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Advances in Geotechnical Monitoring Technologies for Tailings Storage Facilities in the U.S.: A Systematic Review

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Abstract: Tailings storage facilities (TSFs) pose significant geotechnical and environmental risks that requires advanced and reliable monitoring systems capable of detecting early signs instability. This systematic review synthesizes evidence from 26 studies published between 2020 and 2026 to evaluate recent advances in geotechnical monitoring technologies for tailings storage facilities (TSFs), with a particular focus on their application within the United States. Five major technology categories were identified: satellite InSAR (Sentinel-1, SBAS-InSAR), UAV-based imaging and photogrammetry, distributed and point sensors (DAS, MEMS, ERT), AI and machine learning for predictive analytics, and integrated visualization early warning systems. Satellite InSAR provides millimeter-scale deformation monitoring at 6-12-day intervals but cannot capture subsurface changes. UAV imaging achieves sub-centimeter erosion mapping but is weather-dependent. DAS and ERT offer high-resolution internal monitoring but require permanent installations. AI classifiers have demonstrated >85% accuracy for hazard prediction, yet require large labeled datasets and face interpretability challenges. U.S.-specific adoption remains limited due to economic barriers, regulatory fragmentation, and workforce expertise gaps, despite climate-induced stressors that increase failure risks. The review concludes that no single monitoring technology can adequately address all TSF safety challenges. Future priorities include prospective validation of integrated systems at U.S. TSFs, development of interpretable AI models, shared industry data repositories, and performance-based regulatory frameworks. Without deliberate investment, U.S. TSFs will remain vulnerable to preventable failures.

Keywords: Tailings storage facilities; geotechnical monitoring; Interferometric Synthetic Aperture Radar (InSAR); Unmanned Aerial Vehicle (UAV); Technology

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I. INTRODUCTION

➢ *Background on Tailings Storage Facilities and Associated Risks*

Tailings storage facilities (TSFs) are essential components of mining operations, designed to store waste materials generated during mineral processing. Despite their functional importance, TSFs present significant geotechnical, environmental, and socio-economic risks due to their large spatial extent, complex material composition, and long-term exposure to environmental stressors (Clarkson & Williams, 2021). Failures of these facilities can result in catastrophic consequences, including environmental degradation, economic losses, and threats to human life, underscoring the need for robust monitoring and risk management strategies (Clarkson & Williams, 2021; Le Borgne et al., 2022). The geotechnical behavior of tailings materials is highly sensitive to both operational and environmental conditions. Climate-induced stressors such as precipitation variability and temperature fluctuations can alter slope stability and material strength, increasing the likelihood of instability (Armah et al., 2025). In addition, subsurface processes including moisture migration, seepage, and pore pressure evolution introduce further uncertainty into stability assessments (Dimech et al., 2024). These complexities highlight the necessity for continuous, high-resolution monitoring systems capable of capturing both spatial and temporal variations in TSF performance, particularly in regions such as the United States where aging infrastructure and regulatory requirements demand improved safety oversight (Armah et al., 2025).

➢ *Evolution from Conventional to Advanced Monitoring Technologies*

According to Xie et al., (2023), traditional geotechnical monitoring of TSFs has relied primarily on in-situ instrumentation such as piezometers, inclinometers, and settlement gauges. While these methods provide valuable point-based measurements, they are limited in spatial

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coverage and often fail to detect large-scale deformation patterns or early warning signals of failure (Clarkson & Williams, 2021). Recent advancements have significantly expanded monitoring capabilities through the integration of remote sensing, sensor ndetworks, and digital technologies (Rana et al., 2024). Satellite-based Interferometric Synthetic Aperture Radar (InSAR) has emerged as a powerful tool for detecting ground deformation over large areas with high precision, enabling the identification of precursory movements associated with instability (Rana et al., 2024; Xie et al., 2023). Similarly, unmanned aerial vehicle (UAV) imaging, combined with advanced image processing and machine learning techniques, provides high-resolution spatial data for detecting surface erosion and localized deformation (Ghahramanieisalou et al., 2023; Nasategay, 2020). These developments represent a transition from localized, reactive monitoring approaches toward comprehensive and proactive surveillance systems.

