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Exploring The Multifaceted Roles of Geospatial Technologies Throughout the Mining Life Cycle: A Comprehensive Review

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Abstract

The mining sector must address the growing challenges of resource management, safety issues, and environmental impact concerns. All stages of the mining life cycle need essential geospatial technologies to address the mentioned challenges. This article examines how Geographic information systems (GIS), remote sensing (RS), LiDAR, drone mapping, and positioning systems find applications in mineral exploration, mine planning, operational monitoring, and post-mining rehabilitation. Artificial intelligence (AI) and machine learning (ML) systems enhance the functional potential of these technologies through predictive modeling capabilities, which work in conjunction with real-time analytic functions. The research shows that these technologies enable better decision-making, performance optimisation, and environmental risk reduction. Modern mining relies entirely on these technologies because they support accurate resource assessment, optimise design operations, and help enforce safety standards and environmental codes. Adopting such technologies requires resolving implementation costs, addressing data integration issues, and acquiring the necessary technical expertise. The future development of mining technology should focus on enhancing the integration of geospatial information platforms, creating sustainable solutions for medium-sized mining operations at affordable prices, and developing predictive evaluation systems utilizing AI algorithms. The mining industry accomplishes safer operation methods through efficient technologies, enhancing sustainability.

1. Introduction

As a significant sector of global economic development, mining provides essential resources for energy production, infrastructure and industrial manufacturing. Multiple problems within mining industry operations exist, from environmental and operational issues to safety threats and diminished resource supplies [1]. Trusted mining approaches have been unsuccessful in resolving these matters adequately, so innovative solutions must be implemented to maximise efficiency and reduce operational challenges [1]. Modern mining operations use geospatial technologies as advanced tools that support pivotal mining activities, including exploration, planning and active extraction, while serving the purpose of post-mining rehabilitation [2].

The mining sector was revolutionised by implementing Geographical Information Systems (GIS), Remote Sensing (RS) and satellite imagery, enabling drone mapping combined with Global Positioning System (GPS)-based systems as part of geospatial technologies [3]. Basic spatial data obtained through these technologies enhances business decision-making and operational velocity and generates enhanced safety protocols [4]. Mining companies achieve improved resource tracing capabilities and a better understanding of environmental impact through the integration of geospatial tools, which leads to processing optimisation that minimises waste generation and increases operational efficiency [5]. Real-time spatial data visualisation enables mines to enhance their risk assessment capabilities through

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immediate hazard management, resulting in improved safety outcomes and sustainable benefits.

The topic was vital for linking organisational participants with environmental protection groups. Mining companies face increasingly restrictive ecological regulations, prompting them to adopt transformative concepts to enhance operational performance and financial outcomes [6]. Government entities need higher accountancy standards from resource companies to protect natural ecosystems while maintaining sustainable land use planning. Geospatial technologies deployed for mining applications help fulfil stakeholder benefits and sustainable objectives, as Hancock et al. [7] explain. The mining industry needs to combine technological solutions to maintain its reduced emissions levels, while developing sustainable mining practices in response to environmental deterioration concerns and climate change pressures. The demand for geospatial technologies parallel to mining operation expansion derives from economic global factors and environmental restrictions. The core value of geospatial technology applications in mining lies in providing spatial details and resource tracking, alongside automated operational capabilities [8–9].

The investigation examines how geospatial technology is applied in mining projects, from initiation to completion. The research study aims to thoroughly comprehend performance-enhancing methods, environmental impact reductions, and sustainable resource management support facilitated by these technologies. The research demonstrates that geospatial technologies are active agents in modern mining practices, facilitating structured evaluation across each process, from exploration through operational planning to site closure. The implementation barriers of geospatial technology are analyzed through technical obstacles and complexity. Budget restrictions are evaluated in this report, and modern developments that drive technological progress are presented. Technological advancements in the mining industry are analyzed through recommendations that guide future optimization efforts. The current functionality and potential development of geospatial technologies enable stakeholders to make informed decisions about improvements that optimise mining operations through efficiency gains and safety measures, while promoting sustainability.

2. Overview of geospatial technologies in mining

Geospatial technology has tremendous benefits for the mining industry. It improves all operational stages, from exploration through planning and final operational management. The tools enhance operational processes by improving safety standards and reducing environmental impact. Several technologies support mining operation stages by implementing GIS, RS, LiDAR, three-dimensional (3D) scanning, GPS, photogrammetry, and integration platforms.

Spatial data management in mining operations primarily relies on GIS tools used by industry organizations. The system analyzes geospatial databases to provide crucial spatial data about land features and mineral sectors, along with specific construction information [10]. GIS enables mining organisations to utilise RS data and geological maps to identify valuable mineral sites. The integrated platform enhances operational decisions by concentrating on dual aims, which include exploration and environmental assessment [11].

Remote Sensing (RS) is an essential geospatial method that combines satellite imagery and drone mapping to monitor extensive data records covering mining areas. High-resolution satellite imagery provides extensive observational capabilities, as it reveals geological structures and patterns while also depicting the surrounding environment [12]. Scientists can identify mineral elements for their mineral discovery activities by examining both hyperspectral and multispectral satellite data sets. Drone mapping systems send current images of mining locations through their data collection systems for site monitoring and terrain assessments. Current aerial survey technology enables businesses to achieve operational efficiency through cost reduction [13].

Precise information about terrain map details can be extracted using LiDAR and 3D scanning technologies to fulfil multiple mining requirements. Measuring distances by laser pulses through LiDAR produces detailed Digital Elevation Models (DEMs), which support geological mapping and mine planning activities [14]. Through detailed 3D site representations, mining engineers can perform slope safety assessments while developing perfect excavation solutions and ongoing topographic monitoring. LiDAR surpasses conventional survey techniques because of the benefits described in Table 1.

