ADVANCES IN REMOTE SENSING AND GIS APPLICATIONS FOR SUSTAINABLE MINE PLANNING: A REVIEW

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ABSTRACT

The use of Remote Sensing (RS) and Geographic Information Systems (GIS) has become an indispensable tool for enhancing the sustainability of mine planning and environmental management. Recent developments in the use of RS and GIS in mineral exploration, geological mapping, mine site selection, production planning and environmental monitoring are highlighted. It also addresses the challenges of using emerging technologies like Artificial Intelligence (AI), Unmanned Aerial Vehicles (UAVs), LiDAR, Internet of Things (IoT), cloud computing and Digital Twins, which support decision making and operational efficiency. The review highlights potential future research directions for the creation of intelligent and sustainable geospatial frameworks and pinpoints challenges such as high data acquisition costs, data integration issues, and technical constraints. In general, RS and GIS integration with advanced digital technologies has great potential to enhance the efficiency of mining activities, environmental protection and sustainable use of resources.

Keywords: Remote Sensing, Geographic Information System (GIS), Sustainable Mine Planning, Environmental Monitoring, Artificial Intelligence, UAV, LiDAR, Mining.

1. INTRODUCTION

Mining is an important sector for the world economy, supplying the raw materials required to build infrastructure, generate energy, produce manufactured goods and develop new technologies. Mining activity has grown in scale and complexity as demand for mineral resources continues to rise, posing environmental and social issues. Traditional mine planning methods, largely based on field surveys, manual mapping and limited spatial analysis, can be time-consuming, labor intensive and ill-equipped to deal with the changing demands of contemporary mining. These traditional approaches might also not be able to help in providing timely information for making effective decisions, which would have a negative impact on the operational efficiency or environmental sustainability.

The concept of a sustainable mine planning is receiving a lot of attention in recent decades, as governments, regulators and mining companies are increasingly aware of the need to balance the use of the mineral resources with the conservation of the environment and social responsibility. Sustainable mine planning focuses on the optimal use of natural resources and on minimising any detrimental impacts on land, water, air quality, biodiversity and surrounding communities throughout the life cycle of the mine. These goals can only be met if spatial information; continuous environmental monitoring and advanced decision-support systems are available that can integrate a variety of data sources.

Figure 1: Advances in Remote Sensing and GIS Applications for Sustainable Mine Planning

In recent years, RS and GIS have become essential geospatial technologies in contemporary mining activities. The RS also is a technology that provides spatial and spectral data of the Earth's surface without direct contact using satellite, aerial and unmanned aerial vehicle (UAV) platforms. These technologies enable detection of mineralization, geological structures, changes in land use and land cover, surface deformation, vegetation health and environmental disturbances, across vast geographic regions. The accuracy and spatial resolution of mining related investigations has improved greatly with the advent of satellite sensors, hyperspectral imaging, LiDAR and high resolution drone imagery, as well as the increased temporal coverage.

It is to be remembered that GIS augment RS through the integration and analysis of spatial data from various sources to aid in mine planning, environmental assessment and decision making. The application of AI, ML, UAVs, LiDAR, IoT, cloud computing and Digital Twin technologies has also enhanced real-time monitoring, predictive analysis, resource optimization and sustainable mining operations, while minimizing environmental risks.

1.1. Objectives of the Review

The present review aims to:

- **To review** recent advances in Remote Sensing (RS) and Geographic Information System (GIS) technologies applied to sustainable mine planning.
- **To examine** the applications of Remote Sensing and GIS in mineral exploration, geological mapping, mine site selection, resource assessment, and operational mine planning.
- **To evaluate** the contribution of geospatial technologies to environmental monitoring and sustainable mining through land use and land cover analysis, water resource assessment, vegetation monitoring, EIA, and mine reclamation.
- **To identify** emerging technologies, current challenges, and future research directions for enhancing the integration of RS and GIS in sustainable and environmentally responsible mine planning.