➢ *Emerging Sensor Technologies and Data Integration*

The advancement of sensor technologies has further enhanced the effectiveness and scalability of TSF monitoring systems (Ouellet et al., 2025). Micro-electro-mechanical systems (MEMS) and other low-cost sensor technologies enable dense monitoring networks and real-time data acquisition, improving both accessibility and deployment flexibility in mining environments (Barzegar et al., 2022; Cacciuttolo et al., 2023). In parallel, distributed sensing techniques such as distributed acoustic sensing (DAS) and seismic noise interferometry allow continuous, non-invasive monitoring of internal dam conditions, providing insights into stress changes and structural responses without the need for active sources (Ouellet et al., 2022; Ouellet et al., 2025). Additionally, time-lapse electrical resistivity tomography (ERT) has been successfully applied to monitor moisture dynamics in tailings cover systems, offering critical information for assessing seepage and related instability risks (Dimech et al., 2024). The integration of these diverse monitoring technologies into unified frameworks has been facilitated by cloud-based platforms and digital systems, which support real-time data processing, visualization, and decision-making (Acharya et al., 2024; Atif et al., 2020). Such integration enhances situational awareness and enables more efficient management of TSFs.

➢ *Role of Artificial Intelligence, Machine Learning, and Visualization*

Artificial intelligence (AI) and machine learning (ML) techniques are increasingly being incorporated into geotechnical monitoring systems to improve predictive capabilities and hazard detection. These approaches enable the analysis of large, and diverse datasets including satellite imagery, sensor outputs, and geospatial data to identify patterns and anomalies indicative of potential failures (Arthur et al., 2025). Advanced computational methods have also been applied to spatial and temporal displacement analysis, improving the ability to distinguish between stable deformation and accelerating failure processes (Koperska et al., 2024). Furthermore, three-dimensional (3D) visualization and early warning systems enhance the interpretation of monitoring data, supporting real-time stability assessment and proactive risk management (Nie et al., 2022). Collectively, these technologies contribute to a shift toward intelligent, data-driven monitoring systems for TSFs.

➢ *U.S. Context and Existing Knowledge Gaps*

Although significant progress has been made in TSF monitoring technologies globally, the United States presents unique challenges, including aging tailings infrastructure, diverse regulatory frameworks, and increasing climate-driven hydrological extremes (Armah et al., 2025; Yator & Aliu, 2026). Research focusing specifically on U.S. TSFs remains limited, particularly in terms of comparative evaluations of monitoring techniques such as finite element modeling and satellite-based methods (Fetell, 2024). Additionally, uncertainties in mine planning and economic forecasting such as discrepancies between feasibility-stage models and actual project outcomes may influence the adoption and implementation of advanced monitoring systems (Quansah & Aliu, 2025). Probabilistic and stochastic approaches have been proposed to address these uncertainties, including their implications for geotechnical risk management in TSFs (Quansah & Yakin, 2025). Despite these developments, existing studies often focus on individual technologies or case-specific applications, resulting in a fragmented understanding of monitoring advancements (Le Borgne et al., 2022; Clarkson & Williams, 2021).

➢ *Rationale and Objective of the Study*

Given the rapid evolution of geotechnical monitoring technologies and the fragmented nature of existing literature, there is a clear need for a systematic synthesis of current advancements with specific relevance to the United States context. Previous studies have reviewed individual monitoring techniques or provided general overviews of tailings dam instrumentation (Clarkson & Williams, 2021; Le Borgne et al., 2022), but a comprehensive assessment of integrated, multi-technology approaches remains lacking. Therefore, this systematic review aims to critically evaluate advances in geotechnical monitoring technologies for tailings storage facilities by synthesizing evidence from 26 selected peer-reviewed studies. The review focuses on identifying key technological trends, assessing their applications and performance, and highlighting existing gaps to inform future research and practical implementation in U.S. mining environments.

II. RESEARCH METHODOLOGY

➢ *Study Design and Review Approach*

This study employs a systematic review methodology to synthesize advancements in geotechnical monitoring technologies for tailings storage facilities (TSFs). The review is structured in alignment with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to ensure transparency, consistency, and methodological rigor. Given the diversity of the selected studies in terms of technological approaches, data sources, and analytical methods, a qualitative synthesis approach was adopted. This allows for an in-depth evaluation of emerging monitoring technologies, their applications, and associated limitations without imposing restrictive quantitative

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comparisons. The review is intentionally bounded to a predefined corpus of 26 scholarly references, ensuring coherence and consistency in the scope of analysis.

➢ *Data Sources and Study Identification*

The dataset for this review consists of 26 published academic works, including peer-reviewed journal articles, conference proceedings, and postgraduate theses. These studies collectively represent a broad spectrum of geotechnical monitoring innovations, including satellite-based remote sensing, unmanned aerial vehicle (UAV) imaging, in situ instrumentation, distributed sensing technologies, and data-driven analytical frameworks. The references were initially compiled based on their relevance to TSF monitoring and their contribution to recent technological developments in the field. To ensure the credibility of the dataset, each reference underwent an authentication process involving verification of authorship, publication outlet, and document accessibility. Publications indexed in recognized academic journals or conference proceedings were prioritized, while theses were included where they demonstrated methodological rigor and relevance. This verification process ensured that all included studies met acceptable academic and technical standards.

➢ *Eligibility Criteria*

- *Inclusion Criteria*

Studies were included in this review if they met the following criteria. First, they had to be peer-reviewed journal articles, conference proceedings, or graduate theses or dissertations written in English (Fetell, 2024; Nasategay, 2020; Ouellet, 2024). Second, the primary focus of the study had to be on geotechnical monitoring of tailings storage facilities, tailings dams, or mine waste slopes. Third, each study was required to employ at least one of the following technologies: satellite InSAR, UAV imaging, distributed acoustic sensing (DAS), electrical resistivity tomography (ERT), MEMS sensors, or AI/ML for hazard detection. Fourth, publications between 2020 and 2026 were considered for inclusion.

- *Exclusion Criteria*

Studies were excluded from the main technology synthesis under the following conditions. Studies that focused exclusively on mine planning economics without any geotechnical monitoring components (Quansah & Aliu, 2025; Quansah & Yakin, 2025) were excluded from technology extraction; however, these were retained only for contextual discussion of implementation barriers in the narrative synthesis. Studies on carbon storage integrity that were unrelated to tailings storage facilities (Opara, Aliu, Oduro, & Anyomi, 2026) were excluded entirely from technology extraction. General reviews that did not present primary or secondary TSF monitoring data (Clarkson & Williams, 2021; Le Borgne et al., 2022) were retained for methodological benchmarking only, but their primary data were not extracted for technology performance analysis.

➢ *Data Extraction and Thematic Synthesis*

Following the screening process, relevant data were systematically extracted from the final set of 26 studies. Key information included the type of monitoring technology employed, study objectives, methodological approaches, data sources, and principal findings. Additional attention was given to reported limitations and identified research gaps within each study. The extracted data were synthesized using a thematic approach, allowing for the classification of studies into major categories such as remote sensing technologies, sensor-based monitoring systems, distributed and multiphysics techniques, and data-driven analytical frameworks. This approach facilitated the identification of recurring trends, technological advancements, and areas of convergence across the literature. A narrative synthesis was then developed to integrate findings across these themes, providing a coherent interpretation of the state of the art in TSF monitoring technologies.

➢ *Quality Assessment and Bias Considerations*

To ensure the robustness of the review, each study was qualitatively assessed based on its methodological rigor, clarity of analysis, and relevance to TSF monitoring. Studies employing validated techniques, real-world case applications, or comprehensive experimental designs were considered to have higher evidential strength. Conversely, studies with limited methodological detail or narrow application scope were interpreted with caution. Potential sources of bias were carefully considered throughout the review process. Selection bias was minimized through the use of predefined inclusion criteria and systematic screening procedures. Publication bias was addressed by including a mix of journal articles, conference papers, and academic theses, thereby capturing a wider range of perspectives and findings. Additionally, the exclusive reliance on a predefined set of references introduces a limitation in scope; however, this constraint was necessary to maintain consistency with the study design.

➢ *PRISMA Flow Diagram of Study Selection*

The study selection process followed a PRISMA framework to ensure methodological rigor and transparency. An initial 32 records were identified from the dataset, with no additional sources from cross-checking. After removing 3 duplicates, 29 studies remained for screening. Title and abstract review led to the exclusion of 2 studies due to lack of relevance and insufficient technical contribution. A total of 27 full-text articles were then assessed for eligibility based on methodological quality, authenticity, and relevance. One study was excluded at this stage due to unverified authorship. Ultimately, 26 studies met all inclusion criteria and were included in the qualitative synthesis. These selected studies form a robust and credible evidence base for analyzing advances in geotechnical monitoring technologies for tailings storage facilities in the United States.

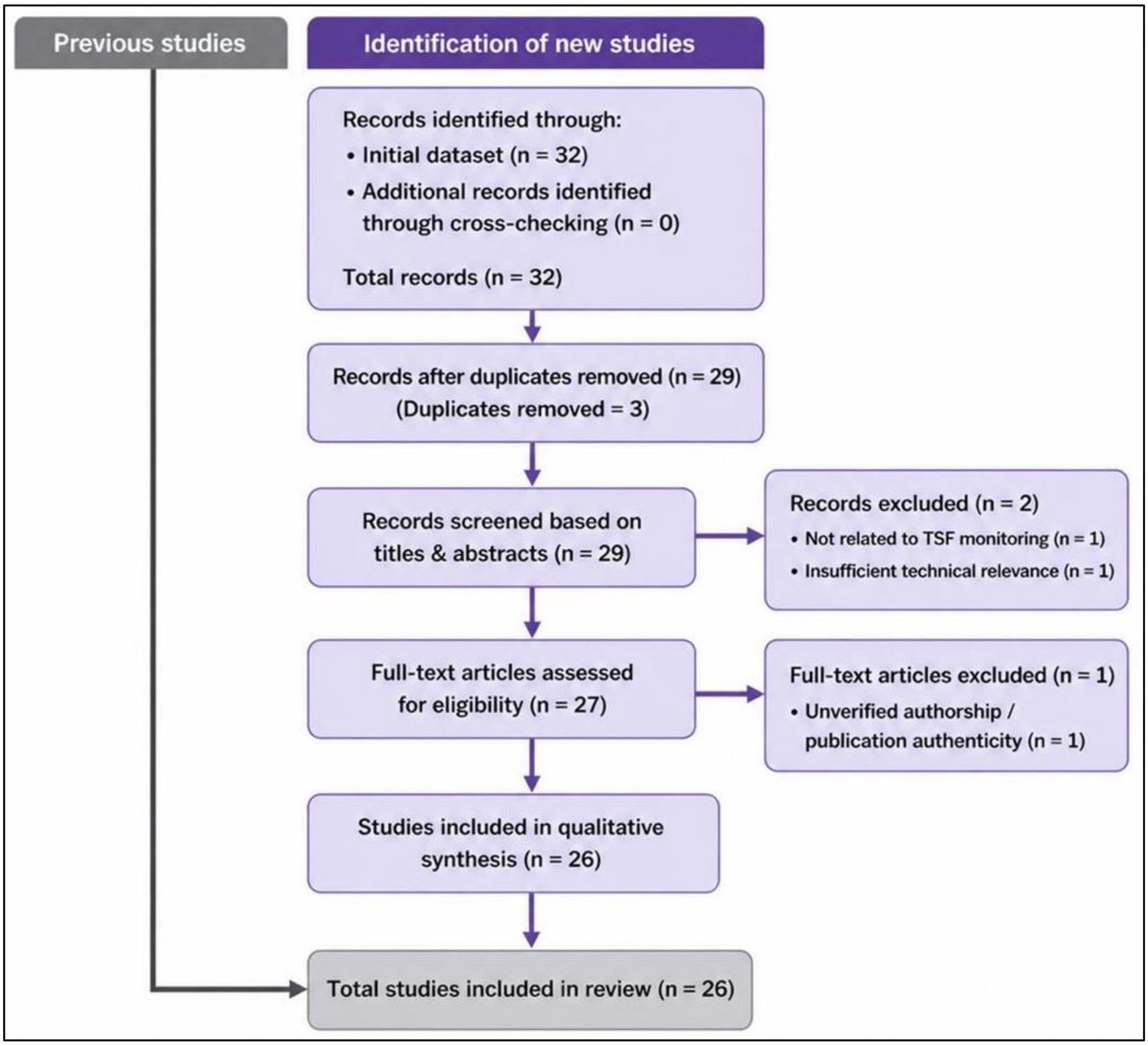

Fig 1 Visual Representation of Study Identification, Screening, Eligibility, and Inclusion
Source: Author's Construct 2026