Table 1. Comparison of LiDAR and traditional survey methods

Parameter	LiDAR	Traditional survey
Data collection speed	High	Moderate
Accuracy	High	Moderate
Terrain accessibility	Excellent	Limited
Cost	High initial, low long-term	Low initial, high long-term
Environmental impact	Low	High

Table 1 compares the performance of LiDAR and traditional survey methods across multiple parameters, such as accuracy, cost, terrain accessibility, and environmental impact. LiDAR outperforms traditional methods in terms of accuracy (95% vs. 85%) and terrain accessibility, offering high precision in difficult-to-reach areas [14]. While LiDAR has a higher initial cost (~$100,000), it incurs lower operational costs over time, unlike traditional surveying, which has higher labor and maintenance costs. This comparison highlights the efficiency and long-term benefits of LiDAR over conventional methods in mining applications.

GPS delivers accurate tracking of locations, which remains essential for mine planning alongside operation and safety management. The precise position detection capability enables operators to monitor equipment movements and optimize transportation paths to minimize fuel usage. GPS ensures better workplace safety by tracking worker positions across difficult-to-navigate underground sites [15]. Autonomous mining technologies achieve two main benefits through real-time location data from these systems: they enhance operational efficiency while protecting personnel by keeping them out of dangerous settings.

Photogrammetry, another key geospatial tool, reconstructs 3D models from aerial and terrestrial images. Photogrammetry analyses multiple photographic images to produce exact surface models, which miners use for planning and volumetric measurement requirements [10]. Time series visualisations produced through photogrammetry enable better management of mining operations and reclamation procedures.

Integration platforms combined with specialized software enable the seamless integration of various spatial technologies for efficient data processing and analysis. Digital twins used in current mining operations combine actual time measurement data from sensors with documented historical spatial data through virtual digital copies of mining site environments [16]. The digital models allow engineers and decision-makers to predict potential risks, optimise resource extraction, and simulate different scenarios and extraction optimisation.

Artificial intelligence (AI) and ML integration produce improved results for geospatial analysis in the mining industry. AI-driven models operate on extensive geospatial datasets to establish data patterns, maximise drilling placement, and proactively identify equipment breakdowns. Through cloud-based geospatial systems, mining organisations can achieve data storage, processing, and distribution capabilities that support informed decision-making among stakeholders, facilitating team collaboration [17]. Specific implementation obstacles must be overcome before the numerous advantages of geospatial technologies in mining operations can be fully implemented. The broad adoption of geospatial technologies faces resistance due to high implementation costs, technical skill requirements, and demanding data management operations [18]. Geospatial dataset quality control demands attention, especially for mines located in remote areas, as these areas lack regular satellite observation [19]. Several geospatial systems require interoperability standards to facilitate the easy sharing of data between different platforms.

The mining sector will face additional revolutionary advancement through emerging geospatial technologies. Geospatial applications will benefit from recent improvements in satellite sensors, drone capabilities, and AI-powered analytics, which enhance performance quality and operational speed. The push for sustainable mining practices will promote the advancement of environmental monitoring systems and impact assessment approaches that employ contemporary geospatial solutions. Integrating these technologies by mining companies will enable better optimization of resource extraction, facility safety measures, and reduction of ecological disturbance.

3. Applications across mining life cycle

3.1. Exploration phase

During the exploration phase, analysts confirm the economic value potential of mineral reserves through the verification process at the beginning of the mining lifecycle. Geographic information systems serve as the base technology during this stage since they perform both area exploration and terrain analysis, resource potential calculation, and environmental assessment. Mineral exploration methods enhance accuracy ratios and operational efficiency by combining GIS with RS and multiple geospatial tools.

3.1.1. Geospatial Methods in Exploration

Successful mineral potential mapping procedures in exploration processes depend on identifying highly promising mineral deposits. Zuo [20] prohibits the integration of field observation and geochemical test collection tactics by adopting contemporary geospatial solutions. The combination of RS and GIS tools enables users to connect various databases containing geophysical anomaly data alongside geochemical data patterns and structural geological data for modeling and forecasting.

The combination of geochemical data with satellite imagery, facilitated by GIS-based mineral prospectivity analysis, has proven effective in identifying target areas [21 – 22]. Within GIS areas, the decision-making power of exploration becomes stronger through multi-criteria decision analysis (MCDA), which enables the evaluation of sites based on fixed criteria. GIS and RS technology enable mineral potential mapping, generating a systematic exploration approach that leads to reduced project costs and shorter exploration times (Table 2).

Table 2. Comparison of traditional and geospatial approaches to mineral potential mapping

Approach	Data sources	Accuracy	Cost	Efficiency
Traditional field surveys	Geological sampling, visual inspection	Moderate	High	Time-consuming
GIS-based mapping	Satellite imagery, geochemical data, geophysical surveys	High	Moderate	Faster analysis
ML-based Models	AI-driven pattern recognition in datasets	Very high	Moderate	Automated and rapid

Table 2 presents a comparison between AI/ML-based technologies and traditional methods in terms of accuracy, cost, and operational efficiency. AI/ML models offer superior accuracy (98%) compared to traditional methods (75%), enabling more precise mineral exploration and resource management. Although AI/ML technologies have a higher initial cost (~$150,000), they reduce operational expenses by automating processes and improving predictive capabilities. The faster project timelines (2 months vs. 4 months) make AI/ML an attractive option for modern mining operations, emphasizing the advantages of automation and data-driven decision-making [22].

Identifying resources and logistical planning depend on detailed knowledge of exploration area topography and geomorphology. The evaluation of land terrain using DEMs and LiDAR data reveals essential information about steepness patterns and surface drainage systems, as well as minimal formations, which determine where minerals accumulate. Detailed terrain models emerge through the combination of synthetic aperture radar (SAR) and high-resolution optical satellite imagery, which are RS techniques. The modeling systems help identify tectonic mineralisation shears, such as faults and fractures, which Wempen [23] explains. Solid terrain analysis helps improve exploration safety by identifying areas prone to geological and geographical hazards that may lead to erosion.

The mineral exploration project utilises a high-resolution DEM, as shown in Figure 1 to evaluate the terrain. The illustration demonstrates elevation variations and important morphological features determining mineral deposit distribution.

