BILINGUAL PUBLISHING GROUP

Journal of Environmental & Earth Sciences
https://journals.bilpubgroup.com/index.php/jees

REVIEW

Sustainable Development in Mining: The Role of Ventilation, Geodesy, and Remote Sensing

Yapeng Li

Shanxi Coking Coal Fenxi Mining Group Shuangliu Coal Mine, Lvliang City 033300, China

ABSTRACT

The mining industry is a sustainable development that needs coordinated solutions, which may address the issues of worker safety, energy and emissions, enhance geotechnical risk management, and improve environmental transparency throughout the mine life cycle. This review brings together the importance of mine ventilation, geodesy, and remote sensing as the enabling technology for sustainable mining and how their integrated application can help change the current periodic compliance monitoring and decision-making processes to continuous, evidence-based management. The field of ventilation is discussed as a safety-critical system, which manages contaminant and heat, as well as an important component of underground mine power demand, with opportunities for efficiency improvements by ventilation-on-demand, high-efficiency fans, and data-driven control. The review of geodesy as the spatial foundation of mining activities, enabling the precision of excavation, volumetric responsibility, and monitoring of deformations to associated hazards (subsidence, slope instability, and tailings storage facilities mobility) with a specific focus on the traceability of measurements and uncertainty, is presented. Such remote sensing modalities as optical, thermal, LiDAR, and radar interferometry are evaluated in terms of characterizing the baseline, disturbance mapping, tracking the environmental effect, and wide-area deformation monitoring during operations and post-closure stewardship. The review also covers information fusion and online mine platforms integrating ventilation telemetry, geodetic net, and remote sensing time series, presenting the technical, organizational, and governance challenges associated with interoperability, validation, cybersecurity, as well as long-term data stewardship. Lastly, research gaps and future directions are also determined,

*CORRESPONDING AUTHOR:
Yapeng Li, Shanxi Coking Coal Fenxi Mining Group Shuangliu Coal Mine, Lvliang City 033300, China; Email: 13012020809@126.com

ARTICLE INFO
Received: 5 January 2026 | Revised: 27 February 2026 | Accepted: 3 March 2026 | Published Online: 21 April 2026
DOI: https://doi.org/10.30564/jees.v8i4.13229

CITATION
Li, Y., 2026. Sustainable Development in Mining: The Role of Ventilation, Geodesy, and Remote Sensing. Journal of Environmental & Earth Sciences. 8(4): 230–245. DOI: https://doi.org/10.30564/jees.v8i4.13229

such as standardized uncertainty reporting, a strong multi-sensor early warning system, and scalable architectures that can be used in mines with different degrees of digital maturity.

Keywords: Sustainable Mining; Mine Ventilation; Geodesy; Remote Sensing; Deformation Monitoring

1. Introduction

Mining is still one of the pillars of contemporary industrial society, which provides raw materials needed to support infrastructures, the energy system, digital technologies, and the global shift into the realm of low-carbon economies [1,2]. Simultaneously, the mining process is inherently linked to extensive environmental disruption, energy-intensive, occupational hygiene and safety hazards, as well as future land-use implications [3]. Since the world is still screaming out the need for minerals, especially those that are critical and strategic, the issue of the mining industry is no longer about the efficiency of extracting the resource, but more about how mining can be done in a way that does not disregard the concept of sustainable development.

Sustainable development in the mining industry is often seen through the lens of a harmonious combination of environmental conservation, social responsibility, and economic feasibility in the life cycle of the mine, i.e., exploration and development, operation, closure, and post-operation stewardship [4]. The increased regulatory pressures, pressure on investors associated with environmental, social, and governance (ESG) performance, and increased scrutiny by the public have increased the need to develop transparent, measurable, and verifiable sustainability practices. In this respect, technological systems that allow constant control, minimization of risk, and maximization of performance take a determining role in making sustainability not only a commitment on paper, but a participatory reality.

Out of the extensive list of technologies used in the contemporary mining industry, ventilation systems, geodetic measurements, and remote sensing technologies take one of the most prominent places [5–7]. These three areas, though traditionally discussed as independent technical disciplines, together form the basis of most of the essential sustainability delivery in the mining sector, including worker health and safety, energy efficiency and emissions reduction, geotechnical stability, environmental impacts monitoring, and long-term land rehabilitation. Their growing integration, which is enabled by digitalization, automation, and data integration, presents fresh possibilities of enhancing the sustainability performance in a holistic and evidence-based way. An integrated view of sustainable mining requires linking measurement and control technologies to outcomes across safety, environment, and efficiency; **Figure 1** provides the conceptual framework used in this review to structure these interactions and their feedback.

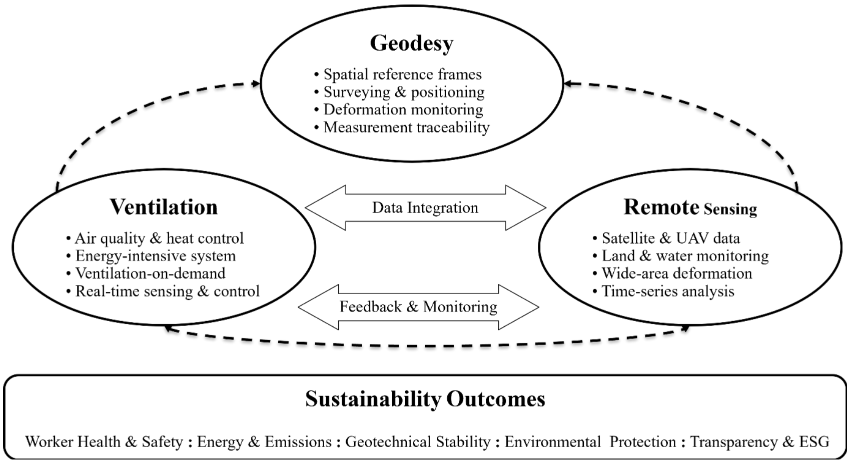

Figure 1. Conceptual framework linking ventilation, geodesy, and remote sensing to sustainability outcomes in mining, highlighting data flows and feedback loops across safety, energy/emissions, geotechnical stability, and environmental performance.

The underground mining operations are inherently associated with the mine ventilation that will guarantee the acceptable air quality, thermal comfort, and the dilution of the hazardous gases, dust, and diesel particulate matter. Ventilation is, however, also one of the greatest energy consumers in underground mines, and in many cases, 30–50% of overall site electricity is consumed by ventilation. With mining ventures moving deeper and requiring more geologically difficult locations, the demand for ventilation grows exponentially, and the cost of operations and the emission of greenhouse gases are multiplied. Ventilation has therefore become a major leverage point as far as enhancing the environmental and economic sustainability of underground mining goes. Such innovations as ventilation-on-demand, high-efficiency fans, real-time sensor networks, and digital control systems have proven to hold much potential in terms of energy-saving and safety as well as safety improvement. However, deployment of this kind of technology presents new issues regarding system integration, reliability, and verification of safety-critical performance [8,9].

