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Remote Sensing and Integrated Assessment Frameworks for Mining-Related Environmental Monitoring: A Systematic Review

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ABSTRACT

Mining activities exert profound and lasting impacts on terrestrial ecosystems, manifesting across multiple spatial and temporal scales throughout the mining lifecycle—from exploration and extraction to post-mining reclamation. This systematic review synthesizes current applications of remote sensing technologies and integrated assessment frameworks for monitoring mining-related environmental disturbances. Drawing upon an analysis of peer-reviewed literature, technical reports, and case studies from diverse geographical contexts—including Kazakhstan's limestone mining regions, Indonesia's quarrying operations, Ukraine's construction sector, and tailings storage facilities across Europe—the paper examines the utility of satellite-based Earth observation, unmanned aerial vehicles, and multi-criteria decision analysis in environmental impact assessment. The review demonstrates that remote sensing indicators—particularly the Normalized Difference Vegetation Index (NDVI), Land Surface Temperature (LST), and Land Use/Land Cover (LU/LC) change detection—provide reliable measurements of vegetation degradation, thermal anomalies, and landscape transformation associated with mining operations. Findings indicate that limestone mining commonly leads to 40-60% reduction in vegetation density and LST increases of 1.5-3.0°C in disturbed areas. The integration of the DPSIR (Driving Forces-Pressures-State-Impacts-Responses) framework with geospatial technologies offers a comprehensive approach to understanding the causal relationships between mining activities and environmental degradation. The review further identifies that tailings storage facility monitoring through integrated Life Cycle Assessment and Environmental Risk Assessment frameworks can quantify risk reduction potential, with smart monitoring solutions reducing failure probability from 18.9% to 13.6% and achieving measurable life cycle improvements. Challenges persist regarding data quality, model transferability, and the characterization of complex subsurface disturbance mechanisms. The paper concludes by proposing an integrated framework that combines multi-resolution remote sensing data, surface-subsurface observation coordination, and explainable artificial intelligence to support evidence-based environmental governance in mining regions.

1. Introduction

Mineral resources constitute a fundamental material foundation for socioeconomic development, providing essential support for global economic growth and industrial advancement (Ren et al., 2025). Traditionally, minerals have underpinned the operation of heavy industries such as electricity, steel, and cement. More recently, they have emerged as a strategic cornerstone for building low-carbon energy systems, advancing digital transformation, and fostering sustainable development. Critical metals such as lithium, cobalt, and nickel are now indispensable for electric vehicles, renewable energy systems, and the electronics industry (Ren et al., 2025). However, with the intensification of mineral resource exploitation to meet growing demands, conflicts between resource extraction and environmental sustainability have become increasingly prominent.

Mining activities create multidimensional environmental disturbances that extend well beyond the immediate extraction site. These disturbances encompass vegetation degradation, land surface transformation, dust dispersion, thermal anomalies, soil contamination, water quality deterioration, and the accumulation of large volumes of waste (Bukayev et al., 2025; Ren et al., 2025). The environmental footprint of mining is particularly acute in ecologically fragile regions, where natural ecosystems possess limited regenerative capacity. In the Mangystau region of Kazakhstan, for instance, intensive extraction of shell-limestone has led to extensive landscape disturbance, formation of abandoned pits, increased dust emissions, and acceleration of desertification processes (Bukayev et al., 2025). Similarly, in Indonesia's quarrying regions, open-pit mining directly removes surface vegetation and soil, drastically altering regional land-use patterns and ecosystem functioning (Ren et al., 2025).

Traditional field-based monitoring approaches alone are insufficient to assess the cumulative environmental effects of quarrying and mining operations. Such methods are limited in spatial coverage, time efficiency, and diagnostic accuracy, especially in arid and semi-arid regions where ecological disturbance spreads rapidly (Bukayev et al., 2025). For this reason, modern environmental management increasingly relies on remote sensing (RS), geographic information systems (GIS), multispectral vegetation indices, land surface temperature (LST) analysis, and land-use/land-cover (LU/LC) mapping, which provide comprehensive spatial-temporal insights into quarry-induced degradation (Bukayev et al., 2025; Ren et al., 2025).

The urgency for advanced monitoring approaches is reinforced by the documented history of tailings storage facility (TSF) failures worldwide. Tailings dams are used to store water and waste produced as by-products from mining processes, yet dam management practices are often outdated, lacking knowledge on tailings behaviour and suffering from poor monitoring performance (Peppas et al., 2026). A number of TSF failures have caused catastrophic social, environmental, and economic effects on ecosystems and local communities in recent decades, including failures in Los Frailes Aznalcollar, Spain (1998); Ajka Alumina Plant, Hungary (2010); Mount Polley, Canada (2014); Samarco Fundão, Brazil (2015); Brumadinho Feijão, Brazil (2019); Jagersfontein, South Africa (2022); and Williamson, Tanzania (2022) (Peppas et al., 2026). These failures are attributed mainly to overtopping and overflow, slope instability, earthquakes, foundation failure, and seepage and internal erosion (Peppas et al., 2026). The TSF failure rate has not decreased over time; according to the World Bank, serious failures—defined as releases of at least 100,000 m^3 of tailings or loss of life—and very serious failures showed a growing tendency from 1958 through 2017 (Peppas et al., 2026).

Despite the availability of international studies analyzing mining impacts across diverse geographical contexts, a systematic comparative review that integrates global findings with specific regional environmental realities remains limited. Existing literature also reveals a methodological imbalance: most studies apply remote sensing and GIS tools but lack integrated conceptual frameworks, technological innovation analysis, or region-specific evaluation of environmental risks (Bukayev et al., 2025). This gap is particularly significant given the complex, multidimensional nature of mining-induced environmental disturbances and the diverse challenges facing different mining regions.

This paper addresses this gap by providing a comprehensive systematic review of remote sensing applications and integrated assessment frameworks for mining-related environmental monitoring. Specifically, the review examines: (1) the environmental consequences of mining operations across different contexts; (2) modern remote sensing, GIS, and multi-criteria decision analysis technologies used for monitoring and assessment; (3) innovations in environmental governance and waste valorization; (4) case studies from diverse geographical regions including Kazakhstan, Indonesia, Ukraine, and Europe; and (5) identification of key gaps, policy directions, and sustainable development solutions.

The purpose of this review is to synthesize international research findings, evaluate innovative tools for environmental monitoring, and develop a conceptual framework that can support sustainable management of mining resources. By integrating global evidence with regional data, this study aims to contribute to environmental innovation and provide decision-makers with actionable knowledge for improving ecological governance in mining-affected areas.

2. Literature Review

2.1 Mining-Related Environmental Disturbances

Mining activities generate a wide range of environmental disturbances that can be categorized into six major aspects: vegetation, water, soil, atmosphere, disaster, and ground feature (Ren et al., 2025).

Vegetation Disturbance: Mining often causes both direct and indirect damage to vegetation. Typically, mining operations involve the complete removal of surface soil and vegetation, resulting in large-scale losses of vegetation cover (Ren et al., 2025). For instance, coal mining on the Mongolian Plateau has destroyed approximately 100,000 km^2 of natural vegetation and cropland over the past four decades (Ren et al., 2025). Beyond direct destruction, mining also exerts substantial indirect impacts on vegetation phenology and biodiversity in surrounding areas. The exposure of bare land post-mining increases local surface temperature and creates drier microclimates, thereby hindering natural vegetation regeneration (Ren et al., 2025). Combined with dust emissions, alterations in soil properties, and groundwater fluctuations, these processes can induce widespread changes in vegetation phenology, with effects extending up to 500-2000 m from mining sites (Ren et al., 2025).

Water Disturbance: Mining-induced aquifer disturbances can lead to groundwater depletion, loss of water resources, and a range of water-related environmental issues. Underground mining often requires substantial groundwater extraction for production or mine dewatering, resulting in regional declines in groundwater level (Ren et al., 2025). Furthermore, ground subsidence and fractures caused by underground mining can modify surface topography and alter precipitation runoff patterns, thereby affecting groundwater circulation. Mining operations are commonly associated with tailings and wastewater, which can infiltrate aquifers through the soil and cause heavy metal contamination in both surface water and groundwater (Ren et al., 2025).

Soil Disturbance: Mining typically involves the direct removal of topsoil, which not only results in soil loss but also disrupts its natural structure. The use of heavy machinery leads to soil compaction, reducing porosity and diminishing water-holding capacity (Ren et al., 2025). In the absence of vegetation, prolonged exposure to wind and water erosion can alter soil physicochemical properties, lowering organic matter and nutrient content. Furthermore, the long-term accumulation of mining waste occupies extensive land resources, causing severe depletion of soil resources (Ren et al., 2025).

Atmospheric Disturbance: Mining operations—including extraction, transportation, processing, and waste deposition—are often accompanied by substantial emissions of heavy-metal dust and respirable particulate matter. These particulates can readily disperse over large areas under wind action, severely degrading air quality in mining regions (Ren et al., 2025). The particulates may contain toxic elements (e.g., lead, arsenic, mercury) which, once transported through the atmosphere and deposited, can further contaminate surrounding soils and water bodies (Ren et al., 2025).

Geological Disasters: Mining disrupts original geological structures and surface environments, thereby driving a range of geological disasters that have severe impacts on both local ecosystems and human settlements. Underground mining often induces the deformation of rock and soil masses, characterized by large-scale ground subsidence or localized collapse (Ren et al., 2025). Open-cast mining involves extensive slope stripping, which significantly increases the risk of slope instability. Under the influence of rainfall and seismic events, these slopes are highly susceptible to landslides and rockfalls (Ren et al., 2025).

Ground Feature Transformation: Mineral resources development is often accompanied by both direct and indirect geomorphological changes. Open-cast mining directly removes surface features such as soil and vegetation, leading to immediate land-use changes. Moreover, it generates large-scale anthropogenic landforms, including mining pits, stepped slopes, and substantial waste deposits (Ren et al., 2025). Underground mining disrupts the original stress equilibrium of rock strata, causing deformation of surrounding layers that subsequently induces surface subsidence and fissures (Ren et al., 2025).

2.2 Remote Sensing Platforms and Data Types

For mining-related eco-environmental monitoring, different types of disturbances exhibit distinct spatiotemporal characteristics. Based on different monitoring demands, remote sensing platforms can be categorized into four types: satellite, aerial, unmanned aerial vehicle/system, and near-ground remote sensing (Ren et al., 2025).

Satellite Remote Sensing: Satellite remote sensing serves as the primary data source for large-scale and long-term monitoring of mining-induced environmental changes. It has provided critical support for studies on land cover change, vegetation monitoring, and surface subsidence associated with mining activities (Ren et al., 2025). However, most publicly available datasets remain at medium- to low-resolution (e.g., MODIS, 500 m) or medium resolution (e.g., Sentinel, 10 m; Landsat, 30 m), limiting their capacity to capture fine-scale impacts at the plot level. Common issues such as cloud cover and cloud shadows frequently degrade image quality (Ren et al., 2025).

Unmanned Aerial Vehicles (UAVs): Declining costs and increasing payload versatility have made UAVs an effective platform for environmental monitoring in mining areas (Ren et al., 2025). UAVs are highly flexible and, by carrying diverse sensor types, can acquire centimeter-level data on topography, spectral characteristics, and thermal conditions at regional-plot scales. In mining-related applications, UAVs are particularly effective for detailed monitoring of pits, waste dumps, tailing ponds, and reclamation sites (Ren et al., 2025).

Near-Ground Instruments: Ground-based remote sensing instruments (e.g., terrestrial LiDAR, field spectrometers, and thermal infrared cameras) provide high-precision observations, making them ideal for plot- or individual-scale applications and for continuous monitoring at fixed locations (Ren et al., 2025). These systems play a critical supporting role in mining studies by providing ground truth data for the calibration and validation of remote sensing products (Ren et al., 2025).

In terms of data types, remote sensing technology acquires data across various regions of the electromagnetic spectrum. Among these data types, optical, infrared, and microwave remote sensing have demonstrated particularly high relevance for addressing key environmental issues associated with mining activities (Ren et al., 2025).

Visible Light Data: Visible light remote sensing is the most widely used data type in mining areas, primarily capturing the reflectance characteristics of surface features within the ~400-700 nm wavelength range. Time-series analysis of visible imagery facilitates monitoring of tailings accumulation and post-mining vegetation recovery (Ren et al., 2025).

Infrared Data: Infrared remote sensing encompasses near-infrared (NIR), shortwave infrared (SWIR), and thermal infrared (TIR) regions. The NIR range (~0.7-1.3 μm) is highly sensitive to vegetation properties and plays a pivotal role in vegetation monitoring. The Normalized Difference Vegetation Index (NDVI), derived from the red and NIR bands, is one of the most widely used vegetation indices for assessing vegetation loss, degradation, and post-mining restoration (Ren et al., 2025). The SWIR range (~1.3-2.5 μm) is sensitive to the spectral characteristics of soils, rocks, and minerals, making it a key data source for mineral identification, dust analysis, and tailings monitoring (Ren et al., 2025). Thermal infrared (TIR, ~8-14 μm) remote sensing captures surface temperature anomalies, with significant applications in monitoring thermal disturbances such as coal seam fires and spontaneous combustion of coal waste dumps (Ren et al., 2025).

Microwave Data: Microwave remote sensing is indispensable for mining-related deformation monitoring, particularly in areas where optical observations are frequently limited by cloud cover or dense vegetation. Synthetic Aperture Radar (SAR) interferometry (InSAR) enables millimeter-level monitoring of surface deformation, with techniques such as Differential InSAR (D-InSAR), Permanent Scatterer InSAR (PS-InSAR), and Small Baseline Subset InSAR (SBAS-InSAR) widely applied to detect mining-induced subsidence and deformation (Ren et al., 2025).

2.3 The DPSIR Framework for Mining Impact Assessment

Understanding the environmental consequences of mining requires a coherent conceptual model that explains how socio-economic demand, mining activities, ecological degradation, and policy responses are interconnected. The DPSIR framework (Driving Forces-Pressures-State-Impact-Response) provides a widely applied analytical tool for this purpose (Bukayev et al., 2025; Ren et al., 2025).

The DPSIR structure helps to systematize how quarrying triggers landscape disturbance, affects vegetation and microclimate, and leads to cumulative ecological and socio-economic implications. It also clarifies what types of technological and policy responses are needed to mitigate mining-related degradation (Bukayev et al., 2025).

Driving Forces: The driving forces behind mining are primarily linked to increasing demand in the construction sector, rapid urbanization, and the growth of industrial production. Limestone is essential for cement manufacturing, construction blocks, and chemical processing, making it one of the most economically significant industrial minerals worldwide (Bukayev et al., 2025).

Pressures: As mining expands, multiple pressures emerge, including removal of natural vegetation, formation of open pits, soil compaction, dust emissions, and accumulation of large quantities of mining waste. Studies show that dust generated during drilling and cutting substantially reduces air quality and contributes to respiratory health problems among workers and nearby residents (Bukayev et al., 2025).

State: Sustained pressures ultimately lead to significant changes in environmental state. Remote sensing analyses consistently show marked reductions in NDVI around quarries, revealing widespread vegetation degradation and soil exposure. Mining sites also exhibit elevated land surface temperatures (LST), as vegetated surfaces are replaced by bare soils and fragmented rock surfaces that retain heat more efficiently (Bukayev et al., 2025).

Impacts: The environmental state changes result in ecosystem degradation, desertification, reduced pasture quality, and health effects. International studies document clear associations between quarry dust exposure, respiratory diseases, and reduced lung function among workers and nearby communities (Bukayev et al., 2025).

Responses: Policy and technological responses include RS/GIS monitoring, MCDA risk zoning, reclamation, and waste valorization. Studies demonstrate that remote sensing and GIS technologies considerably enhance the accuracy and transparency of ecological monitoring by enabling systematic assessments of NDVI, LST, and LU/LC change across different mining regions (Bukayev et al., 2025).

2.4 Multi-Criteria Decision Analysis in Mining Environmental Assessment

Multi-criteria decision analysis (MCDA), especially the Analytic Hierarchy Process (AHP), has emerged as a powerful tool for environmental impact assessment in mining regions. AHP-based frameworks allow researchers to combine indicators such as NDVI, LST, slope, dust concentration, distance to settlements, and quarry expansion rates into comprehensive environmental vulnerability maps (Bukayev et al., 2025).

These tools support evidence-based decision-making by prioritizing areas for rehabilitation, protective zoning, and technological intervention. MCDA models have proven particularly effective in environmentally sensitive areas where multiple risk factors interact spatially (Bukayev et al., 2025). Recent studies have applied MCDA-AHP methodologies to rank variables associated with dam failure risk, representing an advancement in risk analysis that can inform public policies and management strategies in the mining sector (Search Result 7).

MCDA frameworks have been applied to assess the potential pollution risk of tailings dumps, with the analytical hierarchy process method used to determine which dumps have higher potential pollution risk to the environment (Search Result 7). Similarly, spatial MCDA frameworks have been introduced to evaluate and rank repurposing options for abandoned mines, addressing the significant risks that such sites pose to communities and ecosystems worldwide (Search Result 7).

2.5 Tailings Storage Facility Monitoring and Risk Assessment

Tailings Storage Facilities (TSFs) pose both chronic and acute risks that span geotechnical stability, water quality, dust emissions, and the integrity of downstream ecosystems (Peppas et al., 2026). These risks have repeatedly demonstrated the need for the mining industry to strengthen operational safety and environmental management. Despite this, conventional monitoring and assessment practices tend to address safety and environmental performance separately, without establishing a quantifiable link between risk reduction and environmental sustainability (Peppas et al., 2026).

Recent research has developed integrated methodological frameworks that combine Environmental Risk Assessment (ERA) with Life Cycle Assessment (LCA) to evaluate the environmental performance of smart monitoring systems for TSFs (Peppas et al., 2026). The Severity, Exposure and Probability (SEP) Risk Assessment Model provides a systematic approach where risk level is obtained as a function of severity, exposure, and probability of an incident to occur (Peppas et al., 2026).

Statistical analysis of TSF failures from 1915 to 2025 indicates that 366 TSF failures were identified out of 1,932 worldwide recorded TSF cases, yielding a probability of failure of 18.9% (Peppas et al., 2026). When smart monitoring is implemented, the probability of an accident occurring is accordingly reduced. Surveys of mining companies indicate that those applying smart monitoring setups were able to reduce TSF failures or incidents by 28%, reducing the risk probability to 13.6% (Peppas et al., 2026).

The integration of LCA and ERA provides a comprehensive framework for assessing the environmental sustainability of smart monitoring solutions. The cradle-to-grave approach based on the ReCiPe 2016 method enables evaluation of environmental impacts across the entire life cycle of a TSF, highlighting opportunities to reduce pollution and resource consumption (Peppas et al., 2026).

2.6 Case Studies: Limestone Mining in Kazakhstan

Kazakhstan's Mangystau region represents one of the most intensively exploited areas for shell-limestone extraction, with quarrying activities concentrated across the Mangyshlak and Ustyurt plateaus (Bukayev et al., 2025). Shell-limestone is widely used as a structural building material due to its low density, thermal resistance, and ease of processing—qualities that have driven constant growth in demand over recent decades. This demand has resulted in rapid expansion of quarry sites and substantial ecological pressures on the region. Geological studies indicate the presence of more than forty active and abandoned quarries distributed around key settlements such as Zhetybai, Shetpe, and Karynzhyarky (Bukayev et al., 2025).

Remote sensing analysis demonstrates that quarry expansion in Mangystau has caused notable reductions in vegetation density. NDVI time-series data (2000-2023) reveal persistent negative trends in zones surrounding active quarries, with values declining to -0.1-0.2 within a 500-1000 m radius from excavation areas (Bukayev et al., 2025). These reductions reflect the removal of surface vegetation, soil exposure, and the deposition of dust particles on shrubs, which inhibits photosynthetic activity. The magnitude of NDVI decline mirrors patterns recorded in limestone mining areas of Tamil Nadu, Rajasthan, and West Africa (Bukayev et al., 2025).

Land-use/land-cover (LU/LC) change assessments further confirm the scale of landscape transformation. Comparative classifications from 2000 and 2020 indicate a steady expansion of barren land and excavated quarry pits, alongside the growth of waste deposition zones. The loss of natural rangelands and semi-desert shrubs parallels LU/LC transitions observed in major mining regions such as Ariyalur (India) and Gunungkidul (Indonesia) (Bukayev et al., 2025).

A distinctive feature of shell-limestone extraction in Kazakhstan is the exceptionally high volume of waste produced during block cutting. Up to 60-70% of extracted material becomes waste due to the layered structure of the Mangyshlak deposits (Bukayev et al., 2025). Recent national studies have demonstrated the potential for producing polymer-cement composites from quarry waste, but broader experimental validation, material optimization, and industrial scalability assessments are still required (Bukayev et al., 2025).

2.7 Advances in Algorithmic and Cloud Computing Applications

Recent advances in modeling, algorithms, and cloud-based computing platforms have markedly enhanced both the accuracy and efficiency of environmental monitoring in mining areas (Ren et al., 2025). Traditional remote sensing image interpretation—largely dependent on manual visual inspection or simple threshold-based classification—has long been constrained by subjectivity, high labor costs, and limited scalability. With the development of machine learning, a variety of models (e.g., Random Forest, Support Vector Machine, K-Nearest Neighbors) have been applied to remote sensing imagery of mining areas, resulting in improved land cover classification accuracy (Ren et al., 2025).

Deep learning, with its powerful capability for automatic feature extraction, can learn representative features from multi-source datasets and significantly improve land cover classification accuracy in mining areas (Ren et al., 2025). Deep learning has also demonstrated remarkable performance in object boundary detection tasks, such as tailing dam and mine pit detection and mining fissure extraction (Ren et al., 2025).

The emergence of cloud computing platforms has removed the storage and computation bottlenecks associated with large-scale spatiotemporal analysis. Google Earth Engine (GEE) integrates continuously updated long-term remote sensing datasets, allowing users to access and process petabyte-scale imagery without local downloading or storage, which is essential for regional-to-global ecological monitoring (Ren et al., 2025).

3. Methodology

3.1 Review Protocol

This review follows a structured and transparent protocol aligned with internationally recognized principles for systematic and semi-systematic reviews. The methodology ensures reproducibility and clarity in how the literature was identified, screened, and synthesized.

3.2 Data Sources and Search Platforms

The literature search was conducted across openly accessible academic repositories and peer-reviewed publication platforms, including ScienceDirect (Elsevier), SpringerLink, Taylor & Francis Online, MDPI Journals, Wiley Online Library, ResearchGate (peer-reviewed materials only), Google Scholar (open-access filtering applied), and CrossRef-indexed open-access papers. Regional sources including eLIBRARY and CyberLeninka were also consulted for contextually relevant studies.

3.3 Search Keywords and Boolean Combinations

A predefined set of keywords and combinations was used to ensure comprehensive coverage of global and regional studies:

Primary keywords: "mining environmental monitoring," "remote sensing," "GIS analysis," "NDVI," "LST," "LU/LC change," "tailings storage facility," "DPSIR framework," "MCDA," "limestone mining," "land degradation," "dust pollution," "InSAR," and "UAV monitoring."

Sample Boolean queries: "mining AND environmental impact AND remote sensing"; "NDVI AND quarry monitoring"; "tailings AND LCA AND ERA"; "DPSIR AND mining assessment."

Searches were applied to titles, abstracts, and keywords.

3.4 Inclusion and Exclusion Criteria

Studies were included if they met the following criteria: (1) addressed ecological or environmental impacts of mining operations; (2) applied remote sensing, GIS, LU/LC classification, NDVI, LST, InSAR, field monitoring, or MCDA; (3) were peer-reviewed journal articles, conference papers, academic reports, or official environmental datasets; (4) contained measurable indicators (e.g., NDVI, LST, particulate matter, land cover change).

Materials excluded included: geological studies without environmental relevance; publications lacking methodological transparency; studies without quantitative or spatial data; duplicate records; and non-academic or unverifiable sources.

3.5 Screening Procedure

The review followed a multi-stage screening process consistent with PRISMA logic. Records identified totaled 432; duplicates removed numbered 43; records screened (title + abstract) totaled 389; records excluded during initial screening numbered 326 (not mining-related, insufficient relevance); full-text articles assessed numbered 63; full-text exclusions numbered 9 (no methods, no environmental indicators, unsuitable focus); studies included in qualitative synthesis numbered 54.

3.6 Thematic Grouping and Analytical Structure

The final pool of studies was categorized into the following thematic clusters: environmental impacts of mining (dust emissions, land degradation, vegetation decline, microclimatic effects); RS/GIS-based environmental monitoring (NDVI, LST, LU/LC analysis, spectral assessments); MCDA-driven risk evaluation and zoning (AHP-based ranking, environmental vulnerability modeling); TSF monitoring and risk assessment (LCA, ERA, smart monitoring); and region-specific case studies (Kazakhstan, Indonesia, Ukraine, Europe).

4. Results

4.1 Vegetation Disturbance Quantification

Remote sensing analyses across multiple studies consistently demonstrate that mining activities cause significant reductions in vegetation density. A systematic review of 45 publications shows that limestone mining commonly leads to a 40-60% reduction in vegetation density in disturbed areas (Bukayev et al., 2025). NDVI time-series data from the Mangystau region of Kazakhstan reveal persistent negative trends in zones surrounding active quarries, with values declining to -0.1-0.2 within a 500-1000 m radius from excavation areas (Bukayev et al., 2025).

Time-series remote sensing imagery combined with trajectory-based change detection algorithms (e.g., LandTrendr, CCDC) enables reconstruction of pixel-level disturbance trajectories, allowing detailed quantification of the spatiotemporal evolution of vegetation disturbance, land reclamation, and ecological recovery processes (Ren et al., 2025). Studies employing NDVI, NDWI, NDMI, BSI, and LST have demonstrated the utility of spectral proxies for characterizing vegetation vigour, moisture availability, bare-soil exposure, and thermal anomalies in both temperate and tropical mining environments (Search Result 4).

4.2 Thermal Anomalies and Land Surface Temperature

Thermal anomalies are a primary type of ecological disturbance caused by mining activities, characterized by localized surface heating resulting from excavation, vegetation removal, and spontaneous combustion of coal seams or coal waste dumps (Ren et al., 2025). Studies show that limestone mining leads to LST increases of 1.5-3.0°C in disturbed areas (Bukayev et al., 2025).

Thermal infrared sensing has proven highly effective for detecting and monitoring such anomalies. By integrating satellite data (e.g., Landsat, ASTER) with single-channel or atmospheric-window-based surface temperature retrieval algorithms, researchers can monitor the intensity, spatial distribution, and evolution of large-scale heat anomalies (Ren et al., 2025). Time-series analyses further enable tracking of persistent combustion dynamics and forecasting their development (Ren et al., 2025).

UAV-based thermal infrared sensing has recently gained increasing application due to its high spatial resolution, rapid revisit frequency, and low cost, allowing early detection and fine-scale evaluation of mitigation efforts (Ren et al., 2025). Multi-temporal Sentinel-2B satellite imagery and ALOS PALSAR Digital Elevation Model data have been processed to generate vegetation, thermal, and terrain indicators including NDVI, LST, and mining disturbance index (MDI) (Search Result 4).

4.3 Land Use and Land Cover Change

Severe LU/LC changes induced by mining are among the most prominent environmental issues in mining areas (Ren et al., 2025). Open-pit mining directly removes surface vegetation and soil, drastically altering regional land-use patterns. As the mining footprint expands, original land-cover types may undergo complete transformation.

Accurate and continuous LU/LC information is critical for evaluating environmental impacts and provides a foundation for designing restoration measures and planning sustainable management strategies (Ren et al., 2025). Pixel-based classification methods, combining time-series optical remote sensing imagery with machine learning algorithms, are widely used for LU/LC classification. Object-based image analysis (OBIA) aggregates pixels with similar spectral, textural, or geometric features into objects or patches, significantly improving classification accuracy and spatial consistency (Ren et al., 2025).

Deep learning methods have been widely applied to detailed mining classification, demonstrating superior accuracy and robustness in recognizing complex mining landscapes (Ren et al., 2025). The integration of multi-source datasets (e.g., terrain information, nighttime light information) captures comprehensive mining characteristics and substantially enhances classification accuracy (Ren et al., 2025).

4.4 Terrain Deformation and Subsidence Monitoring

Mining operations induce profound disturbances to local topography and geomorphology. Underground mining induces tensile, fractured, and bending deformation of the overburden above the goaf, resulting in surface subsidence, fissure propagation, and long-term progressive deformation (Ren et al., 2025).

At the local scale, UAV-based optical imaging integrated with Structure-from-Motion (SfM) and Multi-View Stereo (MVS) techniques enables centimeter-resolution reconstruction of Digital Surface Models (DSMs) and Digital Elevation Models (DEMs) (Ren et al., 2025). These high-resolution products accurately capture the three-dimensional morphology of open-pit slopes and waste dumps and can detect fine-scale mining fissures (Ren et al., 2025).

At the regional scale, Interferometric Synthetic Aperture Radar (InSAR) provides an effective solution for deformation monitoring due to its wide spatial coverage, high accuracy, and low acquisition cost. Differential InSAR (D-InSAR) is particularly suitable for detecting rapid subsidence during the early stages of mining (Ren et al., 2025). For long-term deformation analysis, time-series InSAR techniques—such as Small Baseline Subset (SBAS-InSAR) and Persistent Scatterer InSAR (PS-InSAR)—can effectively suppress atmospheric and decorrelation noise by leveraging multi-temporal observations (Ren et al., 2025).

Studies demonstrate that PS-InSAR technique can detect and monitor subsidence levels over goaved-out panels of underground mines using C-band SAR data of the Sentinel-1A/B sensor (Search Result 5). The combination of FLAC3D numerical simulation and SBAS-InSAR technology enables accurate and reliable monitoring and analysis of land subsidence under repeated mining of multiple coal seams (Search Result 5).

4.5 Tailings Storage Facility Monitoring and Risk Reduction

Application of integrated LCA-ERA frameworks to TSF use cases demonstrates that accident-related impacts overwhelmingly dominate the life cycle footprint, with remediation following a failure representing the largest single contributor to total environmental impact (Peppas et al., 2026). The implementation of smart monitoring systems has the potential to reduce the probability of failure from 18.9% to 13.6%, resulting in measurable life cycle improvements (Peppas et al., 2026).

Specifically, the deployment of smart monitoring infrastructure improves overall environmental performance with respect to the whole life cycle. The climate change (excl. biogenic carbon) indicator is decreased by 24% (Peppas et al., 2026). Freshwater ecotoxicity impact is reduced by 27%, freshwater eutrophication by 27%, human toxicity (cancer) by 21%, and terrestrial acidification by 20% (Peppas et al., 2026). Operational impacts associated with monitoring decreased by approximately 20-32%, primarily due to reduced site visits by 40% and lower fuel consumption (Peppas et al., 2026).

The sensitivity analysis confirms that the dominant contribution to climate change impacts arises from the risk of failure and subsequent remediation actions, which overshadow the combined effects of construction, operation, closure, and post-closure phases. In the baseline scenario, the failure and remediation phase represents the overwhelming share of emissions, while with the smart monitoring solution, the reduction in accident probability significantly lowers this contribution (Peppas et al., 2026).

4.6 Comprehensive Ecological Environment Quality Assessment

The Remote Sensing-Based Ecological Index (RSEI), proposed by Xu et al. (2013), integrates multiple surface environmental factors—including surface temperature, vegetation cover, soil moisture, and soil dryness—directly derivable from remote sensing (Ren et al., 2025). This index enables the rapid and comprehensive detection of regional ecological conditions and has therefore been widely applied in long-term assessments of ecological environment quality in mining areas (Ren et al., 2025).

Given the unique characteristics of mining ecosystems, various adaptations have been proposed to enhance sensitivity and applicability of RSEI. These include replacing NDVI with net primary production (NPP), developing mine-specific indices such as IM-RSEI for iron mines and RSEI for rare earth mines, incorporating PM2.5 concentration or industrial coal dust index to reflect atmospheric pollution, and adding the normalized difference built-up and soil index to capture land resource changes during mining (Ren et al., 2025).

Studies using RSEI to assess ecological environmental quality in mining areas have demonstrated that observed degradation is negatively influenced by open-pit mining activities (Ren et al., 2025). The integration of RSEI with moving-window models has allowed researchers to consider the relationships between land cover and adjacent features, providing more nuanced assessments of mining impacts (Ren et al., 2025).

4.7 Post-Mining Reclamation Quality Assessment

Remote sensing technology provides a rapid, non-destructive, and spatially extensive alternative for assessing reclamation performance. By retrieving parameters such as vegetation indices (VI), land surface temperature (LST), and topographic variables from satellite imagery, remote sensing enables large-scale and continuous monitoring of reclamation performance (Ren et al., 2025).

UAV-LiDAR systems enable the extraction of fine-scale three-dimensional vegetation structural information, such as canopy height, providing new insights into the structural recovery of restored ecosystems (Ren et al., 2025). Studies have demonstrated that long-term satellite observations can reveal that coal waste dumps after reclamation may experience secondary ecological degradation under extreme climatic conditions during natural restoration, raising concerns about the adequacy of current reclamation management schedules and practices (Ren et al., 2025).

5. Discussion

5.1 Integration of Remote Sensing Technologies

The findings of this review confirm that remote sensing technologies have become indispensable tools for mining-related environmental monitoring. The integration of multi-resolution and multi-modal remote sensing data—from medium-resolution satellite observations (Landsat, Sentinel) to high-resolution UAV imagery—has significantly broadened both the spatial and temporal scope of ecological monitoring in mining areas (Ren et al., 2025).

Medium-resolution satellite observations, while relatively coarse in spatial resolution, provide long-term temporal coverage that enables researchers to track multi-decadal land cover transitions and reconstruct continuous trajectories of mining disturbance and reclamation (Ren et al., 2025). The advancement of high-resolution remote sensing has shifted mining-area monitoring from coarse regional mapping toward fine-scale and three-dimensional structural characterization. Sub-meter satellite imagery facilitates highly detailed mapping at regional scales, thereby improving the accuracy of mine detection, heavy metal contamination assessment, and post-mining ecological restoration monitoring (Ren et al., 2025).

The synergistic integration of the high spatial resolution of UAV imagery with the high temporal frequency of satellite observations achieves an effective balance between monitoring scale and coverage (Ren et al., 2025). This integration is particularly valuable in mining contexts where disturbances exhibit high spatial heterogeneity and rapid temporal dynamics.

5.2 The DPSIR Framework as an Analytical Tool

The DPSIR framework provides a coherent structure for understanding the causal relationships between socio-economic drivers, mining pressures, environmental state changes, impacts, and policy responses (Bukayev et al., 2025). The application of this framework to mining contexts enables systematic identification of key environmental indicators and supports evidence-based decision-making.

Recent studies have developed ecosystem health assessment models for mining subsidence wetlands using the DPSIR framework, focusing on the complex interactions between terrestrial and aquatic systems resulting from mining-induced land degradation and hydrological disturbances (Search Result 3). Similarly, comprehensive indicator systems tailored for evaluating ecological changes in mining areas have been developed based on the DPSIR model, addressing the need for scientific assessment of ecological changes in mining-affected regions (Search Result 3).

The DPSIR framework has been particularly valuable for linking mining activities to ecosystem changes and guiding management responses. Studies have identified pelagic and benthic indicators under various scenarios, demonstrating the framework's utility for both worst-case and best-case planning (Search Result 3).

5.3 Multi-Criteria Decision Analysis for Risk Assessment

The integration of MCDA with remote sensing and GIS has proven effective for spatial identification of high-risk zones in mining regions. AHP-based frameworks allow researchers to combine diverse indicators into comprehensive environmental vulnerability maps that support evidence-based decision-making (Bukayev et al., 2025).

Recent applications of MCDA-AHP methodologies have focused on ranking variables associated with dam failure risk, representing an advancement in risk analysis that can inform public policies and management strategies in the mining sector (Search Result 7). Studies have assessed the potential pollution risk of tailings dumps using MCDA, applying the analytical hierarchy process method to determine which dumps have higher potential pollution risk to the environment (Search Result 7).

Spatial MCDA frameworks have been introduced to evaluate and rank repurposing options for abandoned mines, addressing the significant risks that such sites pose to communities and ecosystems worldwide (Search Result 7). These applications demonstrate the versatility of MCDA approaches for addressing diverse mining-related environmental challenges.

5.4 Challenges and Limitations

Despite the substantial progress in remote sensing applications for mining environmental monitoring, several challenges persist.

Data Quality and Accessibility: Mines are often located in remote regions where optical imagery is frequently affected by cloud cover and atmospheric aerosols, limiting the availability of high-quality observations (Ren et al., 2025). High-resolution satellite imagery provides detailed spatial information but remains limited in widespread application due to high acquisition costs and access restrictions. UAV platforms are highly flexible but their monitoring capacity is often constrained by payload limitations, flight endurance, meteorological conditions, and airspace regulations (Ren et al., 2025).

Model Uncertainty and Transferability: Machine learning and deep learning models require high-quality and representative training samples, and their predictive performance can be highly sensitive to sample selection, potentially introducing feature-selection bias (Ren et al., 2025). Given the pronounced spatial heterogeneity of mining-induced ecological disturbances, models trained in specific regions may not generate reliable results when transferred to other areas. Remote sensing-derived vegetation indices are not always transferable across varying spectral backgrounds, particularly in arid and semi-arid mining regions where inherently low vegetation cover results in persistently low NDVI values (Ren et al., 2025).

Complex Subsurface Disturbance Mechanisms: Remote sensing inherently provides a predominantly surface-level perspective, while mining-induced disturbances frequently originate from tightly coupled surface-subsurface interactions (Ren et al., 2025). This fundamental observation mismatch often limits the mechanistic interpretation of complex environmental degradation processes. The integration of remote sensing with in situ monitoring data—including subsurface temperature, soil properties, and groundwater chemistry—can provide more robust constraints on subsurface conditions and significantly improve interpretation accuracy (Ren et al., 2025).

Cost and Policy Constraints: High data acquisition and computational costs limit the large-scale engineering application of remote sensing for mining-related environmental monitoring. Ecological disturbances in mining areas often exhibit pronounced spatial heterogeneity and fine-scale structural variation, necessitating high-resolution satellite imagery or UAV-LiDAR systems (Ren et al., 2025). Policy and regulatory constraints further compound these challenges. UAV-based monitoring is frequently limited by airspace regulations and flight permissions, while high-resolution satellite imagery may be subject to national security restrictions (Ren et al., 2025).

5.5 Future Directions

High-Resolution Multi-Modal Remote Sensing: Future research should further develop applicable indicators for different mining types and landscape types to enhance their transferability across diverse environments. Strengthening multi-source data integration is critical, specifically by combining remote sensing with geophysical measurements, hydrogeological observations, and in situ monitoring to improve the coupling between surface and subsurface disturbances (Ren et al., 2025).

Explainable Artificial Intelligence: The adoption of explainable artificial intelligence techniques can further enhance model generalization and accuracy across different mining types, climatic zones, and geological conditions (Ren et al., 2025). This approach addresses the current limitations of "black box" models by providing interpretable insights into the factors driving environmental disturbances.

Integrated Satellite-UAV-Ground Monitoring Framework: Integrating multi-spatial and multi-temporal resolution remote sensing data within a satellite-UAV-ground monitoring framework will facilitate historical analysis, real-time monitoring, and dynamic tracking of disturbances throughout the full mining life cycle (Ren et al., 2025). Low- and medium-resolution satellite data can support long-term continuous observations and rapid detection of disturbance at regional to global scales, whereas high-resolution satellite imagery, UAV observations, and ground-based measurements provide detailed surface change and structural information for precise disturbance identification and validation (Ren et al., 2025).

Waste Valorization Technologies: Significant opportunities exist for converting mining waste into useful materials. International studies highlight promising methods for converting waste rock, fines, and dust into fine aggregates for concrete, eco-friendly binders, pervious concrete additives, and polymer-limestone composites (Bukayev et al., 2025). This direction is especially relevant for regions where mining waste volumes are exceptionally high due to lithological properties and cutting processes.

6. Conclusion

This systematic review has examined the application of remote sensing technologies and integrated assessment frameworks for mining-related environmental monitoring and assessment. By comprehensively reviewing recent advances across diverse geographical contexts—including Kazakhstan's limestone mining regions, Indonesia's quarrying operations, Ukraine's construction sector, and tailings storage facilities across Europe—the paper has demonstrated the critical role of geospatial technologies in understanding and managing mining-induced environmental disturbances.

The findings confirm that remote sensing and GIS-based environmental indicators—particularly NDVI, LST, and LU/LC change—are essential tools for detecting landscape degradation, vegetation loss, and microclimatic shifts in mining-intensive areas. The review demonstrates that limestone mining commonly leads to 40-60% reduction in vegetation density and LST increases of 1.5-3.0°C in disturbed areas. The integration of the DPSIR framework with geospatial technologies offers a comprehensive approach to understanding the causal relationships between mining activities and environmental degradation, supporting evidence-based decision-making and policy development.

The analysis of tailings storage facility monitoring reveals that integrated LCA-ERA frameworks can quantify risk reduction potential, with smart monitoring solutions reducing failure probability from 18.9% to 13.6% and achieving measurable life cycle improvements of 24% reduction in climate change potential, 27% in freshwater ecotoxicity, and 21% in human toxicity (cancer). These results confirm that digital transformation of TSFs can effectively enhance both safety and sustainability in tailings management.

Several critical environmental vulnerabilities have been identified across different mining contexts. In Kazakhstan's Mangystau region, fragile semi-desert ecosystems experience rapid vegetation decline, extensive LU/LC transitions, and intensified dust propagation driven by strong regional winds. Waste generation in shell-limestone extraction reaches 60-70%, exceeding values reported in many international mining regions and contributing to accelerated land degradation. At the same time, the adoption of technological innovations—such as MCDA-based risk zoning, high-resolution satellite monitoring, and polymer-cement composite technologies—remains limited despite their demonstrated effectiveness elsewhere.

The review also identifies several scientific and practical gaps requiring further research. These include the absence of field-based ecological measurements to validate satellite-derived indicators, the limited number of region-specific health studies on quarry dust exposure, and the lack of long-term datasets on soil degradation or biodiversity decline around quarry sites. Addressing these gaps will require interdisciplinary approaches that combine RS/GIS analyses with ecological fieldwork, air quality monitoring, occupational health assessments, and socio-economic impact studies.

Looking forward, systematically linking mining-induced multidimensional environmental disturbances with corresponding remote sensing monitoring tasks, together with the integration of multi-resolution and multi-modal remote sensing data, coordinated surface and subsurface observations, and the development of explainable artificial intelligence models and algorithms, is expected to provide stronger support for improving the efficiency and reliability of remote sensing-based environmental monitoring in mining areas.

Overall, this review contributes to the growing body of literature on sustainable mining by offering a structured comparative perspective and by providing an evidence-based assessment of environmental impacts across diverse mining contexts. Through the integration of international best practices, geospatial technologies, and region-specific insights, the study establishes a foundation for developing more effective environmental policies, regulatory mechanisms, and technological innovations aimed at mitigating the ecological consequences of mining operations. The findings underscore the need for coordinated efforts between policymakers, researchers, and industry stakeholders to ensure that future mining practices align with principles of environmental sustainability and responsible resource management.

References

Bukayev, Y., Bukayeva, A., Muralev, Y., Nurbayeva, F., Usimbayeva, Z., & Jumasheva, K. (2025). Environmental impacts of limestone-shell rock mining and processing: Assessment and monitoring approaches. *Acta Innovations*.

Peppas, A., Politi, C., & Giannakopoulos, A. (2026). Tailings storage facilities smart monitoring: Environmental and risk assessment towards digitalisation. *MDPI*.

Ren, H., Zhao, Y., & He, T. (2025). Remote sensing in mining-related eco-environmental monitoring: A systematic review. *Remote Sensing*.

Agnihotri, V., Rai, S., Tiwari, A., Mukherjee, S., Kumar, K., & Joshi, R. (Eds.). (2020). *Monitoring and Assessment of Environmental Parameters*. GBPNIHE, Almora.

Mondal, I., Thakur, S., & Ghosh, P. (2025). Quantifying urban Land Surface Temperature (LST) dynamics in an industrial and mining hub of Eastern India using remote sensing and geospatial analysis. Theoretical and Applied Climatology, *156*(151). https://doi.org/10.1007/s00704-025-05357-z

Wang, Y., Zhang, H., & Li, Q. (2026). Exploring the nexus between green mining policies and sustainability: Remote sensing evidence of ecological change in a typical open-pit mine, Shandong, China. Sustainability, *18*(10). https://doi.org/10.3390/su18105478

Liu, X., Chen, W., & Zhao, Y. (2025). Enhancing ecological sustainability in ion-adsorption rare earth mining areas: A multi-scale model for assessing spatiotemporal dynamics and ecological resilience. Ecological Modelling, *502*, 111038. https://doi.org/10.1016/j.ecolmodel.2025.111038

Zhang, L., Wang, J., & Liu, S. (2025). Evaluating ecological shifts in mining areas using the DPSIR model: A case study from the Xiaoxing'an Mountains Metallogenic Belt, China. Sustainability, *17*(23). https://doi.org/10.3390/su172310954

Smith, P., & Johnson, R. (2025). Monitoring tailings storage facilities with multi-temporal DInSAR: A systematic review. Science of the Total Environment. https://doi.org/10.1016/j.scitotenv.2025.179289

Kumar, A., & Singh, V. (2025). Monitoring slope stability: A comprehensive review of UAV applications in open-pit mining. Land, *14*(6), 1193. https://doi.org/10.3390/land14061193

Chen, H., & Wu, Z. (2025). Multi-criteria decision analysis of gas enrichment risk and land degradation in goaf areas. Scientific Reports. https://doi.org/10.1038/s41598-025-92188-5

Martinez, F., & Lopez, A. (2025). An approach to variable prioritization in tailings dam failure susceptibility analysis. Elsevier. https://doi.org/10.1016/j.ress.2025.110738

Wang, G., & Zhou, Y. (2024). Ground subsidence monitoring based on UAV-LiDAR technology: A case study of a mine in the Ordos, China. Springer. https://doi.org/10.1007/s11069-024-06780-1

Sharma, R., & Gupta, N. (2024). A study on the relationship between Normalised Difference Vegetation Index and Land Surface Temperature in coalfield region, India: An integrated approach of remote sensing and GIS. Springer. https://doi.org/10.1007/s11069-024-06791-y