Spectral Footprints of Gold: Eco-Friendly Exploration in Wasa Amenfi District of Ghana

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Abstract

Gold mining plays a central role in Ghana's national economy. However, conventional exploration approaches, particularly within artisanal and small-scale mining sectors, often rely on trial-and-error methods that lead to extensive environmental degradation. The absence of systematic geological exploration before mining has contributed to deforestation, soil contamination, and landscape disturbance in many gold-bearing regions. This study introduces an eco-friendly and cost-effective remote sensing-based approach, referred to as Green Gold Exploration, for identifying potential gold-rich zones before field excavation. Using Sentinel-2 surface reflectance imagery processed on the Google Earth Engine (GEE) platform, iron oxide and clay mineral spectral indices were derived to detect hydrothermal alteration features commonly associated with gold mineralization. The Wasa Amenfi District in the Western Region of Ghana, a historically active gold-producing area, was selected as the study area. Field validation was conducted using approximately 2,000 soil samples collected at 40 cm depth within a 1 km² sampling grid and analyzed using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) to determine gold concentrations in the soil. Spatial interpolation of laboratory results was performed using Inverse Distance Weighting (IDW). Results demonstrate spatial correspondence between high index values and elevated gold concentrations, with most confirmed gold occurrences located within 1 km of identified alteration zones. The findings confirm the potential of satellite-based spectral analysis as a sustainable pre-exploration tool capable of reducing environmental impacts, lowering exploration costs, and supporting informed decision-making before mining activities.

1. Introduction

1.1 Gold mining, environmental degradation, and the need for sustainable exploration

Gold remains one of the most economically important mineral resources worldwide, contributing significantly to national revenues, employment generation, and regional development. In Ghana, gold mining represents a major pillar of the national economy, positioning the country among the leading gold producers in Africa. However, despite its economic relevance, gold mining, particularly artisanal and small-scale gold mining (ASGM), has been associated with extensive environmental degradation across many mining districts.

In most rural mining communities, exploration activities are commonly undertaken without formal geological investigations. Instead, mining often begins through informal prospecting and trial-and-error excavation, frequently conducted without trained geologists or environmental professionals. This unsystematic approach leads to indiscriminate vegetation removal, repeated excavation of non-mineralized zones, soil compaction, land degradation, and the contamination of surface and groundwater systems (Armah et al., 2014; Arhin et al., 2023). The environmental consequences are further amplified in tropical regions where intense rainfall accelerates erosion and the transport of heavy metals into surrounding ecosystems.

Beyond ecological impacts, these practices pose serious threats to agricultural productivity, food security, and public health in mining communities. Studies have linked mining-induced contamination to the emergence of non-communicable diseases and long-term exposure risks (Arhin et al., 2023). Consequently, there is an increasing urgency to develop exploration techniques that minimize physical disturbance while improving targeting accuracy before mining operations.

In response to these challenges, global mineral governance frameworks increasingly promote sustainable and environmentally responsible mining approaches. Concepts such as green mining, low-impact exploration, and nature-positive resource development emphasize reducing land disturbance during early exploration phases and adopting technologies that support informed decision-making before excavation (Balafrej et al., 2020). These principles form the foundation for modern mineral exploration strategies that seek to balance economic development with environmental protection.

1.2 Role of satellite remote sensing in gold exploration

Satellite remote sensing has emerged as a powerful tool for mineral exploration due to its ability to provide synoptic, repeatable, and cost-effective coverage over large and often inaccessible terrains. Unlike conventional ground-based exploration methods, remote sensing enables the detection of geological and geochemical indicators without direct surface disturbance, making it particularly suitable for environmentally sensitive regions.

Hydrothermal gold deposits are commonly associated with alteration minerals formed through fluid–rock interactions during mineralization processes. These alteration minerals, especially iron oxides (e.g., hematite and goethite) and clay minerals (e.g., kaolinite and illite), exhibit distinctive spectral characteristics in

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the visible, near-infrared (NIR), and shortwave infrared (SWIR) regions of the electromagnetic spectrum. Iron oxides typically show strong reflectance in the red wavelength and absorption in the blue region, while clay minerals display diagnostic absorption features in the SWIR bands (Balafrej et al., 2020; Angulo-Bejarano et al., 2021).