Spatial and measurement Mining operations are based on geodesy and my surveying. Among the key aspects of operational efficiency, resource accountability, and risk management are proper positioning, deformation monitoring, and volume determination. In the process of alignment of underground excavations, monitoring of surface subsidence and tailings storage, geodetic techniques have been used to provide quantitative evidence that is required to present operational decisions as well as regulatory compliance. Over the recent years, geodesy has taken on a larger role than standard surveying to include continuous deformation studies, automatic measurement standards and high-precision reference frames that aid in long-term environmental management. Geodetic data are especially important in detecting early geotechnical instability, which in turn will minimize the chances of disastrous failures with devastating environmental and social outcomes. The geodetic measurements traceability and auditability also lead to the direct contribution of transparent reporting of ESG performance and trust to the stakeholders [10,11].

The application of remote sensing technologies such as satellite-based Earth observation, foot-mounted and unmanned aerial vehicle (UAV) platforms and ground-based remote sensing systems has revolutionized the level and frequency with which the mining processes involved can be monitored. These technologies allow the systematic control of the land-use change, vegetation, surface deformation, water bodies, dust emissions, and thermal anomalies at great spatial stretches and time scales. In that regard, remote sensing is instrumental in setting an environmental baseline, determining the effects of the operations, and determining the success of mitigation and rehabilitation activities. Satellite data is also becoming more high-resolution, and with the development of data analytics and machine learning, it has even become more useful in remote sensing as a near-real-time monitoring and early notification system. Nonetheless, there are still problems with data validation, quantification of uncertainties, and integrating remotely sensed data with in situ measurements and operational data streams [12,13].

Ventilation, geodesy, and remote sensing are discussed separately, even though they constitute a vital part of the business in terms of industry and academia. Such compartmentalization may inhibit the success of sustainability plans, wherein most challenges and effects associated with mining are multi-dimensional and interdependent by nature. As an example, the ventilation efficiency can affect not only the energy usage, but also the working conditions underground that impact productivity and safety, which have their social and economic consequences. Equally, geodetic or remote sensing identified deformation might require alteration in ventilation plans, production plans, or closure plans. Making these data sources integrated into single digital platforms, i.e., mine-wide monitoring platforms or digital twins, provides a route to more flexible, transparent, and more resilient mining [14].

It is on this background that there is an apparent necessity of comprehensive synthesis of the role of ventilation, geodesy, and remote sensing in mining sustainability, as well as the combination of these factors. Although many papers have discussed the technological gains in each field, few of the reviews have focused on the aggregate contribution of these gains in a sustainability context or addressed the synergies that arise due to the integration of data and the systems thinking of such integrations. Besides, the high rate of technological evolution poses some crucial questions on the technology preparedness, obstacles in implementation, data management, and the correspondence between technical innovation and regulatory and social demands [15,16].

This review has the purpose of critically assessing how the field of ventilation systems, geodetic technologies, and remote sensing contributes to the promotion of sustainable mining practices. In particular, the review attempts to: (i) evaluate the contribution of these technologies to some of the sustainability goals, such as energy savings, emission reduction, health and safety, the environment and long-term stewardship; (ii) determine recent technological advances and their maturity to be applied in the industry; (iii) outline the research gaps and future opportunities towards the integration of monitoring and decision support systems; (iv) outline challenges associated with the implementation, data integration, and uncertainty management. This review will offer a systematic insight into how measurement, monitoring, and control technologies could be used to help the mining industry become more sustainable by viewing it through the lens of the lifecycle and focusing on cross-disciplinary integration to offer researchers and practitioners alike a proper insight into the potential of AMC tools in enhancing the sustainability of the mining industry [17].

The rest of the article is structured in the following way. Section 2 is devoted to mine ventilation and its contribution to sustainable underground activities, specifically, to energy use, emissions, and digital control measures. Section 3 discusses how geodesy is important in ensuring the responsible extraction of resources, risk management, and monitoring of the proposed activity post-closure. Section 4 examines remote sensing technologies and their use in environmental monitoring and transparency in the mining lifecycle, and their combination with geodetic and operational data. Lastly, Section 5 summarizes the key results and provides future research and development needs of integrated, sustainability-based mining systems. To situate the three technical domains within a unified sustainable development perspective, **Table 1** summarizes their primary contributions across the mining life cycle from baseline characterization to post-closure stewardship.

Table 1. Sustainability contributions of ventilation, geodesy, and remote sensing across the mining life cycle.

Mining Life-Cycle Phase	Ventilation Contributions	Geodesy Contributions	Remote Sensing Contributions
Exploration & Feasibility	Not typically applicable, but it informs early underground design assumptions	Spatial control for drilling, topography, and baseline deformation	Baseline land cover, vegetation, hydrology, and terrain characterization
Mine Development	Design of primary ventilation circuits and airflow requirements	Alignment of shafts, declines, and tunnels; reference frame establishment	Surface disturbance mapping and construction monitoring
Operations	Control of air quality, heat, and contaminants; energy optimization	Production surveying, deformation monitoring, volume reconciliation	Land-use change, dust and water proxies, subsidence and slope monitoring
Closure	Adjustment of ventilation during drawdown and sealing	Final landform documentation and stability verification	Monitoring of rehabilitation, erosion, and residual deformation
Post-Closure	Limited role except for sealed underground monitoring	Long-term subsidence and infrastructure stability tracking	Long-term environmental recovery and land-use change assessment

2. Ventilation for Sustainable Mining Operations

2.1. Role of Mine Ventilation in Health, Safety, and Sustainability

Underground mining system ventilation is a basic element of the underground mining system, which determines occupational health, safety of operations, and sustainability performance. Its main task is to provide adequate amounts of fresh air to underground workings and also dilute and carry out the toxic pollutants like diesel exhaust gases, blasting fumes, respirable dust, radon, and surplus heat. Poor ventilation has dire short-term effects, such as health hazards to employees, low productivity, and high chances of mishaps. Sustainability also means that effective ventilation cannot survive without the social aspect of mining since it is at the basis of the well-being of workers and the moral obligation of my owners [8,18].

Ventilation also has an impact on the environmental and economic sustainability, besides the health and safety. Trustworthy airflow allocation permits the effective implementation of mechanized and automated machinery and minimizes interruptions caused by air quality limitations, and serves to sustain more profound and intricate mining. Nonetheless, with further development of mines, which delve to deeper levels, ambient rock temperatures increase, and airways length and resistance increase, causing a significant increase in ventilation requirements. These issues have increased the necessity to balance the requirements of safety with the requirements of energy efficiency, and ventilation has become the key area of concern in the design and operation of the underground mines in a sustainable manner [18,19].

2.2. Energy Consumption and Carbon Footprint of Ventilation Systems

One of the biggest areas of energy consumption in underground mines is ventilation systems, which can usually represent a good percentage of all the electricity consumed on the site. Main and auxiliary fans needed to overcome airway resistance and keep the airflow rates in the prescription are the primary sources of energy demand. Further energy is used in cooling systems in deep or hot mines, where ventilation air has to be conditioned to ensure that thermal conditions are acceptable. Consequently, the ventilation is inextricably tied to the operating costs as well as the indirect greenhouse gas emission especially in areas where electricity is produced using fossil fuels [20].

The mine's carbon footprint, which is related to mine ventilation, depends on a number of factors such as the depth of the mine, the complexity of the layout, the rate of production, the composition of the equipment fleet, and the weather. Traditional ventilation methods tend to use the worst-case scenario in the form of constant airflow supply, which results in a high degree of over-ventilation when the activity levels fall. This lack of balance between the supply of airflow and real demand is a significant inefficiency and one of the primary areas of sustainability. Measuring the energy utilization and emissions associated with ventilation has hence become a significant element of environmental reporting as well as the life cycle assessment in the mining industry. Measures like specific energy consumption per ton of ore mined, or per unit of airflow, give a foundation when it comes to benchmarking and the improvement of performance, but must be interpreted with respect given to site-based conditions [21,22].

2.3. Technological Advances toward Sustainable Ventilation

Improvements in technology over the last few years have brought about a higher possibility of reducing the level of energy and environmental footprint of mine ventilation systems. Ventilation-on-demand, which is a dynamic and continuous adjustment of airflow distribution based on real-time data on the equipment location, workforce presence, and environmental conditions, is one of the most influential innovations. Ventilation-on-demand systems have the potential to save a significant amount of energy and be able to comply with safety requirements by only supplying air where and when it is needed. Such systems rely on the quality of sensor network, communications, and control algorithms, which are able to respond to quickly varying operational conditions [20,23].

The technology of the fans has also improved to gain sustainability. The better use of the energy-efficient fan, variable speed drives, and more flexible designs of fans allows for better control of airflow than the traditional fixed-speed systems. The leakage reduction through better ducting, regulators, and stoppings also contributes to better performance of the system, as the ducting required to deliver air to a required destination is present. Simultaneously, the progressive switching to battery-electric or hybrid mining machinery is changing the ventilation demand patterns by trimming down the contaminants that release heat, even though the heat loads and charging infrastructure are creating new constraints in ventilation design [24,25].

There has been an investigation around the integration of renewable sources of energy and energy storage systems into mine power supplies as yet another avenue in minimizing the carbon intensity of ventilation. Although this is not achieved directly by reducing the airflow requirements, it can reduce the emissions associated with it and enhance energy resilience. But their practicality is subject to the site-related factors, such as the connection to the grid, climate conditions, and regulatory policies [26].

2.4. Monitoring, Modeling, and Digitalization of Ventilation Systems

Mine ventilation has become a major enabler of sustainable operation because it has been digitalized. The contemporary ventilation systems are more and more based on dense systems of sensors that detect the airflow, gas concentrations, temperature, humidity, and pressure. Such data streams serve as the basis for monetizing real-time, performance evaluation, and adaptive control. The quality of the data, the reliability of the sensors, and adequate calibration are critical as ventilation choices are life or death decisions, and they can be mistakenly made with severe outcomes [27].

Ventilation modeling has a complementary role as it offers a framework of system design, scenario analysis, and optimization. Airflow distribution and contaminant transport, pressure losses, and airway evaluation through simulation modeling. Best computational fluid dynamics combined with network model-based assessments are very popular in evaluating airflow and contaminant distribution. Such models can be used to support predictive analysis and the need to evaluate alternative ventilation strategies when calibrated using field measurements. More recently, the idea of digital twins has been proposed, which combines real-time data with dynamic models to facilitate the continuous optimization of a system and what-if analysis. Although digital twins have great potential, their application is still challenging, and it will require immense computational assets, interdisciplinary knowledge, and data integration [28,29].

2.5. Sustainability Trade-Offs and Implementation Challenges

Although the advanced ventilation technologies have the evident potential to enhance sustainability, they are not adopted without some difficulties. Initial capital may be a barrier to implementation, especially when the operation is small to medium-sized, due to the high costs associated with retrofitting existing mines. The more automated and data-driven the system is, the more tasks it becomes to operate without new skill sets among the engineering staff and the operational staff. The issue of cybersecurity and system resilience also emerges as a critical one, as the main functions that are safety-critical have become dependent on digital infrastructure. In addition, trade-offs of sustainability need to be handled. The energy efficiency policies must not jeopardize the reliability of ventilation or the security of workers, and any decrease in the airflow must be justified by a stringent risk assessment and the regulatory license. The advantages of energy saving and emissions should be compared to the risks that may arise as a result of system failure or any errors in sensors. In the context of general sustainability, proper ventilation will lead to social acceptance due to preserving the well-being of workers and low impacts of energy consumption and emissions in the community [30].

In short, mine ventilation takes a central place in the quest for sustainable underground mining. It is one of the most important challenges because of the energy density, as well as one of the most promising areas of development in the case of technological advances and digitalization. The concept of ventilation as a dynamic, data-driven entity and not a fixed part of the infrastructure is key to the integration of the safety, environmental, and economic goals of a sustainable mining system [15]. The sustainability leverage of mine ventilation depends on the selection and integration of technologies that jointly satisfy safety constraints and reduce energy intensity; **Table 2** synthesizes the major technology classes, expected benefits, and key implementation limitations.

Table 2. Ventilation technologies and operational strategies and their sustainability implications in underground mining.

Ventilation Technology	Primary Function	Sustainability Benefit	Key Limitations
Conventional fixed airflow ventilation	Continuous contaminant dilution	High reliability and regulatory familiarity	Energy-intensive and often inefficient
Ventilation-on-demand (VOD)	Dynamic airflow allocation	Reduced energy use and emissions	Dependence on sensors, automation, and data reliability
Variable speed drives	Fan speed optimization	Improved energy efficiency	Capital cost and control complexity
High-efficiency fan designs	Reduced aerodynamic losses	Lower lifecycle energy consumption	Retrofit constraints in existing systems
Electrified equipment interaction	Reduced diesel contaminants	Potential reduction in airflow demand	Heat loads and charging infrastructure challenges

3. Geodesy as a Foundation for Responsible Resource Extraction

3.1. Geodetic Principles and Spatial Reference Frameworks in Mining

Geodesy is the scientific and technical basis of all spatial measurements in the mining industry, which allows the precise determination of position, orientation, and deformation in the surface and underground [5,16]. Fundamentally, geodesy can be used to create consistent spatial reference frames based on coordinate systems, datums, and reference networks that enable similarity of measurements with time and across datasets. This uniformity is crucial in mining activities as it ensures spatial integrity of the mine life cycle and comprises exploration, drilling and mine development, mine closure and post-closure monitoring.

These changes have led to the rise of the value of geodetic rigor in mining due to the growing need to use high-precision spatial data. The reference frame errors or datum shifts may be transferred through the working operational procedures, resulting in the misalignment of excavation, false volume calculations, and safety margins. Geodetic accuracy and traceability can be utilized to achieve sustainability benefits to ensure conscientious extraction of resources by reducing dilution and wastage, improving infrastructure siting, and offering auditable documentation to reimburse regulatory compliance and environmental reporting [31].

3.2. Mine Surveying and Operational Efficiency

Mine surveying is one of the practical uses of geodetic concepts in mining. Proper surveying is the basis of virtually every mine planning and execution activity, such as shafts and tunnel layout, blasting and excavation control, and volume of extracted material calculation. In underground mines, accurate direction of development headings minimizes the chance of breakthrough errors, enhances productivity and causes excavation that is unnecessary which saves energy and materials. At the surface, correct topographic surveys are used in designing the pits, optimizing the haul roads, as well as the management of stockpiles, which directly translate into the efficiency of operations and their impact on the environment [5,10].