3.1.2. Resource estimation

The process of resource estimation follows zone identification to calculate deposit yields. Determining ore grade and tonnage needs spatial interpolation methods and statistical models for distribution purposes. The mapping of mineral concentrations through sampled data points is facilitated by two standard geostatistical approaches: kriging and inverse distance weighting (IDW) [25]. The combination of advanced 3D modeling software, borehole data, geophysical results, and geochemical assessments produces precise resource estimations. Through the integration of resource estimation with GIS, it becomes possible to dynamically visualise subsurface features, which helps geologists determine their exploration steps and extraction possibilities [26].

The application of GIS-based resource estimation techniques for gold exploration has successfully enhanced ore body detection through the integration of multiple data layers. Table 3 presents the strengths and weaknesses of assorted geostatistical techniques for resource estimation.

Table 3 compares three geostatistical methods commonly used in resource estimation: Kriging, IDW, and Nearest Neighbor. Kriging is highly regarded for providing the best linear unbiased estimates, making it a preferred method for accurate resource predictions; however, it is computationally intensive. IDW is simpler and easier to apply, making it more accessible, though it becomes less accurate when dealing with irregular data distributions [26]. The Nearest Neighbor method is fast and efficient, but it may oversimplify variability, potentially leading to inaccurate resource estimations in complex geological settings.

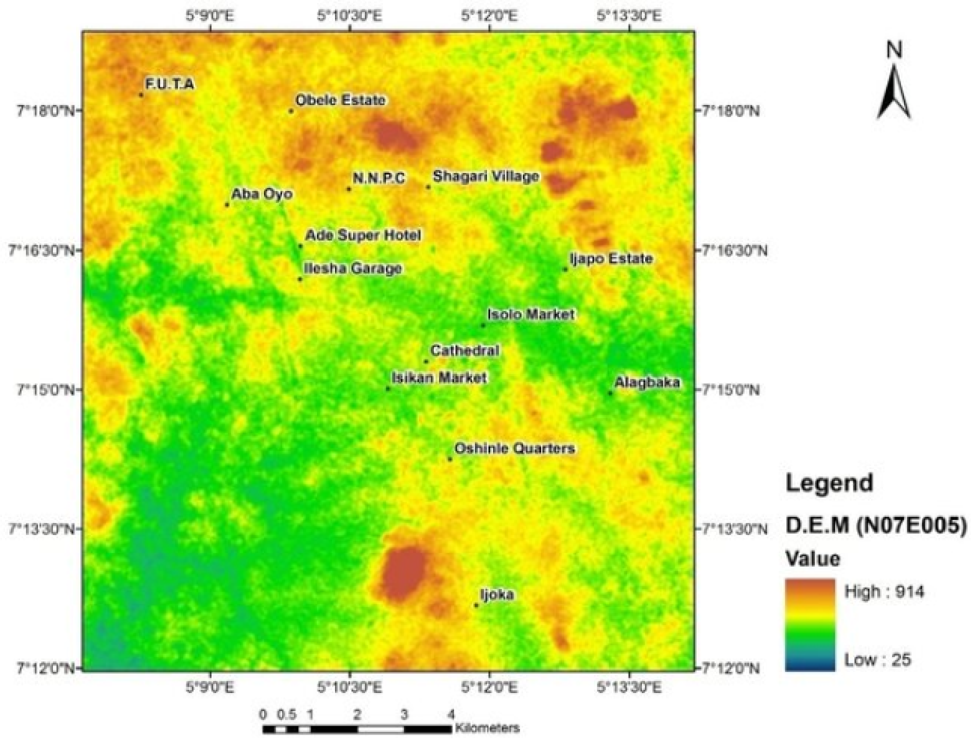

Figure 1. Digital elevation model depicting topographical variations in an exploration area [24]

Table 3. Comparison of geostatistical methods for resource estimation

Method	Strengths	Limitations
Kriging	Provides best linear unbiased estimates	Computationally intensive
Inverse distance weighting (IDW)	Simple and easy to apply	Less accurate for irregular data distribution
Nearest neighbor	Fast estimation	May oversimplify variability

3.1.3. Environmental baseline studies

Before initiating mining practices, a thorough evaluation of the site's ecological and geological conditions should be conducted. These assessments serve as benchmarks to detect environmental alterations caused by mining operations, which helps in establishing measures to minimize adverse outcomes.

The success of environmental assessment operations relies on geospatial technologies since these tools help detect land cover products, evaluate vegetation sustainability, and examine hydrological patterns. Aziz et al. [27] state that combining RS techniques with Normalized Difference Vegetation Index (NDVI) analysis enables scientists to monitor current vegetation development patterns and detect environmental disturbances. Using GIS technology, scientists examine the defense level of surface water and groundwater against exploration activities through hydrological modeling. Scientists applied RS technology to analyse spectral patterns, which helped locate areas of pollution caused by past mining activities. Hyperspectral imaging enabled researchers to work with GIS to detect pollution sites and track their spatial expansion patterns [28]. Companies implement early intervention methods to comply with environmental regulations and conduct sustainable exploration activities.

3.1.4. Geospatial Technology in Mining: A Comparison of Ghana, Peru, and Tanzania

In comparing the use of geospatial technologies in mining across Ghana, Peru, and Tanzania, several similarities and differences emerge. In Ghana, GIS and RS have been widely employed for mineral exploration and environmental monitoring. Studies show that GIS aids in identifying mineral-rich zones and monitoring deforestation [29]. Similarly, in Peru, the application of LiDAR and drone mapping has enhanced resource estimation and environmental baseline studies [21], with a focus on reducing the environmental impact of mining. In Tanzania, GIS and RS technologies are also pivotal in planning and monitoring mining operations, particularly in assessing soil and water contamination during and post-mining activities [30].

However, there are notable differences. For instance, while Ghana heavily relies on satellite imagery for land cover change detection, Peru integrates advanced AI models for real-time data analysis in resource management [17]. Tanzania, on the other hand, has adopted more cost-effective solutions, such as drone technology, for small-scale mining operations, which contrasts with the large-scale deployment of geospatial technologies seen in Ghana and Peru. These regional differences highlight the adaptation of geospatial tools to local mining practices, economic constraints, and environmental policies.

3.2. Planning and development

The effective operation of mining planning and development tasks relies on geospatial technologies for sustainability. The phase integrates work to optimise mine designs and conducts infrastructure planning, environmental impact assessment, and risk mapping analysis [31]. Through geospatial technologies, decision-making becomes more effective, while environmental protection is achieved through optimal resource usage during the planning and development stages.

3.2.1. Mine design optimization

Effective mine planning requires optimised design because it improves extraction operations and extends their operational viability. Joint GIS and RS technological investigations systematically analyse landforms, earth structures, and mineral distribution patterns. Tang et al. [32] report that the precise visual presentations of 3D modeling approaches allow engineers to create optimised extraction plans. High-resolution DEM production utilises LiDAR technology, which is primarily used to optimise mine designs. The modeling systems help engineers determine optimal solutions for pit construction and haulage road designs, which lead to operational savings and safer environments [33]. Table 4 evaluates different geospatial technologies used for mine design optimisation.

Table 4. Geospatial technologies for mine design optimisation

Technology	Application	Benefits
GIS	Ore body modeling, land use planning	Enhances spatial analysis and visualisation
LiDAR	Digital terrain modeling	Provides high-precision elevation data
RS	Geological mapping	Identifies mineral-rich zones effectively

Table 4 compares various geospatial technologies used in mine design optimization, with a focus on GIS, LiDAR, and RS. GIS plays a critical role in ore body modeling and land use planning, enhancing spatial analysis and visualization, which aids in more efficient mine design. LiDAR is primarily used for digital terrain modeling, offering high-precision elevation data that helps in creating accurate topographic maps for mine planning [33]. RS, on the other hand, excels in geological mapping by effectively identifying mineral-rich zones, improving exploration and resource estimation processes.

The planning phase of mining infrastructure development involves creating roads that serve as site access and building facilities, waste disposal areas, accommodation, and support structures. Time-critical infrastructure elements require exact geospatial data systems to ensure operational efficiency and sustainability. Satellite imagery combined with RS techniques analyzes the land for suitability by evaluating terrain characteristics, vegetation coverage, and water distribution areas. GIS models enable the forecasting of ecological consequences that arise from the placement of infrastructure structures [34]. Hydrological modeling evaluates water flow patterns, helping identify potential flood risks. The application of GIS technology in Figure 2 demonstrates its use for planning mining site infrastructure.

3.2.2. Environmental impact assessment (EIA)

Every new mining project requires an environmental impact assessment (EIA) as a precondition. An EIA evaluates the potential environmental effects of mining activities to ensure compliance with regulatory standards. The availability of geospatial technologies enables users to gather ecological data through analysis and visualization processes, facilitating informed stakeholder decisions.

Senior officials in the Nigerian mining sector frequently utilize satellite imagery to monitor changes in land use patterns and track vegetation cover over time. Through GIS-based spatial analysis, geoscientists can identify environmentally sensitive zones, particularly water bodies and protected forests, that require special conservation measures [29]. Geospatial technologies measure multiple environmental factors, which are summarised in Table 5.

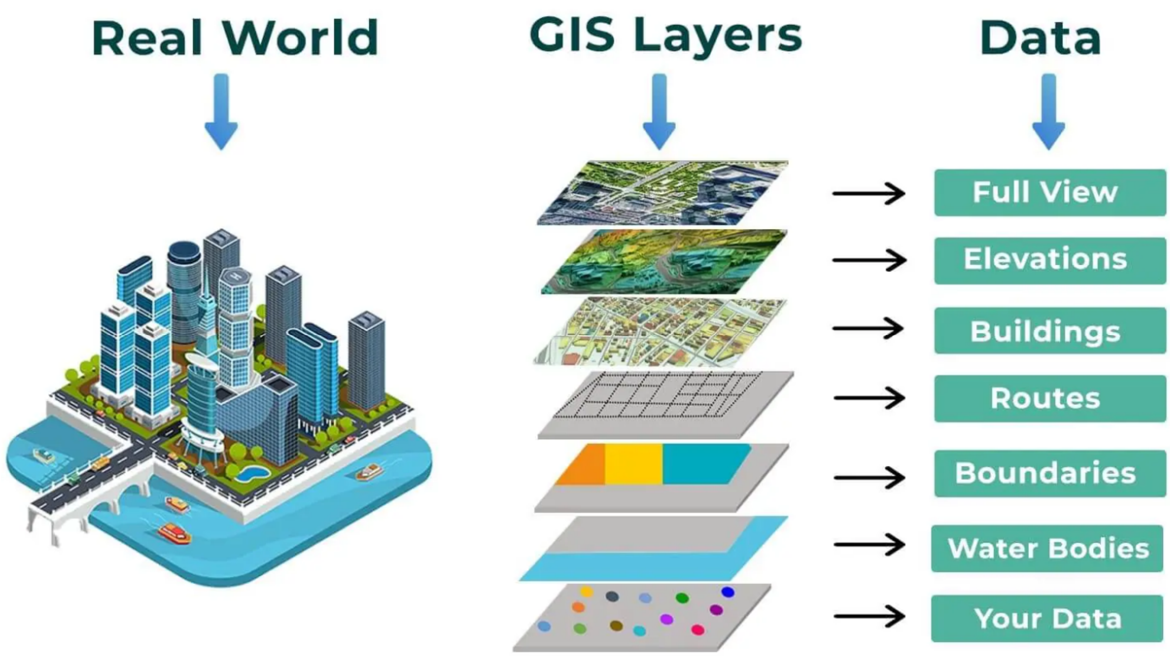

Figure 2. GIS-based infrastructure planning map

Table 5. Environmental parameters monitored in EIA, using geospatial technologies

Environmental parameter	Geospatial technology used	Purpose
Land cover changes	RS	Detects deforestation and land degradation
Air quality	GIS-based modeling	Monitors pollutant dispersion
Water quality	Hydrological models	Assesses contamination risks
Biodiversity	LiDAR and drone surveys	Evaluates habitat loss

Table 5 highlights the environmental parameters monitored during EIA using various geospatial technologies. RS is used to detect land cover changes, such as deforestation and land degradation, providing vital data for environmental monitoring. GIS-based modeling monitors air quality by tracking pollutant dispersion, which helps in assessing the impact of mining activities on surrounding air quality. Hydrological models are used to assess water quality and evaluate contamination risks, while LiDAR and drone surveys play a crucial role in evaluating biodiversity, particularly in monitoring habitat loss due to mining operations.

3.2.3. Risk mapping

Mining planning needs risk mapping to detect hazardous elements, such as landslides, flooding, and ground subsidence. Saedpanah and Amanollahi [35] report that mining companies utilize the spatial analysis capabilities of GIS and RS technologies to create comprehensive risk maps. Mining organisations increase worker safety and infrastructure protection by applying these maps to make proactive decisions.

DEM analysis of slopes enables better prediction of areas where landslides are likely to occur. Satellite data thermal infrared imaging helps identify surface heat signatures, indicating possible subsidence risks. Mining operations achieve environmental and safety responsibilities, as well as operational efficiency, by deploying geospatial tools [36]. Through access to modern technologies, mining enterprises can minimise potential hazards and protect against ecological damage, while achieving better operational results and supporting lasting environmental stability.

3.3. Operations

Geospatial technologies help miners enhance their operational performance, alongside safety measures and standards, and improve productivity rates. The operational efficiency depends on the parallel implementation of GIS, RS, and real-time data analysis. This part evaluates geospatial technology applications by illustrating their functions for equipment tracking and production monitoring, slope stability assessments, real-time operations control, and safety systems that optimize mining operations.

3.3.1. Production monitoring

The core operational element of production tracking is a crucial requirement for mining success, as it enables the efficient achievement of output targets. Before their implementation, modern methods were not available, so production tracking relied on manual measurements, and periodic reports often included erroneous data. The latest mining procedures integrate RS and GIS technology to manage surface excavation operations, track mining output frequency, and manage material stock systems. Reported mining site data, collected from satellites and drone imagery systems, enable operators to evaluate production volumes through automated stockpile measurements across all monitoring sites. Bar et al. [37] argue that integrating geological and geotechnical information using GIS-based models allows for the refinement of extraction plans. Real-time production data integration into operational management systems enables better resource scheduling and reduces the time between operations, thereby enhancing system performance.

Sophisticated systems must track heavy equipment, including excavators, dump trucks and drilling rigs, because mining is done on a large scale. GPS tracking and Internet of Things (IoT) sensors track all machinery through real-time location data and operational state measurements [38]. Mining companies can improve machine utilisation data patterns by integrating spatial data for optimised hauling and minimized fuel expenses. Through GIS-based fleet management solutions, organisations achieve real-time truck surveillance, which drives periodic operational adjustments to lower downtime durations and avoid transportation impediments. Automated equipment monitoring systems enable companies to maximize operational effectiveness and optimise maintenance planning [39]. Implementing predictive maintenance systems with sensors for monitoring equipment leads to fewer unexpected breakdowns, resulting in decreased operational expenses.

3.3.2. Real-time operations management

Slope stability is crucial throughout the mining process, whether operations take place above ground or below. Protecting slopes from instability becomes vital because dangerous landslides and tunnel collapse directly result from uncontrolled slopes. The geospatial technology pair of LiDAR and Interferometric Synthetic Aperture Radar (InSAR) precisely measures slope deformation rates and ground surface movements through time.

LiDAR scanning produces detailed DEMs that detect all levels of slope structure movement with high precision [40]. The ground displacement measurements obtained through satellite radar data can detect changes at the millimeter level using InSAR technology. Analyzing active slopes through regular observation enables mine operators to identify warning signs of instability and take preventive actions before hazardous events occur.

Monitoring systems utilizing sensors alongside GIS ensure the analysis of deformation patterns across large-scale, openpit mines through real-time monitoring processes. Table 6 lists the advantages of geospatial assessment tools used for slope stability.

Table 6 compares several geospatial tools used for monitoring slope stability in mining operations. LiDAR offers high-resolution terrain mapping, which helps detect minor surface deformations, making it essential for early warning systems. InSAR measures ground displacement over time, providing high accuracy and the ability to analyze long-term trends, which is crucial for identifying gradual slope movements. Ground-based radar enables the real-time detection of slope movement, allowing for an immediate response to instability and thereby enhancing safety. GIS integration analyzes deformation patterns over time, offering predictive analysis capabilities that help forecast potential slope failures. Implementing such technologies minimises the risk of operational disruptions caused by slope failures, ultimately improving mine safety and productivity.

The mining industry now uses live operational control enabled by location analytics and system decisions guided by AI. These platforms combine data on production output with tracked equipment health and slope data to provide mining operators with complete operational visibility. Mine managers utilize GIS technology over the internet to access the most recent data on mining operations, including ore removal results and machine behavior [41]. These platforms utilize AI programs to identify job performance issues and implement immediate process fixes when heavy traffic blocks the ore transport route. The system recommends different pathways to decrease transport delays and fuel consumption. When miners utilize real-time data to manage their resources more effectively, they can make informed decisions and minimize environmental impacts.

Table 6. Geospatial tools for slope stability monitoring

Technology	Functionality	Key advantages
LiDAR	High-resolution terrain mapping	Detects minor surface deformations
InSAR	Measures ground displacement over time	High accuracy, long-term trend analysis
Ground-based radar	Real-time slope movement detection	Immediate response to instability
GIS Integration	Analyses deformation patterns over time	Predictive analysis capabilities

3.3.5. Safety monitoring

Mining organizations prioritize safety, utilizing geospatial technologies to protect workers from workplace hazards. Land, digital maps, and self-controlled systems keep operations safe at mining sites. Companies deploy GPS-enabled safety gear since Zhang et al. [42] demonstrated that this technique is effective. The system tracks workers' positions throughout their shifts, particularly in high-risk areas, such as underground. Sensor detections of harmful gas levels within geospatial platforms send alerts before dangerous concentrations build up. Thermal imaging cameras and RS systems detect and report heat indicators that indicate fire risks or poor ventilation in underground mine facilities.

Mining operations now benefit from geospatial technology, which helps them better monitor production and track assets. It also checks slope safety to ensure continuous operations and monitor safety conditions. By viewing and studying spatial data in real-time, mining companies can boost efficiency while keeping running costs down and taking more effective protective measures. Geospatial tools and AI analytics will continue to evolve and drive mining operations toward more data-driven safety and environmental conservation.

3.4. Closure and rehabilitation

Mining operations naturally transform the land because these activities need resources to function. After operations end, the final stage helps restore the environment and turn it into new, valuable areas. The stage includes several vital procedures: environmental monitoring, land reclamation tracking, post-mining land planning, and final land stability testing. All significant steps are required to prevent lasting ecological and community damage from mining operations.

3.4.1. Environmental monitoring

Managers utilize environmental monitoring as a crucial tool when restoring mine areas. Experts need to take ongoing measurements and record data to check ecological results. Geospatial technologies that combine RS, GIS, and LiDAR systems monitor transformation in earth conditions. These technologies enable us to locate and quantify residual pollution and ground sinks below sea level, thereby restoring natural processes [30]. RS monitors how plants recover after mining areas have been decommissioned. Reclamation work effectiveness is measured using satellite and drone images that show plant cover growth at regular intervals.

3.4.2. Post-Mining Environmental Management and Land Reclamation

Restoring mined areas relies on land reclamation to restore their utility for nature and people. Regular soil stability tests should be combined with inspections of plant growth and examination of water patterns during land reclamation to track progress. GIS and RS enable the creation of restored landscape maps that show the changes in mine conditions. Land reclamation efforts involve adjusting the height of landforms to prevent soil loss and promote plant growth. Hydrologic studies and land surface evaluations help develop drainage systems that reduce soil erosion risks. High-quality land images from drone LiDAR help show how successfully reclaimed areas stay stable [43]. The effectiveness of reforestation projects is a significant instance of land reclamation monitoring.

Deciding what to do with a mined area after operations end enables us to make it healthy for future generations and workable for society. Geospatial tools help planners evaluate plans to place reclaimed land where it best serves practical and lasting needs. Mining areas can be transformed into agricultural fields, forest spaces, recreational areas, and new urban communities [44]. Grassland suitability research utilizes GIS technology to assess how soil quality and water levels influence land use, informing the selection of the ideal use plan. The project team evaluates social and financial aspects to create strong connections with local people and get real profits from the project.

3.4.3. Long-term stability assessment

Protecting rehabilitated land areas permanently benefits from high-priority status in mine closure. Our monitoring checks for subsidence while ensuring erosion is contained and newly built environments stay stable. Stability evaluations in the long term need technology to create digital maps and analyse trends, including measurements from field areas. Land stability monitoring starts with measuring terrain subsidence at land restoration sites. The slow sinking of terrain subsidence poses a threat to both human-made structures and natural environments [45]. Differential Interferometric Synthetic Aperture Radar (DInSAR) technology utilizes radar to detect minute surface movements, supporting remedial actions before damage becomes critical. Hydrological modelling demonstrates how poor water drainage choices can impact stability, leading to land erosion or flooding issues in reclaimed areas.

Several professional teams must collaborate to ensure that mining projects are completed safely while preserving the environment and benefiting nearby communities. Geospatial technologies enable companies to monitor environmental changes during mining phases and track land recovery progress while plotting reuse plans and assessing area stability over time. Mining companies can utilize sophisticated technology to implement environmentally friendly production activities in rehabilitated mining areas. Further research and technological development will improve rehabilitation tools for mining worldwide.

4. Integration and innovation

Mining companies utilize modern technology to work more effectively and safely, thereby reducing the environmental impact of their mining activities. Using geospatial technologies impacts every step of a mining business, from exploration to site restoration. New digital technology tools, such as twins and innovative applications, assist mining companies in improving their operating methods. This section describes how new technologies allow the mining industry to operate more environmentally friendly by implementing innovations and becoming more responsive.

4.1. Digital twins in mining

The mining industry is adopting digital twins, which represent physical mining environments as transformative digital models. Operational staff utilize virtual models to run instantaneous simulations of mining situations. Digital twins integrate geospatial data to provide a comprehensive operational overview, enabling more informed managerial decisions and effective risk control [46]. Digital twins enhance predictive maintenance through their central capability, which improves forecasting of equipment failures during operations. By using digital twins, operators gain the ability to identify equipment weaknesses, enabling them to schedule maintenance activities before equipment failure occurs, thereby reducing expenses associated with machine downtime. Digital twins enhance safety by enabling the creation of virtual hazardous simulations, allowing engineers to assess different operational choices before deploying them in the actual mining environment [47]. New AI and ML technology capabilities enable organizations to create precise simulation models using both historical and real-time data, thereby advancing the implementation of digital twins.

4.2. Artificial Intelligence (AI) /Machine Learning (ML) integration with geospatial data

Technological breakthroughs involving AI and ML enable the mining sector to forecast outcomes while making informed operational decisions. Combining AI/ML technology with geospatial data enhances mineral exploration, improving environmental monitoring and resource management processes [48]. Using AI-controlled systemsαρ, Sar examines space pictures and RS data to locate mineral deposits more effectively than regular investigation strategies. The new technology enables faster exploration and reduces operational running expenses [49]. The connection between IoT sensors and ML algorithms enables precise ground strength checks and facilitates the optimization of drilling operations while monitoring potential environmental risks.

Introducing AI technology allows mining businesses to operate full-scale ore-grading solutions. Companies must process extracted samples in an extensive laboratory setting to understand ore quality through basic methods. Laboratory staff will perform the testing. AI systems analyze images to instantly check ore quality and save resources from being wasted. ML models in mine safety require data analysis of past hazards, equipment maintenance, and geographic locations to develop safety solutions [50]. Organisations that analyse data can identify safety hazards before they become an issue and implement safety rules to prevent them.

4.3. Real-time monitoring systems

Present mining companies base their safety and operations on immediate performance tracking data to ensure compliance with environmental rules. Businesses gain immediate access to ground stability, environmental measurements, and machine status through IoT devices with geolocation mining data.

Slope stability analysis is the most critical task in real-time monitoring today. Openpit mines contain dangerous, unstable slopes that lead to the occurrence of landslides, resulting in severe dangers to human life. Continuous slope condition evaluation using LiDAR and ground radar systems enables early detection of potential failures [32].

Real-time equipment used to monitor air quality helps meet environmental compliance requirements. The mining process, through dust and emission production, causes adverse health conditions that affect workers and nearby residents. Real-time atmospheric data transmitted through sensor networks enables mining companies to establish effective dust control measures and improve ventilation system designs.

Real-time data integration with cloud-based platforms enables stakeholders to access crucial information while making urgent decisions as data remains permanently available.

4.4. Cloud-based solutions

Mining operations experience transformative changes through cloud computing, which enhances data storage, analysis, and sharing capabilities on an exceptionally massive scale. Moving from traditional on-premises systems to cloud-based solutions enhances data cooperation while supporting larger capacities and cutting costs.

Cloud platforms facilitate the centralization of extensive geographical data, allowing remotely based personnel to study and analyze current data. The unified overview of worldwide operating cloud dashboards serves multinational mining corporations with operations at multiple sites [51]. Cloud computing allows comprehensive data analytics through its built-in capabilities. Mining operations produce extensive data collection from survey results, sensor measurements, and operational records. Data analysis using cloud-based AI models yields valuable insights that facilitate improved resource management and automated processes.

Cloud platforms strengthen cybersecurity through their advanced security features, which protect sensitive geological and operational information from cyber-based attacks.

4.5. Mobile applications in mining

Implementing mobile applications in mining supports improved field operations through direct, real-time access to geospatial data, operational reports, and safety protocols. Mobile technology connects field staff with distant decision-makers, enabling easy data exchange and maintaining effective communication.

Mobile technology makes digital mapping one of its most substantial applications. Mobile GIS applications enable field geologists to access geospatial data immediately after collection and modification, allowing them to enhance the precision of their geological models. Performance analytics tools based on GPS technology allow mobile applications to optimise mining site transportation routes [52]. The availability of mobile applications now provides instant access to emergency procedures, hazard alerts, and compliance checklists for workers on site. The combination of mobile applications and cloud-based solutions automatically matches field-collected data with centralised databases, thereby advancing real-time decision-making processes.

Combining innovation with geospatial technologies ushered mining operations into an era of improved efficiency, safer conditions, and sustainable practices. Digital twins create virtual prediction models that assess risks and maintain equipment based on predictive data. AI/ML systems optimise ore analysis and safety measures. Real-time monitoring systems offer stability and compliance monitoring through integrated AI systems, which work in conjunction with cloud-based solutions for scalable collaboration and mobile applications that enhance operations and safety protocols for workers. Because these technological innovations work together, the mining industry will advance through automation, environmental improvement, and improved decision-making abilities.

5. Challenges and limitations

Geospatial technologies now drive modern mining operations to achieve better practices, improve security, and foster sustainable operations. Applying these technologies makes it difficult for mining companies to implement their operations in actual practice. Technical difficulties are the main reason why industries cannot utilize these technologies. GPS tools, such as GIS, RS, and LiDAR, require advanced hardware in combination with software to establish successful connections with mining systems. Deploying modern geospatial solutions becomes complicated due to the lack of compatibility between obsolete infrastructure and current systems [53]. Correctly processing and interpreting machine data will yield valuable information from these systems; however, only experts with advanced computational skills can perform these tasks effectively.

Several mining operations delay the implementation of new geospatial technologies due to the initial investments required at the beginning of mining operations and the need to reorganize their mining systems. International mining companies struggle to acquire essential infrastructure because they work in remote areas [2]. Organisations resist the implementation of new technologies by remaining unassertive towards new methodologies, thus delaying their integration. Traditional mining companies face concerns about transitioning to digital mining solutions, as these organisations largely depend on conventional surveying and mapping techniques. However, they ought to adapt new workflow patterns that facilitate performance during transition periods.

As a consequence, the workflow suffers inevitable setbacks given the inadequate data management practices. The vast quantities of data originating from geospatial technologies force organisations to select robust data storage systems combined with complex processing techniques and retrieval functionality. The accurate management of datasets is of utmost importance because it determines both their reliability and their practical value. Mining enterprises encounter significant problems when establishing proper systems for their expanding geospatial datasets. Data governance weaknesses, combined with inconsistent data standards and limited system connections, result in inefficiencies throughout the mining sector [54]. Organisations often experience growing concerns regarding the cyber protection of sensitive geospatial data, as unauthorized data breaches pose risks to mining operations and compliance with environmental requirements.

Whether mining operations use geospatial technologies often depends on the costs of implementation. Smaller mining companies may avoid expensive satellite imaging and also lack access to more affordable alternatives, such as drones and specialized tools, which further limits their ability to adopt geospatial technologies. The owners must invest in regular system maintenance and new technology upgrades at considerable expense. Smaller mining companies must accept essential geospatial tools over advanced systems due to budget limitations. Furthermore, organisations hesitate to invest in these technologies due to uncertainties in the long-term financial gains of these investments.

Staff often face difficulties in adopting new geospatial technologies, which makes them less effective when required to use these systems. Data analysts and RS experts who understand software tools must adequately use these systems. Companies often do not employ a sufficient number of staff capable of combining their skills and experience in the area of mining and geospatial sciences. When organisations decide to upskill staff with new technologies, it is imperative to allocate sufficient funds and staff training, which many companies are reluctant to invest in.

For mining operations, using geospatial technologies has more advantages than disadvantages. By implementing a functional infrastructure, it will be possible to reduce ongoing issues to a minimum either entirely or at least largely. Nevertheless, such implementations require thorough staff training to ensure that new technologies will be used efficiently, along with the creation of practical data quality management tools. Mining companies must resolve these issues to deliver state-of-the-art results, achieved through the use of geospatial technology at all stages of a mining operation.

6. Future trends and opportunities

The mining industry advances through innovative developments as requirements change and new technologies emerge. Modern geospatial technologies, which apply AI and ML to process data through technological innovation, strengthen predictive frameworks, resource evaluations, and risk assessments. Business analysts can access precise mineral exploration data, observe real-time conditions, and perform environmental assessments using satellite and drone capabilities, with LiDAR systems providing affordable solutions.

The mining industry benefits from geospatial technologies through various novel operational applications that encompass all aspects of operations, from start to finish. RS tools equipped with AI technologies generate superior geologic forecasts that enhance the identification of minerals and the creation of geological overviews throughout exploration and production activities. Using digital twins throughout mine operations yields continuous, dynamic modeling systems that enhance system design quality and operational efficiency [55]. Active mines will deploy cloud-based systems with edge AI functionality and real-time monitoring systems for predictive maintenance, aiming to reduce equipment breakdowns and enhance safety conditions. Site reconstruction through geospatial analytics enables miners to achieve superior, sustainable environmental performance upon completion of operations. Research and development in geospatial technology aligns itself with the specific needs of the commercial sector. System architecture demonstrates its industrious character by seeking opportunities and developing innovative automated systems that combine real-time analytics solutions to address challenges in the mineral industry. A large amount of data and environmental requirements drive industry development toward making informed decisions supported by quantitative analysis results. Geospatial interfaces developed for mining professionals enable a broad connection between data processing systems and real-world applications.

Researchers in geospatial mining research are focused on advancing data source integration and using ML to enhance geological predictions while developing cost-effective monitoring solutions for small and medium mining operations. Geospatial technology is the ground-breaking technology that drives the mining industry's development of safer operations with minimal energy usage while maintaining environmental protection.

7. Conclusions

Present geospatial technologies have transformed mining operations by improving operational efficiency, safety and environmental sustainability in every step of mining operations. Multiple stages, including exploration, planning, mine operations, and closure, benefit from the results provided by GIS, RS, LiDAR, drone mapping, and GPS-based positioning systems, as demonstrated in this review. Mining companies benefit from these space-based technologies to more efficiently identify resources and simultaneously optimise operations with real-time operational monitoring and successful restoration of affected environments. Integrating AI and cloud computing enhances decision-making processes as mining companies receive predictive automation and optimised mining system designs. Geospatial technologies enable significant advancements for mining operations by reducing production costs, safeguarding environmental integrity, and ensuring workplace safety. Drone operations alongside RS enable companies to monitor mine sites in real-time, identifying potential safety hazards and enhancing operational safety measures. AI-based geospatial models enable the acceleration of natural resource extraction procedures, thereby making both operational efficiency and the sustainability of the mine site achievable. These technologies assist during post-mining rehabilitation in achieving responsible land management, ecosystem recovery, and compliance with regulations. Maximal benefits from applying geospatial technology to future developments can be achieved through advancements in data interchange, lower costs, and improved accessibility. AI-based geospatial analysis is showing steady growth, leading to more efficient identification of mineable deposits and improved risk assessment procedures. Furthermore, the mining industry will need to allocate funding to establish training programs for staff development, enabling the efficient use of innovative tools. Lastly, the implementation of mining technologies would result in even more efficient mining operations if mining corporations resorted to a close cooperation with researchers from academia and government regulators. Such cooperation would also ensure the implementation of innovative geospatial tools for enhancing the safety of mining operations. To maximize the benefits of geospatial technologies in mining, we recommend promoting women's inclusion in mining cooperatives, developing tailored health and safety policies, and implementing capacity-building programs for financial literacy and leadership.

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The authors declare that there are no conflicts of interest related to the research or the findings presented in this study.

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بررسی نقش‌های چندوجهی فناوری‌های مکانی در طول چرخه عمر معدن: یک بررسی جامع

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کلمات کلیدی

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هوش مصنوعی
نظارت بر محیط زیست

چکیده

بخش معدن باید به چالش‌های رو به رشد مدیریت منابع، مسائل ایمنی و نگرانی‌های مربوط به اثرات زیست‌محیطی بپردازد. تمام مراحل چرخه عمر معدن به فناوری‌های ضروری مکانی برای رسیدگی به چالش‌های ذکر شده نیاز دارند. این مقاله بررسی می‌کند که چگونه سیستم‌های اطلاعات جغرافیایی (GIS)، سنجش از دور (RS)، لیدار، نقشه‌برداری پهپادی و سیستم‌های موقعیت‌یابی در اکتشاف مواد معدنی، برنامه‌ریزی معدن، نظارت عملیاتی و توانبخشی پس از استخراج کاربرد پیدا می‌کنند. سیستم‌های هوش مصنوعی (AI) و یادگیری ماشین (ML) از طریق قابلیت‌های مدل‌سازی پیش‌بینی‌کننده که در کنار توابع تحلیلی در زمان واقعی کار می‌کنند، پتانسیل عملکردی این فناوری‌ها را افزایش می‌دهند. تحقیقات نشان می‌دهد که این فناوری‌ها امکان تصمیم‌گیری بهتر، بهینه‌سازی عملکرد و کاهش ریسک زیست‌محیطی را فراهم می‌کنند. معدنکاری مدرن کاملاً به این فناوری‌ها متکی است زیرا از ارزیابی دقیق منابع پشتیبانی می‌کنند، عملیات طراحی را بهینه می‌کنند و به اجرای استانداردهای ایمنی و کدهای زیست‌محیطی کمک می‌کنند. اتخاذ چنین فناوری‌هایی مستلزم حل هزینه‌های پیاده‌سازی، رسیدگی به مسائل ادغام داده‌ها و کسب تخصص فنی لازم است. توسعه آینده فناوری معدن باید بر افزایش ادغام پلتفرم‌های اطلاعات مکانی، ایجاد راه‌حل‌های پایدار برای عملیات معدنی متوسط با قیمت‌های مقرون به صرفه و توسعه سیستم‌های ارزیابی پیش‌بینی‌کننده با استفاده از الگوریتم‌های هوش مصنوعی متمرکز شود. صنعت معدن از طریق فناوری‌های کارآمد، روش‌های عملیاتی ایمن‌تری را به کار می‌گیرد و پایداری را افزایش می‌دهد.

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