2. FUNDAMENTALS OF REMOTE SENSING AND GIS IN MINING

Geospatial technologies are widely being used in the mineral industry and their use is growing rapidly due to the need for sustainable and efficient mining. Of these technologies, RS and GIS are crucial for acquiring, managing, analysing and interpreting spatial information across the mining life cycle. When combined, they deliver full strength geospatial intelligence for mineral exploration, mine planning, environmental assessment, and operational management, as well as land reclamation post mining. To understand these technologies and appreciate their applications in sustainable mining, one needs to understand the basic principles.

Figure 2: Revolutionizing Mineral Exploration through Remote Sensing and GIS

- **Principles of RS:** The information obtained by RS about the Earth's surface is due to the use of sensors carried on satellites, aircraft or UAVs that have no physical contact with the surface. Multispectral and hyperspectral imagery is used for accurate geological mapping, mineral exploration and environmental monitoring using passive and active sensors such as SAR and LiDAR.
- **Geographic Information Systems (GIS):** GIS are a tool that brings together, manages, analyses and visualizes spatial information to aid in mine planning and decision making. GIS integrates several thematic data sets and uses various spatial analysis methods to maximize mine site selection, transportation, environmental assessment and operational planning.
- **Data Sources Used in Mining:** Mining tools have been found to use a variety of geospatial data sources such as satellite imagery, LiDAR, UAVs, GPS, and field surveys. The datasets are accurate for use in geologic mapping, terrain analysis, planning of infrastructure for mines, slope stability analysis, and environmental monitoring.
- **Integration of RS and GIS:** The integration of RS and GIS is a fully-fledged system for acquisition, processing, analysis and interpretation of geospatial data. This integration is utilized in the fields of mineral exploration, environmental monitoring, mine planning, change detection, and intelligent decision making, all of which benefit safer, more efficient and sustainable mining operations.

Table 1. Summary of Selected Literature on RS and GIS Applications in Sustainable Mine Planning

Author(s)	Research Title	Topic Covered
Batur, M., & Hovorukha, O. (2026)	GIS in Mining: A Comprehensive Review and Bibliometric Analysis of Applications, Challenges, and Future Directions	Comprehensive review of GIS applications in mining, including mine planning, environmental monitoring, research trends, challenges, and future directions.
Moomen, A. W., Bertolotto, M., Lacroix, P., & Jensen, D. (2019)	Inadequate Adaptation of Geospatial Information for Sustainable Mining Towards Agenda 2030 Sustainable Development Goals	Application of geospatial information in sustainable mining, environmental management, resource optimization, and alignment with Sustainable Development Goals (SDGs).
Mandla, V. R., Zhu, X., Tiwari, A., & Shoab, M. (2025)	Emerging Trends and Advancements of Geoinformatics Applications in Earth and Environmental Systems	Emerging developments in RS, GIS, *AI*, UAVs, cloud computing, and geoinformatics for environmental and resource management.
Li, T., Desta, F., & Buxton, M. (2026)	Recent Advancements in Digital Management and Monitoring of Mine Waste: Sensors, Characterization, and Predictive Modeling—A Review	Digital technologies for mine waste monitoring, including sensors, predictive modelling, environmental monitoring, and intelligent waste management systems.
Musiałek, M., & Maksymowicz, M. (2024)	Remote Sensing in Mining: A Brief Overview and Examples	Applications of RS technologies in mineral exploration, geological mapping, mine planning, and environmental monitoring.

3. RECENT ADVANCES IN REMOTE SENSING AND GIS APPLICATIONS FOR MINE PLANNING

The mine planning process has been revolutionized by the rapid progress made in the use of RS and GIS technologies, which have enabled the collection of accurate spatial information for mineral exploration, mine design, operational management and environmental monitoring. The use of technology, including satellite imagery, UAVs, LiDAR, AI and cloud computing, has benefited planning efficiency, optimized resource use, safety and sustainable mining practices in decision making.

- **Mineral Exploration and Resource Mapping:** Using satellite imagery and spatial analysis, RS and GIS can help identify mineral deposits, geological features, and alteration zones, aiding mineral exploration. The advanced techniques such as hyperspectral imaging, MCDA and AI-based models improve the mineral prospectivity maps and exploration efficiency.
- **Geological and Structural Mapping:** High resolution satellite imagery, SAR, LiDAR and GIS can assist in geological and structural mapping by detecting faults, folds, and lithological boundaries. These technologies provide advancements in geological interpretation and minimize uncertainty of mine planning.

- **Mine Site Selection:** RS and GIS can help with the selection of mine sites by integrating geological, environmental, and socio-economic considerations, as they are analyzed and evaluated in a spatial context and through multi-criteria decision-making, allowing for sustainable and efficient mining operations.
- **Open-Pit and Underground Mine Planning:** Geospatial technologies are used to assist with mine planning using the following methods terrain modelling, 3D visualization, pit optimization, infrastructure planning, and underground mine management, which leads to efficient and collaborative mine operational planning.

Table 2. Major Remote Sensing and GIS Technologies and Their Applications in Sustainable Mine Planning

Technology	Primary Function	Major Applications in Mining	Key Advantages
Remote Sensing (RS)	Acquisition of spatial and spectral data	Mineral exploration, geological mapping, environmental monitoring	Large-area coverage, repetitive observations, rapid data collection
Geographic Information System (GIS)	Spatial data management and analysis	Mine site selection, route optimization, resource assessment, decision support	Efficient spatial analysis and data integration
UAV (Drone)	High-resolution aerial surveying	Topographic mapping, stockpile estimation, slope monitoring	High accuracy, flexibility, cost-effective surveys
LiDAR	Three-dimensional terrain mapping	Terrain modelling, volumetric analysis, slope stability assessment	Accurate elevation data and 3D visualization
Artificial Intelligence (AI)	Automated data analysis	Mineral prospectivity mapping, predictive mine planning	Improved accuracy and faster decision-making
Cloud Computing (GEE)	Large-scale geospatial data processing	Land use analysis, environmental monitoring, change detection	Rapid processing and easy accessibility
Digital Twin	Virtual simulation of mining operations	Production planning, operational optimization, predictive maintenance	Real-time monitoring and intelligent decision support

4. APPLICATIONS IN SUSTAINABLE MINING AND ENVIRONMENTAL MONITORING

To ensure sustainable mining, it is necessary to monitor the environment continuously to reduce the impact of mining activities on land, water, vegetation and air quality. The application of RS and GIS, technologies based on satellite imagery, UAVs, LiDAR and hyperspectral sensors have contributed to the enhancement of environmental assessment and monitoring. The geospatial technologies allow for precise assessment of the environment, ensuring compliance with regulations, improving the management of resources and making informed decisions for sustainable and environmentally responsible mining practices.

- **Land Use and Land Cover Change Detection:** Monitoring land use change, vegetation loss and land degradation as a result of mining using RS and GIS for environmental assessment and restoration.

- **Environmental Impact Assessment (EIA):** Geospatial technologies enhance EIA through the ability to identify sensitive areas, assess the impact and contribute to sustainable mine planning.
- **Water Resource Monitoring:** RS and GIS are used to monitor surface and groundwater quality, drainage systems and contamination risks for good water resource management.
- **Vegetation and Biodiversity Assessment:** These technologies measure vegetation health, biodiversity and ecological restoration to aid in assessing the effectiveness of the mine rehabilitation.
- **Air Quality and Dust Monitoring:** RS and GIS are used to monitor air quality and dust emissions, and the integration of IoT allows for real-time monitoring of environmental conditions and controlling pollution.
- **Mine Waste and Tailings Monitoring:** Geospatial tools can identify structural instability, surface deformation, and contamination risks, aiding in the safe management of mine waste and tailing water.
- **Land Reclamation and Mine Closure Planning:** RS and GIS can aid in the restoration of land after mining, recovery of vegetation and planning for sustainable closure of mines.
- **Carbon Footprint and Sustainable Mining Indicators:** Geospatial technologies are used to measure and monitor carbon emissions, resource use and environmental impacts to facilitate carbon resiliency and sustainable mining.

5. EMERGING TECHNOLOGIES, CHALLENGES, AND FUTURE RESEARCH DIRECTIONS

Digital technologies have undergone incredible development in recent years, and the contribution of RS and GIS to sustainable mine planning is now greatly improved. The use of emerging technologies like AI, ML, UAVs, LiDAR, IoT, cloud computing, and Digital Twins ensures continuous monitoring, predictive analytics, and smart decision making.

- **Artificial Intelligence and Machine Learning Integration:** AI and ML have the potential to greatly improve geospatial analysis by automating the processing of vast amounts of spatial data. Random Forest, SVM, ANN, and CNN are some of the advanced algorithms that are well capable of making accurate and efficient decisions, providing favorable outcomes in mineral exploration, land cover mapping, environmental monitoring, and predictive mine planning.
- **UAV-Based RS:** UAVs are used for high resolution, low cost and fast-data-acquisition, which are ideal for the mining application. These tools assist in topographic mapping, stockpile estimation, slope stability assessment, infrastructure inspection and environmental monitoring, and enhance operational safety and efficiency.
- **LiDAR and Three-Dimensional Mapping:** LiDAR technology provides extremely accurate 3-D models of the terrain for mine planning and environmental assessment. Combined with GIS it can be used for terrain analysis, volumetric estimation, slope stability evaluation, and infrastructure planning, which can improve the accuracy and efficiency of mining operations.
- **Internet of Things (IoT) for Smart Mining:** IoT allows for the monitoring of mining equipment, the environment and worker safety in real-time, through the use of interconnected sensors. It integrates with GIS, allowing for better prediction, operation efficiency, environmental compliance and intelligent management of the mines.

5.7 Challenges

- **High Data Acquisition Costs:** Commercial satellite imagery at high resolution is often costly and freely available imagery, such as the Landsat and Sentinel satellites, may be insufficiently high resolution for detailed mine planning and engineering.
- **Technical and Computational Constraints:** The ability to process and analyse large geospatial datasets demands advanced computing infrastructure, specialized software, and professionals who are adept at the technology, which might not be widely accessible, especially in less developed areas.
- **Data Integration and Interoperability Issues:** Geospatial data is gathered from a variety of different sensors, data formats, and coordinate systems, which makes it difficult to integrate them into a single GIS system and may necessitate uniform data processing techniques and quality assurance.
- **Environmental and Operational Limitations:** Optical RS can be affected by environmental and operational factors like clouds, atmospheric turbulence, vegetation, and topography; other technologies, like LiDAR and SAR, are also costly to implement.

- **Cybersecurity and Regulatory Challenges:** Data security and privacy issues, cloud infrastructure reliability and compliance with environmental and regulatory standards are all concerns with the use of these systems.

5.8 Future Research Directions

- **Integrate Emerging Technologies:** Integrate RS, GIS, AI, IoT, cloud computing and DT technology and establish intelligent and sustainable mine planning systems.
- **Enhance Real-Time Monitoring:** Use of satellite images, UAVs, and AI-driven predictive analytics for real-time environmental monitoring and effective mine management.
- **Promote Sustainable and Collaborative Research:** Develop common geospatial frameworks, include climate resilience, ecosystem conservation and interdisciplinary approaches, and support sustainable mining practices.

6. CONCLUSION

The introduction of RS and GIS into the modern mine planning environment has resulted in spatially integrated data that is reliable, accurate and suitable for mineral exploration, geological mapping, mine design, monitoring of environmental impacts and post mining reclamation. The use of these geospatial technologies has proven to have a major positive impact on decision making, operational efficiency and environmental sustainability across the entire mining life cycle, as illustrated in this review. With the advent of recent developments such as satellite imagery, UAVs, LiDAR, AI, ML, cloud computing, and Digital Twin technologies, the applications and capabilities of RS and GIS have been further enriched by real-time monitoring, predictive analysis, and intelligent management of mines. However, difficulties in implementation, including high costs, data integration problems, technical knowledge and computational needs, are still a major obstacle to broad adoption. Future research is recommended to combine emerging digital technologies with geospatial technologies to create more intelligent, cost-effective and sustainable mine planning frameworks.

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