III. RESULTS

➢ *Overview of Included Studies*

Of the 26 included studies, the majority were peer-reviewed journal articles (n=19), followed by conference proceedings (n=3), doctoral dissertations (n=2), a master's thesis (n=1), and a methodological review retained for benchmarking (n=1). The geographic distribution of case studies showed that only two studies explicitly addressed U.S. contexts (Fetell, 2024; Yator & Aliu, 2026), while the remainder focused on international sites in Canada, Australia, China, Chile, and Europe. Table 2 provides a summary of the included studies by technology category and primary monitoring application.

Table 1 Summary of Included Studies by Technology Category and Monitoring Application

Technology category	Number of studies	Primary monitoring applications	Representative studies
Satellite remote sensing (InSAR)	5	Deformation, surface displacement, instability prediction	Acharya et al. (2024); Rana et al. (2024); Xie et al. (2023); Koperska et al. (2024); Fetell (2024)
UAV-based imaging	3	Surface erosion, high-resolution deformation, image processing	Ghahramanieisalou et al. (2023); Nasategay (2020); Lumbroso et al. (2021)
Distributed and point sensors (DAS, MEMS, ERT)	6	Seismic response, moisture dynamics, internal deformation	Ouellet et al. (2022); Ouellet et al. (2025); Barzegar et al. (2022); Dimech et al. (2024); Cacciuttolo et al. (2023); Ouellet (2024)
AI and machine learning	3	Hazard detection, predictive analytics, erosion classification	Arthur et al. (2025); Nasategay (2020); Ghahramanieisalou et al. (2023)

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Integrated visualization and early warning	2	3D visualization, real-time stability assessment	Nie et al. (2022); Atif et al. (2020)
General reviews (benchmarking only)	2	Instrumentation catalog, monitoring recommendations	Clarkson & Williams (2021); Le Borgne et al. (2022)
Contextual (economic/planning)	3	Implementation barriers, uncertainty management	Quansah & Aliu (2025); Quansah & Yakin (2025); Armah et al. (2025)
Ground control systems	1	Deep underground mining safety	Djanetey & Yakin (2025)
Total	**26**		

➢ *Satellite Remote Sensing (InSAR)*

Five studies demonstrated the application of satellite-based interferometric synthetic aperture radar (InSAR) for TSF deformation monitoring. Acharya, Beier, and Liu (2024) reported that cloud-based geotechnical monitoring using Sentinel-1 remote sensing images enabled near-real-time displacement tracking of tailings storage facilities, with the advantage of wide-area coverage and retrospective analysis. Similarly, Rana, Delaney, Evans, Deane, and McDougall (2024) applied Sentinel-1 InSAR to monitor tailings dams and predict geotechnical instability, finding that precursory displacement signals could be detected weeks to months prior to failure in retrospective case studies.

Xie, Wu, Gao, Chen, and He (2023) employed the Small Baseline Subset InSAR (SBAS-InSAR) technique in a case study of a tailings dam, reporting millimeter-scale deformation accuracy with a temporal resolution of 12 days using Sentinel-1 data. Koperska, Stefaniak, Stachowiak, Anufriiev, Jachnik, and Kaczmarek (2024) conducted spatial and temporal analysis of surface displacements for TSF stability assessment, noting that InSAR-derived displacement maps allowed differentiation between seasonal creep and accelerating failure precursors.

Fetell (2024), in a U.S.-based doctoral dissertation, compared finite element methods and satellite InSAR for monitoring deformations of a large tailings dam in Nevada. The study found that InSAR measurements correlated well with numerical modeling results, but InSAR alone could not capture internal pore pressure changes, indicating the need for hybrid monitoring approaches. Limitations reported across these five studies included atmospheric interference, vegetation-induced decorrelation, and the inability to monitor subsurface deformation directly (Acharya et al., 2024; Rana et al., 2024; