases) and reduces safe access to water for domestic use [22]. Where mercury is used, there is a recognized risk of bioaccumulation in aquatic food webs and potential human exposure via fish and drinking water pathways [20].

Because economic drivers sustain mining activity, effective remediation and regulation must combine environmental measures with socio-economic alternatives. Policies that focus only on enforcement without provision of viable livelihoods are likely to displace or criminalize miners rather than produce durable environmental gains. Therefore, any rehabilitation or regulation strategy should be co-designed with local communities, prioritize livelihood diversification, and include incentives (technical, financial, and market access) that make low-impact alternatives attractive and sustainable.

5. Limitation of Study

Despite the robustness of the methodology, this study is subject to certain limitations. First, the temporal resolution of the Sentinel-2 imagery (limited to three selected years) may not capture intra-annual variations in vegetation dynamics or long-term mining disturbances. Second, field observations were concentrated during specific periods (January–March), which may not reflect conditions during the rainy season when environmental impacts such as erosion and runoff intensify. Third, the spatial resolution (10m) of the satellite imagery may not detect fine-scale changes in smaller or newly created mining pits. Lastly, logistical challenges in accessing remote sites and interacting with artisanal miners posed constraints in data collection and local stakeholder interviews. Future studies should consider integrating high-resolution UAV data, seasonal field surveys, and community-based assessments to enrich analysis.

6. Conclusions and recommendations

This study provides a comprehensive assessment of the environmental impacts of alluvial gold mining in the Betare-Oya locality in Cameroon from 2021 to 2025. The spatiotemporal analysis was performed from the year 2021 to 2024, while field observation and ground truthing were carried out in the early months of 2025 (January to March). The results reveal significant land degradation, declining vegetation health, deteriorating water quality, and changing land use/land cover patterns due to mining activities.

Field observations and Google Earth Pro analysis revealed deforestation of the original forest cover lost in active mining areas. Soil erosion was widespread, with topsoil loss in active mining zones. Abandoned mining pits filled with stagnant water were a common sight, posing a risk to public health and aquatic ecosystems. Alluvial gold mining has significant impacts on water quality, both directly and indirectly. Direct impacts include the discharge of sediment, mercury, and other pollutants into rivers and streams. Sedimentation increases turbidity, reduces light penetration, and smothers aquatic habitats. Mercury, which is used to amalgamate gold, can bioaccumulate in the food chain and pose a serious threat to human health. Indirect impacts include the alteration of river courses and drainage patterns, which disrupt aquatic ecosystems and affect downstream water users. Deforestation and soil erosion also increase runoff and sedimentation, further degrading water quality.

Satellite image analysis from BSI and NDVI confirmed the trends observed in the field and Google Earth Pro analysis. The BSI results showed an increase in bare soil from 2021 to 2024, indicating a significant increase in land degradation. The NDVI results showed a decrease in vegetation, further confirming the decline in vegetation health.

LULC classification and change detection analysis revealed that mining activities are driving deforestation and land degradation, with significant changes from dense vegetation to bare land and mine site over the years.

The different analyses (BSI, NDVI and LULC) complement each other to provide a comprehensive understanding of the environmental impacts of mining. The results show that mining activities are having a cascading effect on the environment, leading to land degradation, declining vegetation health, deteriorating water quality, and changing land use/land cover patterns.

This study contributes to scientific knowledge by providing a comprehensive assessment of the environmental impacts of alluvial gold mining in the Betare-Oya region. The study also demonstrates the value of remote sensing for monitoring environmental changes in mining-affected areas. The findings provide valuable information for policymakers, regulatory agencies, and environmental managers to design and enforce sustainable mining policies and develop effective mine closure and rehabilitation plans.

Further research is needed to quantify the relative contribution of artisanal and semi-mechanized mining to the overall environmental impacts. It would also be valuable to investigate the efficiency of different mining techniques and the potential for adopting more sustainable practices, such as mercury-free gold extraction methods. A more detailed understanding of the socioeconomic context of mining is crucial for developing effective policies and management strategies. Future research should investigate the income levels of miners, the distribution of benefits from mining, and the social impacts of mining on local communities. It would also be valuable to explore alternative livelihood options that could reduce the reliance on mining. It would also be valuable to investigate the impacts of mining on aquatic biodiversity and the health of local communities that rely on these water sources. The implementation of water quality monitoring programs is essential for tracking the impacts of mining and developing effective mitigation measures. Future research should focus on assessing the impacts of mining on biodiversity, soil fertility, and ecosystem services. It would also be valuable to develop ecological models to predict the long-term consequences of mining and to identify potential restoration strategies.

6.1. Recommendations

The findings of this study point to urgent, actionable interventions bridging environmental management and socioeconomic realities. The following combines best-practice measures with feasible steps tailored to the Betaré-Oya context.

6.1.1. Formalization & Governance

Formalize artisanal miners through cooperatives and licensing: Promote registration, technical training and formal cooperatives so miners can access markets, training and incentives for environmental compliance. Formalization helps bring mining activity under regulatory oversight while preserving livelihoods.

Strengthen local regulatory capacity: Provide training and resources for municipal and regional offices (mines, environment, and water) to monitor and enforce permit conditions, progressive rehabilitation, and water protections. Use simple compliance checklists and mobile reporting tools to assist field officers.

Require Environmental Management Plans (EMPs) and financial guarantees: For operations above minimal thresholds, require EMPs that include progressive rehabilitation and a modest financial assurance (bond) to ensure closure and restoration.

6.1.2. Mercury Reduction and Safer Processing

Behavioral interventions and supply control: Combine technical training with local agreements to reduce mercury availability (buy-back or regulated sale points) and partner with health agencies to monitor exposure.

6.1.3. Progressive Rehabilitation and Ecological Restoration

Progressive rehabilitation: Require and incentivize progressive backfilling, topsoil conservation, regrading and contouring during and immediately after excavation. This reduces erosion and seed bank loss.

Revegetation with native species and agroforestry: Use native trees and fast-establishing groundcovers suited to local ecological conditions; where appropriate, combine with fruit or timber species that can provide future income.

Constructed wetlands and sediment control: At processing and discharge sites, install sediment traps, settling ponds, and constructed wetlands to reduce turbidity and contaminants reaching river systems.

6.1.4. Livelihood Diversification and Community Development

Microfinance and enterprise support: Develop targeted microfinance, value-chain development and small-business training to support alternative livelihoods (agroforestry, sustainable timber).

Skills and market linkage programs: Vocational training (mechanics, masonry, agro-processing) and facilitation of market access reduce dependence on mining income over medium term.

Community benefit sharing: Ensure that formalized operations contribute to local infrastructure (water, schools, and clinics) through transparent mechanisms to reduce social tensions and incentivize compliance.

6.1.5. Monitoring, Community Participation and Data Use

Community-based monitoring: Pair community monitoring with remote sensing dashboards (NDVI/BSI change alerts) maintained by regional agencies or universities.

Integrated monitoring plan: Combine remote sensing (to detect land cover change and bare-soil expansion) with in-situ water quality monitoring and periodic socioeconomic surveys to measure livelihood impacts.

Public transparency and data sharing: Publish monitoring results and rehabilitation progress on local notice boards and regional portals to build accountability

Author Contributions

F.A.Z.; Conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, original draft preparation. S.F.; review and editing, visualization, supervision. D.M. and B.L.N.; project administration. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

This study did not require formal approval from an Institutional Review Board, as it involved non-invasive field observations and voluntary interviews with local participants. All participants provided informed consent prior to participation. The study was conducted in accordance with ethical research principles, ensuring privacy, confidentiality, and voluntary participation, and following the guidelines of the Declaration of Helsinki to protect the rights and well-being of all participants.

Informed Consent Statement

Not applicable.

Data Availability Statement

Desk review of journals, books, internet as provided in the reference section.

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Conflicts of Interest

The authors declare no conflict of interest

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