Developments in surveying technology have altered the traditional measurement practice that was traditional. The rate of spatial measurements has been improved by the use of automated total stations, laser scanners, inertial navigation systems and satellite-based positioning technologies. The tools allow almost continuous tracking of mine geometry and allow making decisions more responsively. Contributing to the sustainability of resource utilization by eliminating uncertainty in the spatial data, modern geodetic systems lead to more effective utilization of resources and minimize the risk of rework or environmental disturbance due to design errors [32,33].

3.3. Deformation Monitoring and Geotechnical Risk Management

Deformation monitoring and geotechnical risk management are two of the most important roles played by geodesy in sustainable mining. Stresses caused by mining may result in deformation of the ground, subsidence, slope instability, and structural failures that are very dangerous to workers, infrastructures, and the community around them. Geodetic monitoring systems present quantitative data on ground movements that allows to spot the dangerous trends in time and taking the appropriate mitigation measures [16,34].

Surveillance of surface and underground deformations is often based on benchmarks, global receivers of the global navigation satellite system, and automated total stations with support of remote sensing (e.g., interferometric synthetic aperture radar). Such measurements are able to detect slow and fast motions, which can be used to establish warning levels and risk-based decision models. Geodetic monitoring has, in the recent past, been integrated as an indispensable part of responsible management and regulatory control in the context of tailings storage facilities where failure may have disastrous environmental and social outcomes [35,36].

The process of deformation monitoring needs pertinent measurements, sound interpretation, and uncertainty measurements. The major difficulty is to identify noise and the presence of meaningful deformation signals, especially in complicated geological contexts. Geodesy is a source of defensible, traceable data, which can be used to facilitate open-minded risk reporting and enhance the stakeholders' trust in the mining activity and its safety and viability [37].

3.4. Geodesy in Mine Closure and Post-Closure Stewardship

Not only is geodesy an element of active mining operations, but also mine closure and post-closure when the questions of long-term environmental stability and compatibility of land-use take center stage [38]. To monitor the outcome of rehabilitation, as well as monitor additional deformation or subsidence once the mining activities are ceased, spatial data is needed to effectively record end-stage landforms. The long-term monitoring programs that, in most instances, are based on geodetic reference networks, which are developed as a result of the operations is likely to ensure continuity and comparability in the measurements over long periods of time.

Post-closure monitoring, which involves geodesy, aids in sustainable development because it assists in the early indications of slowed-down motions of the ground, erosion, or deteriorating infrastructure. This knowledge is valuable in the conservation of the ecosystems, water sources, and the locals. Moreover, access to viable geodetic records will facilitate accountability and support the legal and regulatory processes, which entail mine closure conditions. To that extent, geodesy could provide both technical and ethical support to a long-term custodianship of mined landscapes [39]. Geodesy contributes to sustainability not only during production but also through long-term stewardship obligations; **Figure 2** summarizes how geodetic functions evolve across the mine life cycle while maintaining continuity through stable spatial reference frameworks.

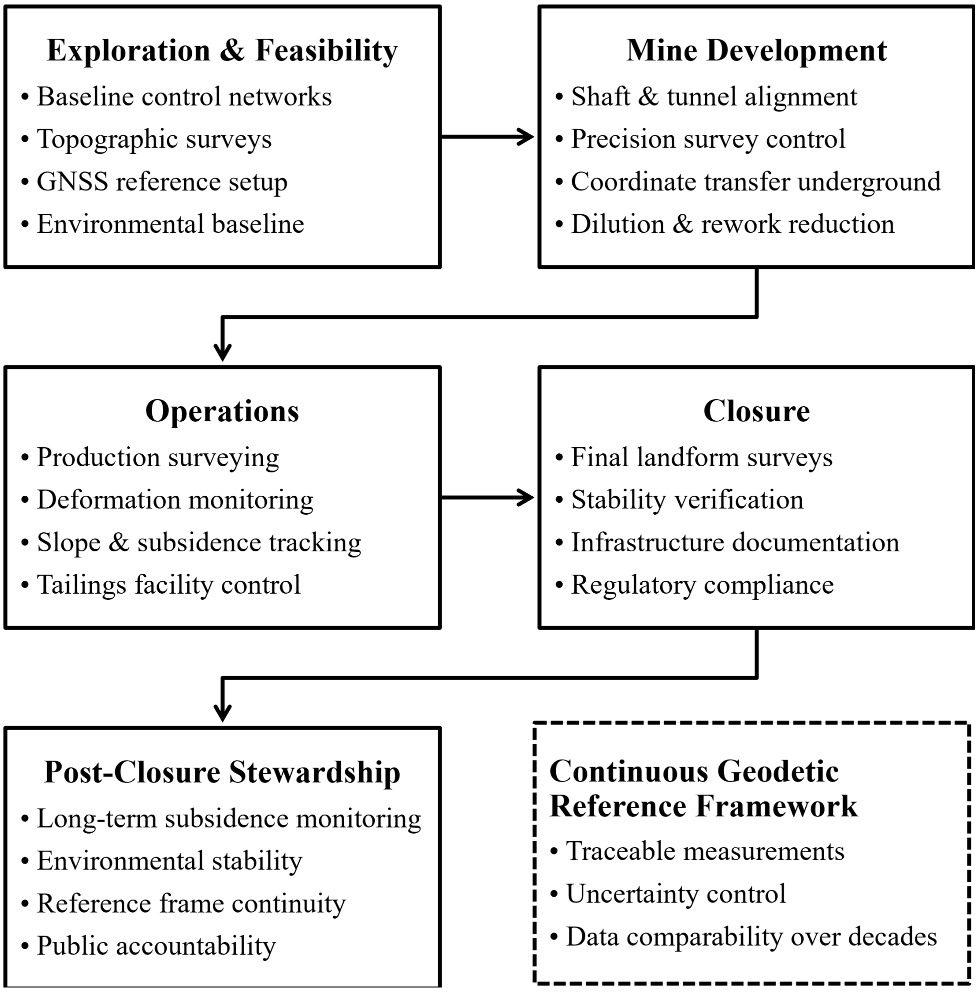

Figure 2. Geodetic monitoring across the mining life cycle, showing continuity of reference frames and the evolution of surveying and deformation monitoring objectives from development to post-closure stewardship.

3.5. Data Governance, Standards, and Integration with Other Monitoring Systems

With more volumes and complexity of geodetic data, good data governance turns out to be a focus area of sustainable mining [40,41]. There is a need to have standardized metadata and quality control practices from documentation that ensures that spatial data remains interpretable and reliable across time. Other monitoring systems, such as ventilation data and remote sensing products, are becoming increasingly important in the analysis and decision support of geodetic data.

Geodesy can be used to introduce greater levels of holiness in the evaluation of mining impacts and risks, as it has the potential to be integrated with digital mine platforms and environmental monitoring systems. Spatial and temporal relationships produced by shared reference frames and time synchronization enable exploration of spatial relationships and temporal relationships between various datasets that are utilized to support advanced analytics and predictive models. Nevertheless, data ownership, cybersecurity, and long-term availability are also problematic in terms of such integration, in particular, with the monitoring of post-closure and the transparency of the population [42,43].

Overall, geodesy has a core contribution to the responsible and sustainable mining in the form of precise, traceable, and combinable spatial data across the mine life cycle [44]. Its investments are not only in operational efficiency and reduction of risks, but also in environmental stewardship and trust of the stakeholders. The need to have a good geodetic framework and practice will only increase as the mining systems are becoming more digital and networked, making this practice more of a core value in the sustainable development of mining. Because deformation and stability risks require both high-precision local measurements and wide-area surveillance, **Table 3** compares commonly used geodetic and remote sensing techniques in terms of scale, typical accuracy, and practical constraints, clarifying why multi-sensor monitoring is increasingly adopted.

Table 3. Geodetic and remote sensing techniques for deformation and stability monitoring: scales, typical performance, and constraints.

Technique	Spatial Scale	Typical Accuracy	Monitoring Target	Strengths	Limitations
GNSS monitoring	Local to regional	mm–cm	Subsidence, surface deformation	High precision, continuous	Requires infrastructure and a clear sky view
Automated total stations	Local	sub-mm–mm	Slopes, walls, and underground openings	Very high accuracy	Line-of-sight constraints
InSAR	Regional	mm–cm	Subsidence, TSFs, slopes	Wide-area coverage, historical analysis	Decorrelation, atmospheric effects
UAV photogrammetry	Local	cm	Stockpiles, pit walls, rehabilitation	High resolution, flexible deployment	Weather and regulatory constraints
Terrestrial LiDAR	Local	mm–cm	Slopes, structures	Dense point clouds	Limited spatial coverage

4. Remote Sensing for Environmental Monitoring, Impact Assessment, and Transparency

4.1. Role of Remote Sensing in Sustainable Mining

The concept of remote sensing has turned out to be an essential contribution to moving mining towards sustainability, as the method permits systematic, repeatable, and spatially comprehensive monitoring of environmental and operational procedures. Unlike conventional ground-based surveillance, remote sensing technologies are capable of offering synoptic coverage of extensive and often inaccessible regions, and this attribute is especially useful in the spatial scale and complexity of mining operations. Remote sensing can be used to provide an objective evaluation of the environmental change, the risk evolution, and adherence to the regulatory and social expectations through constant or regular observation [45,46].

Remote sensing also plays a role in each stage of the mining life cycle in the context of sustainable development. In the exploration and project development, it aids in background characterization of the land cover, the hydrology, and the ecological situation. In its operations, it allows tracking the surface disturbance, a proxy of emission, and geotechnical stability. After the closure, remote sensing enables a long-term assessment of the success of the rehabilitation and recovery of the environment. The applicability of the lifecycle puts remote sensing as a major facilitator of transparency and accountability on the mining sustainability performance [47].

4.2. Remote Sensing Technologies and Observables Relevant to Mining

There is a great variety of remote sensing technologies that are used in mining, and all of which complement one another by informing about the environmental and physical processes. The use of optical and multispectral satellite images is a common method of mapping land-use change, vegetation health, and surface disturbance due to mining activities. Hyperspectral records also make it easier to detect mineralogical and geochemical signatures and facilitate the use of hyperspectral data in both exploration and environmental monitoring tasks. The temperature pattern of the surface at any given time can be detected using thermal remote sensing, and this can be a sign of spontaneous combustion in waste dumps, water discharge aberrations, or sources of heat in a process [48,49].

Another method where synthetic aperture radar and interferometry can be used is deformation monitoring, since both technologies are largely unaffected by cloud cover and lighting [50]. The techniques have found application especially in the detection of ground subsidence, slope movements, and deformation of tailings storage facilities over large regions and long durations. At smaller spatial scales, high-resolution mapping of topography, stockpiles, and infrastructure can be done with airborne and unmanned aerial vehicle platforms with photogrammetric or LiDAR sensors. Remote sensing based on the ground, e.g., terrestrial radar and laser scanners, offers a continuous observation of the areas of concern where rapid deformation can take place. Collectively, these technologies constitute a multi-scale observational system that can be used to measure the sustainability in a comprehensive way.

4.3. Applications across the Mining Life Cycle

The main role of remote sensing in setting environmental baselines before the mining process is paramount in the impact assessment and rehabilitation evaluation that follows the mining process. Remote sensing assists objective comparisons between pre- and post-mining conditions by having been proven to offer historical and pre-disturbance data on vegetation, water bodies, and landforms. In the course of operations, time-series analysis of data collected by satellites and UAVs will make it possible to trace the expansion of the surface, the growth of waste facilities, and the alteration of the ecosystems around them. There is a growing use of such analyses to check on the adherence to land-use permits and environmental management plans [46,51].

Another level of critical contribution to sustainable mining by remote sensing is that of water-related impacts [52]. Surface water extent, sediment plumes, and moisture pattern changes can be tracked through time, which will give indirect measurements of water quality and hydrological change. Dust emissions are difficult to measure directly in space, but can be estimated using plume tracking and changes in surface reflectance with the help of meteorological data. During the post-closure and closure stages, remote sensing assists in monitoring the long-term success of revegetation, erosion, and landscape stabilization, and it is relevant in adaptive management and regulatory assurance.

4.4. Data Processing, Analytics, and Uncertainty Considerations

Remote sensing can be useful in sustainable mining, whereby data availability, as well as effective processing and analysis, is also important. Raw remote sensing data should be preprocessed with great caution to achieve spatial and temporal consistency by performing geometric, atmospheric, and co-registration. The trends and anomalies associated with mining operations are typically detected by change detection techniques, such as simple differencing, to more sophisticated time-series and machine learning-based techniques [53].

Although there has been an improvement in analytics, the issue of uncertainty has been a major issue in remote sensing usages. Data quality and interpretation can be affected by sensor resolution, revisit frequency, atmospheric conditions, and surface heterogeneity. Ground measurements and geodetic measurements are thus needed to validate and calibrate the remote sensing products. The uncertainty and methodological assumptions must be reported transparently when the remote sensing data is going to be utilized in regulatory compliance, risk management, or in communicating to the population [54]. The solution of these problems enhances the reliability of remote sensing as a decision-support tool for sustainable mining.

4.5. Integration with Geodesy, Ventilation, and Digital Mine Systems

Remote sensing has full sustainability potential that is achieved when it is combined with other monitoring and control systems in a mining operation. The ability to spatially align products of remote sensing with appropriate reference frameworks of geodetic systems allows the accurate combination of remote sensing products with survey data, deformation measurements, as well as mine planning models. The temporal integration enables observation of remotely sensed data to be connected to operational events, ventilation conditions, and measurements of the environment, and offers deeper contextual insights about changes being observed [46,55].

This integration is useful in the formulation of digital mine platforms and decision-support systems, integrating surface and subsurface information on a variety of scales [56]. As an example, the signals of deformation observed with the help of the satellite radar can be identified with the progress of excavation underground or modification of the ventilation scheme, and this will contribute to the risk evaluation and reaction strategy. On a larger scale, integrated datasets will result in more transparent reporting on sustainability, as observed environmental outcomes can be connected with the way operations are conducted. But to attain this integration, data governance, interoperability, and long-term accessibility should be given due consideration especially in terms of mine closure and disclosure to the public.

A critical barrier to integrated mine monitoring lies in the complexity of data fusion across ventilation telemetry, geodetic networks, and satellite observations. These systems operate at fundamentally different spatial and temporal scales: ventilation sensors provide high-frequency, localized measurements; geodetic networks offer high-precision but spatially discrete deformation data; and satellite observations deliver wide-area coverage at comparatively lower temporal resolution. Aligning these datasets requires robust spatial referencing and time synchronization frameworks.

Furthermore, data heterogeneity in format, resolution, and uncertainty structure complicates integration. Ventilation telemetry is often continuous and operationally driven, whereas geodetic and remote sensing datasets require preprocessing, filtering, and validation. Propagation of uncertainty across fused datasets remains insufficiently standardized, limiting confidence in integrated analytics.

Additional challenges include data interoperability across proprietary platforms, calibration inconsistencies between in situ and remote measurements, and the lack of unified data governance frameworks. Addressing these challenges is essential for enabling reliable multi-sensor early warning systems and digital mine observatories.

In conclusion, remote sensing has become an effective and multifunctional instrument that can help in sustainable development in mining. It increases the impact assessment and risk management and transparency throughout the mining lifecycle by allowing the objective, large-scale, and continuous monitoring of environmental and physical processes. Integrating with geodetic measurements and operational data, remote sensing can help bring about a more comprehensive and evidence-based approach to sustainable mining to match technological possibilities with societal and environmental demands [42,53]. Moving from fragmented monitoring to adaptive, auditable sustainability management requires integration of subsurface control and surface observation; **Figure 3** proposes an architecture for a digital mine observatory that unifies ventilation, geodesy, and remote sensing within a decision-support workflow. To translate technical capability into sustainable outcomes, implementation barriers and research priorities must be treated as system-level issues; **Table 4** consolidates the principal challenges and future directions for integrated monitoring, modeling, and governance.

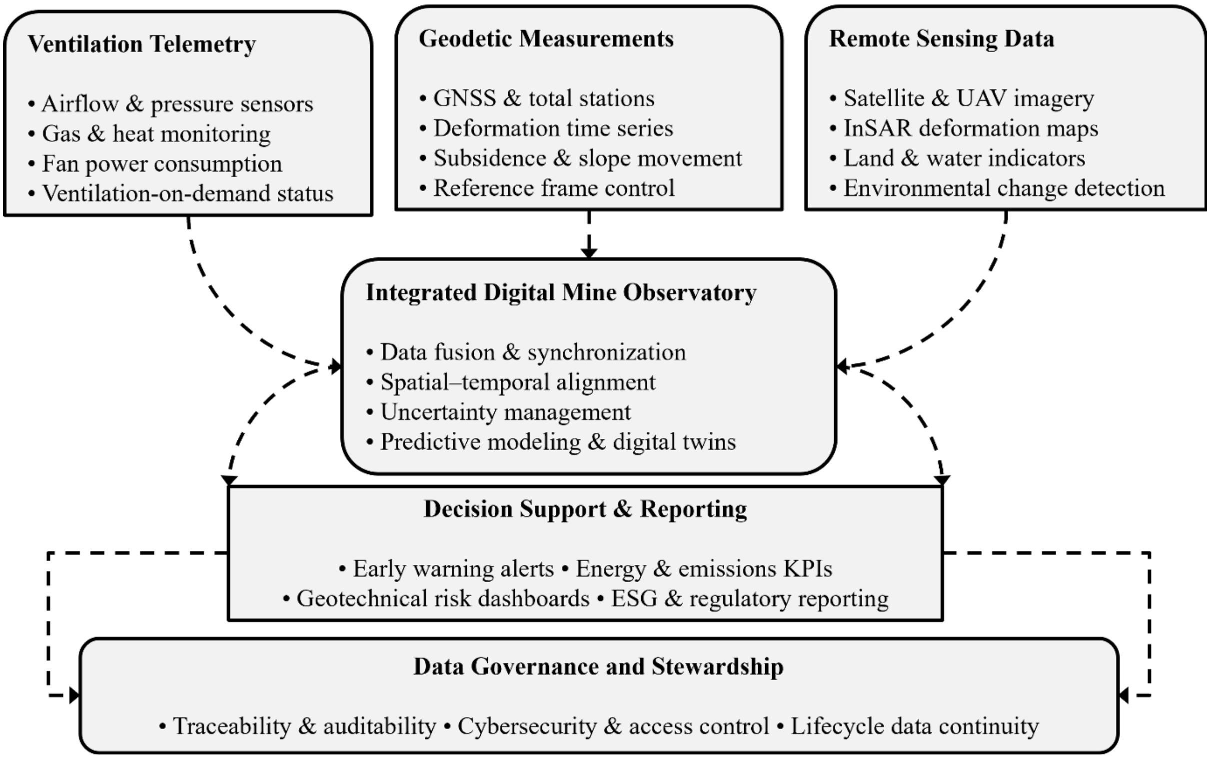

Figure 3. Integrated digital mine observatory architecture combining ventilation telemetry, geodetic measurements, and remote sensing time series to support decision-making, early warning, and auditable sustainability reporting.

Table 4. Challenges, sustainability implications, and future research directions for integrated ventilation–geodesy–remote sensing systems.

Domain	Current Challenge	Sustainability Impact	Future Research Direction
Ventilation	Energy-intensive baseline designs	High emissions and operating costs	Predictive, AI-assisted ventilation control
Geodesy	Fragmented monitoring systems	Delayed hazard detection	Unified deformation thresholds and standards
Remote sensing	Uncertainty and validation gaps	Misinterpretation of environmental impacts	Standardized uncertainty reporting
Data integration	Interoperability and governance	Limited decision support	Digital twins and open data models
Lifecycle stewardship	Post-closure data continuity	Long-term environmental risk	Persistent monitoring frameworks

5. Conclusion

The concept of sustainable development in mining cannot be achieved by making small technological advancements in one specific area; rather, it must be a system-wide approach that connects the operations of a company with its past outcomes regarding worker health and safety, energy and emissions output, environmental protection, and long-term custodianship. In this larger context, ventilation, geodesy, and remote sensing are not only technical domains of specialization but also facilitating infrastructures of sustainable mining. Ventilation controls the productivity and habitable conditions of underground mines and is one of the most significant types of energy requirements in deep mining. Geodesy gives reason to an accountable excavation, tracking of deformations, and reportable accountability throughout the mine life cycle by giving it the spatial fidelity and traceable value of measurement. Remote sensing is also scalable, repeatable, and land, water, and ground stability observation, enhancing environmental control and ensuring disclosure to regulators, investors, and communities.

One of the key lessons of this review is that the sustainability value of such domains grows considerably when they have to be considered as an integrated ecosystem of monitoring and control instead of individual functions. There are more efficient ventilation methods like ventilation-on-demand that could help decrease the intensity of energy and emissions, and safe and reliable implementation is also subject to sound sensing, calibration, and verification practices. Geodetic networks and deformation monitoring can be used to give important early warning signals on geotechnical hazards, especially on slopes, subsidence, and tailings storage facilities, and can be reinforced by combining with remote sensing products, e.g., InSAR and high-resolution UAV-based terrain models. Remote sensing, in its turn, will be easier to put into action when outputs are normalized to the reference frames, checked against ground measurements, and interpreted regarding its operational context, such as the production plans, infrastructure developments, and underground conditions. The combination of these capabilities underlies the transition from periodic compliance checking to continuous risk management and dynamic environmental performance.

Simultaneously, this review demonstrates the ongoing issues that restrict wider application and influence. The reliability of sensors in adverse mine conditions, intermittent and uncertain data in remotely sensed products, and difficulties in calibration of models due to changing networks of ventilation and geomechanical processes over time are all technical barriers. Organizational issues are the necessity of interdisciplinary working processes, the training of the workforce, and the accurate definition of the data quality and decision limit. Issues of governance are also critical and these include cybersecurity, metadata and interoperability standards, chain-of-custody to measure safety-critical, long-term maintenance of monitoring records (especially during closure and post-closure stages when accountability goes beyond active production). Even some advanced monitoring cannot help form trust or make defensible decisions without any reasonable uncertainty quantification and clear communication of restrictions.

To ensure applicability across diverse mining contexts, monitoring systems must be designed as scalable architectures that align with varying levels of digital maturity. At the foundational level, operations typically rely on standalone ventilation measurements, periodic geodetic surveys, and externally sourced remote sensing data, primarily supporting compliance and basic risk identification. As digital capacity increases, intermediate systems integrate these datasets through centralized databases and shared spatial reference frameworks, enabling semi-automated processing and near-real-time monitoring. More advanced operations adopt fully integrated digital platforms, where ventilation telemetry, geodetic networks, and remote sensing time series are combined within unified environments to support predictive analytics and decision-making. At the highest level of maturity, digital twins and AI-driven systems enable continuous data assimilation, automated optimization of ventilation performance, and proactive identification of geotechnical and environmental risks. Such a tiered and scalable framework allows incremental implementation, reduces technological and financial barriers, and ensures that integrated monitoring can support sustainable mining practices across operations with differing resource and infrastructure constraints.

In summary, it is possible to conclude that ventilation, geodesy, and remote sensing represent a useful basis of sustainable mining since they allow quantifying, verifying, and making constant improvements. Their integration will decrease energy and emissions, improve the geotechnical and environmental risk management, and increase the transparency of the mine life cycle. The capacity of the industry to implement operational sustainable development in the future, as mining expands to meet future material demands due to the increased demands on sustainability, is bound to continue to rely on the effectiveness with which the industry deploys and links these measurement, monitoring, and control technologies into coherent and audit-ready as well as decision-relevant systems.

Funding

This work received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

No new data were created or generated in this study.

All data were presented in this work.

Conflicts of Interest

The author declares no conflict of interest.

References

[1] Sovacool, B.K., Ali, S.H., Bazilian, M., et al., 2020. Sustainable minerals and metals for a low-carbon future. Science. 367(6473), 30–33.

[2] Berretta, A., Harvey, R., 2022. Mining for a low-carbon economy: New technologies and integrated governance. In: Hilson, G. (Ed.). Routledge Handbook of the Extractive Industries and Sustainable Development. Routledge: London, UK. pp. 172–190.

[3] Joseph, R., 2025. Environmental issues in mining: A comprehensive review of challenges and strategies for mitigation and rehabilitation. Mining Revue/Revista Minelor. 31(3), 51–71.

[4] Blinova, E., Ponomarenko, T., Knysh, V., 2022. Analyzing the concept of corporate sustainability in the context of sustainable business development in the mining sector with elements of circular economy. Sustainability. 14(13), 8163.

[5] Adero, N., 2023. Mining Surveys with GIS Application: A Contemporary Introduction for Engineers and Geoscientists. In Project Design for Geomatics Engineers and Surveyors, 2nd ed. Taylor & Francis: Abingdon, UK.

[6] Duarte, J., Rodrigues, F., Castelo Branco, J., 2022. Sensing technology applications in the mining industry—A systematic review. International Journal of Environmental Research and Public Health. 19(4), 2334.

[7] Wallace, K., Prosser, B., Stinnette, J.D., 2015. The practice of mine ventilation engineering. International Journal of Mining Science and Technology. 25(2), 165–169.

[8] Yang, B., Yao, H., Wang, F., 2022. A review of ventilation and environmental control of underground spaces. Energies. 15(2), 409.

[9] Shriwas, M., Pritchard, C., 2020. Ventilation monitoring and control in mines. Mining, Metallurgy & Exploration. 37(4), 1015–1021.

[10] Biehichev, S., Ishutina, H., Chumak, L., 2017. Modelling geodetic network to improve reliability of surveying providing of mining operations. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu. 3, 26–31.

[11] Labant, S., Bindzarova Gergelova, M., Kuzevicova, Z., et al., 2020. Utilization of geodetic methods results in small open-pit mine conditions: A case study from Slovakia. Minerals. 10(6), 489.

[12] O'Donnell, M.S., Whipple, A.L., Inman, R.D., et al., 2024. Remote sensing for monitoring mine lands and recovery efforts. Circular. DOI: https://doi.org/10.3133/cir1525

[13] Loots, M., Grobbelaar, S., Van der Lingen, E., 2022. A review of remote-sensing unmanned aerial vehicles in the mining industry. Journal of the Southern African Institute of Mining and Metallurgy. 122(7), 387–396.

[14] Wang, Z., Bi, L., Li, J., et al., 2025. Development status and trend of mine intelligent mining technology. Mathematics. 13(13), 2217.

[15] Saleem, H.A., 2025. Energy consumption reduction in underground mine ventilation system: An integrated approach using mathematical and machine learning models toward sustainable mining. Sustainability. 17(3), 1038.

[16] Owczarz, K., 2020. A review of geodetic and remote sensing methods used for detecting surface displacements caused by mining. In Proceedings of the 6th World Multidisciplinary Earth Sciences Symposium, Prague, Czech Republic, 7–11 September 2020.

[17] Gorman, M.R., Dzombak, D.A., 2018. A review of sustainable mining and resource management: Transitioning from the life cycle of the mine to the life cycle of the mineral. Resources, Conservation and Recycling. 137, 281–291.

[18] Elezaj, S., Beqiri, L., Elezaj, I., 2024. Management of health and environment issues through ventilation in mining lines: An operational and statistical approach. Mathematical Modelling of Engineering Problems. 11(5).

[19] Mohsin, M., Zhu, Q., Naseem, S., et al., 2021. Mining industry impact on environmental sustainability, economic growth, social interaction, and public health: An application of semi-quantitative mathematical approach. Processes. 9(6), 972.

[20] de Vilhena Costa, L., Margarida da Silva, J., 2020. Cost-saving electrical energy consumption in underground ventilation by the use of ventilation on demand. Mining Technology. 129(1), 1–8.

[21] Díaz, E., Fernández, J., Ordóñez, S., et al., 2012. Carbon and ecological footprints as tools for evaluating the environmental impact of coal mine ventilation air. Ecological Indicators. 18, 126–130.

[22] Bharathan, B., Sasmito, A.P., Ghoreishi-Madiseh, S.A., 2017. Analysis of energy consumption and carbon footprint from underground haulage with different power sources in typical Canadian mines. Journal

of Cleaner Production. 166, 21–31.

[23] Dicks, F., Clausen, E., 2017. Ventilation on demand. Mining Report. 153(4), 334–341.

[24] Babu, V.R., Maity, T., Burman, S., 2016. Optimization of energy use for mine ventilation fan with variable speed drive. In Proceedings of the 2016 International Conference on Intelligent Control Power and Instrumentation (ICICPI), Kolkata, India, 21–23 October 2016.

[25] Murphy, T.M., 2006. A Method for Evaluating the Application of Variable Frequency Drives with Coal Mine Ventilation Fans [Master's Thesis]. Virginia Polytechnic Institute and State University: Blacksburg, VA, USA.

[26] Igogo, T., Awuah-Offei, K., Newman, A., et al., 2021. Integrating renewable energy into mining operations: Opportunities, challenges, and enabling approaches. Applied Energy. 300, 117375.

[27] Fisk, W.J., De Almeida, A.T., 1998. Sensor-based demand-controlled ventilation: A review. Energy and Buildings. 29(1), 35–45.

[28] Ren, C., Cao, S.-J., 2020. Implementation and visualization of artificial intelligent ventilation control system using fast prediction models and limited monitoring data. Sustainable Cities and Society. 52, 101860.

[29] Kychkin, A., Nikolaev, A., 2020. IoT-based mine ventilation control system architecture with digital twin. In Proceedings of the 2020 International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM), Sochi, Russia, 18–22 May 2020.

[30] Swanepoel, J., Vosloo, J.C., van Laar, J.H., et al., 2023. Prioritisation of environmental improvement projects in deep-level mine ventilation systems. Mining, Metallurgy & Exploration. 40(2), 599–616.

[31] Moomen, A.-W., Bertolotto, M., Lacroix, P., et al., 2019. Inadequate adaptation of geospatial information for sustainable mining towards Agenda 2030 sustainable development goals. Journal of Cleaner Production. 238, 117954.

[32] Trybała, P., 2025. 3D Surveying of Mining Environments Using Simultaneous Localization and Mapping [PhD Thesis]. Wrocław University of Science and Technology: Wrocław, Poland.

[33] Sokoła-Szewioła, V., Siejka, Z., 2021. Validation of the accuracy of geodetic automated measurement system based on GNSS platform for continuous monitoring of surface movements in post-mining areas. Reports on Geodesy and Geoinformatics. 112(1), 47–57.

[34] Kuldeev, E.I., Rysbekov, K.B., Donenbayeva, N.S., et al., 2021. Modern methods of geotechnic—Effective way of providing industrial safety in mines. Eurasian Mining. 36(2), 18–21.

[35] Atif, I., Ashraf, H., Cawood, F.T., et al., 2020. A conceptual digital framework for near real-time monitoring and management of mine tailing storage facilities. In Proceedings of the International Conference on Innovations for Sustainable and Responsible Mining, Hanoi, Vietnam, 15–17 October 2020.

[36] Cacciuttolo, C., Guzmán, V., Catriñir, P., et al., 2024. Sensor technologies for safety monitoring in mine tailings storage facilities: Solutions in the industry 4.0 era. Minerals. 14(5), 446.

[37] Gupta, M., 2025. Satellite-based geodesy. In: Firozjaei, M.K. (Ed.). Remote Sensing for Geophysicists. CRC Press: Boca Raton, FL, USA. pp. 35–48.

[38] Ugo, P.D., 2021. Sustainability Assessment of Post-Mining Land Use Planning [Master's Thesis]. University of Cape Town: Cape Town, South Africa.

[39] Esau, M., Cole, M.J., Broadhurst, J.L., et al., 2025. Developing a national mine closure risk and opportunities atlas in GIS for South Africa. In Proceedings of the 16th International Conference on Mine Closure, Mine Closure 2023, Reno, NV, USA, 2–5 October 2023.

[40] Tan, Z., Wang, M., Ye, Z., 2025. Methodological system and implementation framework of data governance for intelligent coal mines. Coal Science and Technology. 53(1), 284–295. (in Chinese)

[41] Yang, K., 2023. Data governance system for intelligent mine management and control platform. In Proceedings of the 2023 8th International Conference on Information Systems Engineering (ICISE), Dalian, China, 23–25 June 2023.

[42] Strzałkowski, P., Romańczukiewicz, K., Bęś, P., et al., 2025. The application of VR technology in engineering issues: Geodesy and geomatics, mining, environmental protection and occupational safety. Sensors. 25(22), 6848.

[43] Maté-González, M.Á., Sáez Blázquez, C., Camargo Vargas, S.A., et al., 2025. Integrating advanced technologies for environmental valuation in legacy mining sites: The role of digital twins at Lavrion Technological and Cultural Park. Sensors. 25(19), 5941.

[44] Costantino, D., Angelini, M.G., 2011. Geodetic monitoring applied to a mine area. Applied Geomatics. 3(2), 61–74.

[45] Song, W., Song, W., Gu, H., et al., 2020. Progress in the remote sensing monitoring of the ecological environment in mining areas. International Journal of Environmental Research and Public Health. 17(6), 1846.

[46] McKenna, P.B., Lechner, A.M., Phinn, S., et al., 2020. Remote sensing of mine site rehabilitation for ecolog-

ical outcomes: A global systematic review. Remote Sensing. 12(21), 3535.

[47] Ren, H., Zhao, Y., He, T., 2025. Remote sensing in mining-related eco-environmental monitoring and assessment. Remote Sensing. 18(1), 103.

[48] Loukili, I., Laamrani, A., El Ghorfi, M., et al., 2025. Monitoring land changes at an open mine site using remote sensing and multi-spectral indices. Heliyon. 11(2).

[49] Zwissler, B., Oommen, T., Vitton, S., et al., 2017. Thermal remote sensing for moisture content monitoring of mine tailings: Laboratory study. Environmental & Engineering Geoscience. 23(4), 299–312.

[50] Mohammed, O.I., Saeidi, V., Pradhan, B., et al., 2014. Advanced differential interferometry synthetic aperture radar techniques for deformation monitoring: A review on sensors and recent research development. Geocarto International. 29(5), 536–553.

[51] Firozjaei, M.K., Sedighi, A., Firozjaei, H.K., et al., 2021. A historical and future impact assessment of mining activities on surface biophysical characteristics change: A remote sensing-based approach. Ecological Indicators. 122, 107264.

[52] Smentek, A., Kaczmarek, A., Eksert, P., et al., 2025. Monitoring surface water dynamics in mining areas using remote sensing indices: A review and cross-case analysis. Water. 17(19), 2826.

[53] Werner, T.T., Mudd, G.M., Schipper, A.M., et al., 2020. Global-scale remote sensing of mine areas and analysis of factors explaining their extent. Global Environmental Change. 60, 102007.

[54] Reid, J., Castka, P., 2023. The impact of remote sensing on monitoring and reporting—The case of conformance systems. Journal of Cleaner Production. 393, 136331.

[55] Rochon, G.L., Johannsen, C.J., Landgrebe, D.A., et al., 2003. Remote sensing as a tool for achieving and monitoring progress toward sustainability. Clean Technologies and Environmental Policy. 5(3), 310–316.

[56] Liang, R., 2024. The Development of a Data-Driven Visualisation System and Multimodal Data Fusion Platform for Underground Mines [PhD Thesis]. University of New South Wales: Sydney, Australia.