Multispectral satellite sensors have therefore been widely used to map hydrothermal alteration zones, which often serve as proxies for potential gold mineralization. Spectral indices derived from satellite imagery enhance these mineral signatures by amplifying subtle reflectance differences between altered and unaltered surfaces. Previous studies have demonstrated the effectiveness of iron oxide and clay mineral indices in identifying alteration halos, structural trends, and mineralized corridors in gold-bearing terrains.

The launch of Sentinel-2 has significantly advanced mineral exploration applications due to its improved spectral resolution, particularly in the red-edge and SWIR bands. With a spatial resolution of 10-20 m and free global accessibility, Sentinel-2 data provides an effective balance between spatial detail and regional coverage. When integrated with cloud-based platforms such as Google Earth Engine (GEE), large datasets can be processed efficiently, enabling rapid analysis, reproducibility, and scalability across extensive mining districts.

1.3 Research gap and study objectives

Despite the growing availability of satellite data and cloud computing platforms, the application of remote sensing for environmentally responsible gold exploration remains limited in many West African mining regions. Existing studies often focus on geological mapping or land degradation assessment, with relatively few efforts that explicitly fuse satellite-derived alteration information with direct geochemical measurements for validation, thereby reducing stakeholder confidence in remotely mapped targets and slowing operational uptake. However, recent integrative studies demonstrate that combining multispectral remote sensing with geochemical datasets can significantly improve the reliability of alteration-zone detection and gold targeting, underscoring the importance of validation-driven workflows for exploration decision support (Alimi & Carranza, 2025).

Furthermore, many exploration workflows still rely heavily on qualitative visual interpretation (e.g., colour composites, thresholding, and manual anomaly selection) rather than quantitative integration of spectral indices with laboratory-analyzed soil datasets, which can limit reproducibility and reduce the robustness of exploration outputs for pre-excavation decision-making. In contrast, validated approaches increasingly use systematic field reconnaissance and laboratory confirmation to strengthen the interpretation of hydrothermal alteration derived from multisensory imagery, reinforcing the value of verification in remote sensing–based mineral exploration (Chen et al., 2022; Shebl et al., 2023).

This study addresses these limitations by proposing a Green Gold Exploration framework that integrates multispectral satellite analysis with systematic field validation. Using the Wasa Amenfi District in the Western Region of Ghana as a case study, Sentinel-2 surface reflectance imagery is employed to derive iron oxide and clay mineral indicators of hydrothermal alteration, following established mineral mapping principles using multispectral data. The field component strengthens inference by analyzing approximately 2,000 soil samples (40 cm depth) using Inductively Coupled Plasma Mass Spectrometry (ICP-MS), a widely used exploration geochemistry method for trace-element and gold determination in geological materials, followed by spatial interpolation and overlay analysis to test spatial agreement between mapped alteration zones and measured gold concentrations (Hall, 1992; Tang et al., 2020; Osei et al., 2024).

2. Materials and Methods

2.1 Study Area

The study was conducted in the Wasa Amenfi District, located in the Western Region of Ghana (Figure 1). The district lies within one of Ghana's most productive gold provinces and has a long history of both large-scale commercial mining and artisanal/small-scale gold mining activities, with mining remaining a major land-use driver in the Wassa area (Domingo et al., 2021).

Gold occurrences in this part of southwestern Ghana are closely associated with Paleoproterozoic Birimian (Birimian Supergroup) metavolcanic and metasedimentary successions of the West African Craton, where mineralization is commonly linked to hydrothermal alteration and structural controls typical of West African goldfields (Dzigbodi-Adjimah, 1993). These hydrothermal systems frequently produce alteration assemblages that include iron oxides and clay/sericite-rich zones, providing spectral targets that can be detected using multispectral remote sensing methods for reconnaissance exploration.

The area experiences a humid tropical climate with pronounced wet seasons that can intensify erosion processes and increase sediment mobilization where vegetation is disturbed. Such climatic conditions heighten the environmental sensitivity of mining landscapes, making land disturbance more damaging through enhanced runoff-driven sediment transport during rainy periods (Agodzo et al., 2023). More broadly, research on mining-disturbed catchments shows that disturbance interacts with rainfall seasonality and sediment pathways to amplify sediment routing and downstream impacts, supporting the need for low-disturbance, pre-excavation targeting approaches in wet tropical settings (Domingo et al., 2021).

Figure 1. Wasa Amenfi District in Ghana, a gold-rich district with most Mining areas

2.2 Data and Platform

This study utilized Sentinel-2 Surface Reflectance Harmonized imagery (S2_SR_HARMONIZED), accessed and processed using the Google Earth Engine (GEE) cloud-based geospatial analysis platform. Sentinel-2, operated under the European Space Agency's Copernicus Programme, provides multispectral imagery with 13 spectral bands spanning the visible, near-infrared (NIR), red-edge, and shortwave infrared (SWIR) regions

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of the electromagnetic spectrum, with spatial resolutions of 10 m, 20 m, and 60 m depending on the band (Table 1) (Drusch et al., 2012).

The availability of SWIR and red-edge bands makes Sentinel-2 particularly suitable for mineral exploration studies, as these wavelengths are sensitive to hydrothermal alteration minerals such as iron oxides, hydroxyl-bearing clays, and altered host rocks (El-Desoky et al., 2022; Van Der Meer et al., 2011). Surface reflectance products were selected to minimize atmospheric effects and enhance spectral consistency across the study area.

Google Earth Engine was employed as the primary processing environment due to its capacity for handling large satellite datasets, performing pixel-based mathematical operations, and enabling reproducible workflows. GEE provides efficient cloud computation, eliminating the need for local data storage while ensuring rapid processing of multispectral imagery at regional scales (Gorelick et al., 2017). This platform is increasingly adopted for mineral exploration and environmental monitoring in data-limited regions due to its scalability and accessibility.

Data / Material	Description	Source
Sentinel-2 Surface Reflectance (S2_SR_HARMONIZED)	Multispectral satellite imagery (visible, NIR, SWIR bands) used for iron oxide and clay mineral spectral index computation	European Space Agency (ESA) Copernicus Programme (accessed via Google Earth Engine)
Google Earth Engine (GEE)	Cloud-based geospatial analysis platform used for image processing, spectral index computation, and spatial analysis	Google Earth Engine
Soil samples	Approximately 2,000 soil samples were collected at 40 cm depth using a 1 km × 1 km systematic grid for geochemical validation	Field survey (Wasa Amenfi District, Ghana)
ICP-MS laboratory analysis	Inductively Coupled Plasma Mass Spectrometry used to quantify gold concentration in soil samples	Certified geochemical laboratory in Ghana

Table 1. Materials and data used with their sources

2.3 Spectral Indices for Gold Exploration

Gold mineralization is commonly associated with hydrothermal alteration processes that modify the mineralogical composition of host rocks. These processes typically produce alteration assemblages dominated by iron oxides (e.g., hematite, goethite) and clay minerals (e.g., kaolinite, illite, sericite), which exhibit diagnostic spectral characteristics detectable by multispectral satellite sensors (Van der Meer et al., 2012).

To enhance these mineralogical signatures, two spectral indices were derived from Sentinel-2 imagery: the Iron Oxide Index (IOI) and the Clay Mineral Index (CMI) using Equation (1).

The Iron Oxide Index was computed using Equation (1).

$$IOI = \frac{B4-B2}{B4+B2} \quad (1)$$

where **B4** represents the red band (665 nm) and **B2** represents the blue band (490 nm) of Sentinel-2.

Iron oxide minerals typically exhibit high reflectance in the red region and strong absorption in the blue region due to electronic transitions of ferric iron (Fe^{3+}). Consequently, elevated IOI values are indicative of oxidized surfaces and alteration zones, which are commonly associated with gold-bearing hydrothermal systems (Van Der Meer et al., 2011). Mapping these zones provides an effective reconnaissance-level approach for identifying potential mineralized corridors.

The Clay Mineral Index was calculated using Equation (2).

$$CMI = \frac{B11-B8}{B11+B8} \quad (2)$$

where **B11** corresponds to the SWIR band (1610 nm), and **B8** corresponds to the NIR band (842 nm).

Clay minerals formed through hydrothermal alteration exhibit characteristic absorption features in the SWIR region due to hydroxyl (-OH) molecular vibrations. Higher CMI values, therefore, indicate enhanced clay content and altered lithologies, which frequently occur within gold-hosting hydrothermal systems (El-Desoky et al., 2022; Van Der Meer et al., 2011). The integration of iron oxide and clay mineral indices provides complementary information, improving the delineation of alteration halos associated with mineralization.

2.4 Field Sampling and Laboratory Analysis

To validate satellite-derived alteration features, extensive field-based geochemical sampling was conducted across the study area. Approximately 2,000 soil samples were collected following a systematic sampling design to ensure spatial consistency and representativeness. Samples were obtained at a depth of 40 cm to minimize surface contamination and reflect geochemical signatures linked to subsurface mineralization processes (Haldar, 2018; Osei et al., 2024).

Sampling locations were distributed using a uniform 1 km × 1 km grid, a commonly adopted reconnaissance-scale spacing in mineral exploration geochemistry. This grid-based approach allows effective identification of geochemical anomalies while maintaining operational feasibility over large areas (Haldar, 2018).

All samples were analyzed using Inductively Coupled Plasma Mass Spectrometry (ICP-MS), a highly sensitive analytical technique capable of detecting gold at trace and ultra-trace concentrations. ICP-MS is widely regarded as one of the most reliable methods for gold determination in exploration geochemistry due to its low detection limits, high precision, and multi-element analytical capability (Hall, 1992; Haldar, 2018; Tang et al., 2020; Osei et al., 2024). The resulting gold concentration data formed the basis for spatial modelling and validation of satellite-derived alteration zones.ICP-MS operates by ionizing sample elements in a high-temperature argon plasma and measuring their mass-to-charge ratios, allowing precise quantification of elemental concentrations. Gold concentration (C_{Au}) for each sample was expressed in parts per billion (ppb) using Equation 3.

$$C_{Au} = \frac{I_{Au}}{I_{std}} \times C_{std} \quad (3)$$

Where:
I_{Au} is the measured signal intensity of gold, I_{std} is the signal intensity of the calibration standard, and C_{std} is the known concentration of the calibration standard (Hall, 1992).
The resulting gold concentration dataset formed the primary input for spatial modeling and validation of satellite-derived alteration zones.

2.5 Spatial Interpolation of Gold Concentration

Laboratory-derived gold concentrations were spatially interpolated using the Inverse Distance Weighting (IDW) method. IDW is a deterministic interpolation approach based on the assumption that the influence of a sampled point decreases with increasing distance from the prediction location (Burrough & McDonnell, 1998).
The estimated gold concentration at an unsampled location x_0 is computed using Equation (4).

$$Z(x_0) = \frac{\sum_{i=1}^{n} w_i Z(x_i)}{\sum_{i=1}^{n} w_i} \quad (4)$$

Where:
$Z(x_i)$ is the measured gold concentration at the sample location i, w_i is the weight assigned to sample i, and n is the number of neighboring samples considered. The weighting function is defined using Equation (5).

$$w_i = \frac{1}{d_i^p} \quad (5)$$

Where:
d_i is the distance between the prediction location and the sampled point, and p is the power parameter controlling the rate of distance decay.
Higher values of $p$assign greater influence on nearby samples, enhancing local anomaly expression, which is particularly important in mineral exploration applications where ore-related geochemical signatures are spatially localized (Rutter et al., 1991).

Given the relatively dense and evenly distributed sampling grid employed in this study, the IDW method was considered suitable for generating a continuous gold concentration surface capable of highlighting geochemical anomalies relevant to exploration targeting.

2.6 Spatial Overlay Analysis

To evaluate the spatial relationship between remotely sensed alteration features and field-measured gold concentrations, a spatial overlay analysis was performed within a Geographic Information System (GIS) environment. The interpolated gold concentration surface was spatially integrated with iron oxide index (IOI) and clay mineral index (CMI) maps derived from Sentinel-2 imagery.
High-alteration zones were identified by applying threshold values to the spectral indices based on their statistical distribution. Pixels exceeding the upper percentile thresholds were classified as anomalous. The combined alteration index (AI) was expressed as Equation (6).

$$AI = IOI + CMI \quad (6)$$

Where:
IOI represents the iron oxide index values, and CMIrepresents the clay mineral index values.
Areas exhibiting simultaneously high AI values and elevated gold concentrations (C_{Au}) were interpreted as potential gold-rich zones using Equation (7).

$$Gold_{zone} = (AI \geq T_{AI}) \cap (C_{Au} \geq T_{Au}) \quad (7)$$

Where:
T_{AI} and T_{Au} represent threshold values defining spectral and geochemical anomalies, respectively.
Spatial proximity analysis was further conducted to evaluate the distance between high-gold soil samples and mapped alteration zones. Zones located within a defined buffer distance (≤ 1 km) from high-index anomalies were considered strongly associated with hydrothermal alteration systems.

This integrative approach strengthens interpretation confidence by directly linking satellite-derived spectral responses with laboratory-measured geochemical evidence, thereby reducing uncertainty associated with satellite-only exploration models (Sekandari et al., 2020; Khaleghi, 2020). The combined remote sensing-geochemical framework, therefore, provides a robust, environmentally friendly pre-exploration tool capable of guiding targeted field investigations while minimizing unnecessary land disturbance.

3. Results and Discussion

3.1 Spectral Index Mapping

The spectral index analysis revealed clear spatial patterns associated with hydrothermal alteration across the Wasa Amenfi District. The iron oxide index (IOI) map (Figure 2a) shows elevated values reaching a maximum of approximately 0.33, while minimum values ranged to about -0.43 (Figure 2a). Areas exhibiting high IOI values are spatially clustered rather than randomly distributed, suggesting strong geological control rather than surface noise or vegetation effects.

Similarly, the clay mineral index (CMI) map (Figure 2b) exhibited high values of up to 0.20, with lower values approaching -0.44 (Figure 2b). These elevated CMI zones form elongated and clustered features that align with known mineralized corridors within the district. The coincidence of high IOI and CMI values indicates the presence of hydrothermal alteration assemblages dominated by iron oxides and clay minerals, which are commonly associated with gold mineralization in Birimian terrains (Sekandari et al., 2020).

The spatial continuity observed in both indices suggests that alteration processes extend across district-scale structures, consistent with regional shear zones and fluid pathways characteristic of West African gold belts (Angulo-Bejarano et al., 2021).

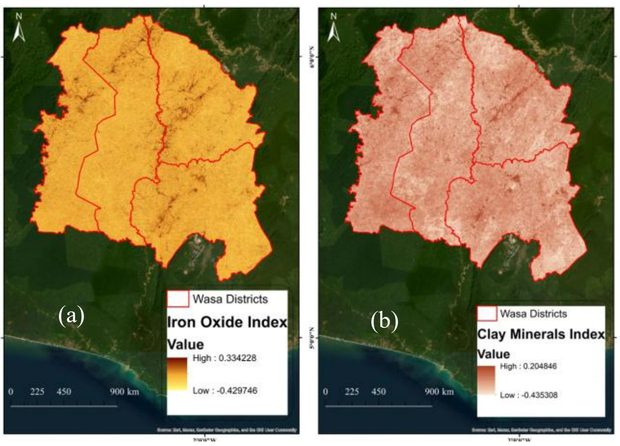

Figure 2. Spectral Index Map of Wasa Districts (a) IOI (b) CMI showing gold-rich areas

3.2 Field-Based Gold Distribution

Results from ICP-MS laboratory analysis of approximately 2,000 soil samples revealed measurable and spatially coherent gold concentrations across the study area. Gold concentrations ranged from background levels (< 0.01 ppm) to anomalous values exceeding 0.11- 0.83 ppm, as illustrated in the gold concentration map (Figure 3b).

The IDW interpolation produced distinct clusters of elevated gold concentration rather than random dispersion (Figure 3a). These clusters are concentrated primarily within the central and eastern portions of the district, indicating geological rather than anthropogenic control. Such spatial coherence is typical of structurally controlled hydrothermal gold systems where mineralization occurs along fractures, shear zones, and lithological contacts (Hall, 1992; Haldar, 2018; Tang et al., 2020; Osei et al., 2024).

The presence of continuous anomalous zones confirms that the sampling density (1 km × 1 km grid) was sufficient to capture regional-scale geochemical variability and supports the reliability of the interpolated gold surface.

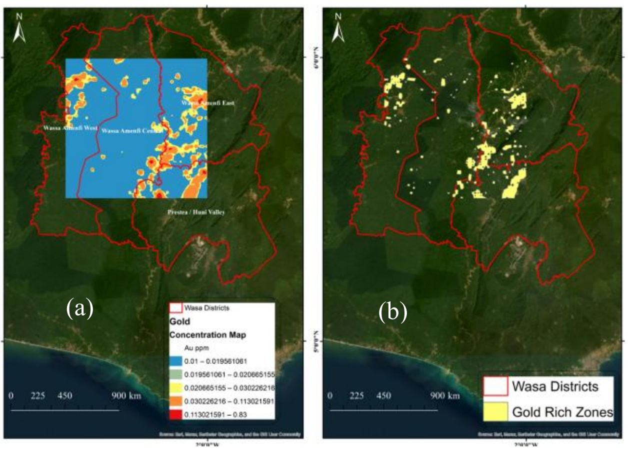

Figure 3. Coherent gold concentrations across the Wasa Districts from sampled soils at 40cm depth (a) IDW interpolation (b) Gold-rich areas

3.3 Integration of Remote Sensing and Field Data

Overlay analysis integrating the iron oxide index, clay mineral index, and field-derived gold concentration data demonstrates strong spatial agreement between satellite-derived alteration zones and measured gold enrichment (Figure 4).

Most gold-rich soil samples fall directly within areas exhibiting high IOI and high CMI values, while additional gold occurrences are located within a 1 km proximity buffer around these high-index zones. This spatial relationship strongly supports the interpretation that hydrothermal alteration mapped using Sentinel-2 imagery reflects subsurface mineralization processes rather than superficial surface effects.

Furthermore, several known mining sites within the Wasa Amenfi District spatially coincide with areas of overlapping high iron oxide and clay mineral indices (Figure 4), providing independent validation of the remote sensing results. The convergence of three independent datasets, spectral indices, laboratory geochemistry, and known mining locations, substantially increases confidence in the identified gold-rich zones.

This integrative result demonstrates that multispectral satellite imagery, when combined with systematic geochemical validation, can reliably delineate exploration targets before field excavation.

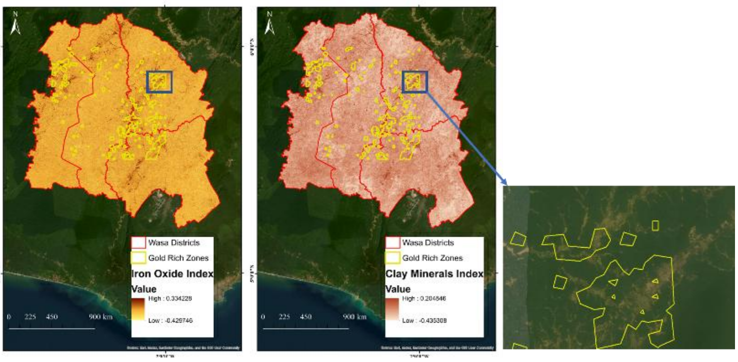

Figure 4. Integrated IOI, CMI, and field-derived gold concentration areas in the Wasa Districts

The results of this study confirm the effectiveness of spectral index-based remote sensing for identifying gold mineralization indicators in tropical mining environments. Iron oxide enrichment and clay mineral alteration are widely recognized as key expressions of hydrothermal systems associated with orogenic gold deposits (Balafrej et al., 2020).

The strong correspondence observed between high IOI-CMI zones and ICP-MS-measured gold concentrations indicates that Sentinel-2 multispectral data are capable of capturing alteration features relevant to mineral exploration, even under dense vegetation conditions typical of southwestern Ghana. This finding aligns with recent studies demonstrating the growing applicability of Sentinel-2 data for alteration mapping in complex geological terrains (Sekandari et al., 2020; Angulo-Bejarano et al., 2021).

Importantly, the results highlight the limitations of traditional trial-and-error exploration practices. Many gold-rich zones identified through field sampling align precisely with spectral anomalies that could have been detected before excavation. This underscores the potential of remote sensing–driven pre-survey tools to reduce unnecessary land disturbance, limit deforestation, and minimize environmental degradation.

The Green Gold Exploration framework proposed in this study provides a practical pathway toward environmentally responsible mineral development. Through the guiding of field exploration to high-probability zones, the approach improves exploration efficiency while supporting sustainable mining policies in developing countries where access to costly geophysical surveys is limited.

4. Conclusion

This study demonstrates that high values of iron oxide and clay mineral spectral indices derived from Sentinel-2 imagery effectively delineate gold-rich zones in the Wasa Amenfi District of Ghana. Spectral index mapping revealed coherent hydrothermal alteration patterns consistent with regional geological controls. Field validation using approximately 2,000 soil samples analyzed by ICP-MS confirmed elevated gold concentrations within these alteration zones. Spatial overlay analysis further showed that most gold-rich locations fall directly within or within 1 km of high iron oxide and clay mineral index values. Additionally, known mining areas spatially coincide with the mapped alteration zones, providing independent confirmation of the results. The integration of satellite remote sensing, geochemical sampling, and spatial analysis forms a robust, cost-effective, and environmentally friendly framework for mineral exploration. The proposed Green Gold Exploration approach offers a valuable decision-support tool capable of guiding exploration activities before physical excavation, thereby reducing environmental degradation, improving target efficiency, and supporting sustainable resource development.

This framework is scalable and transferable and can be applied to other gold-bearing regions across Ghana and sub-Saharan Africa.

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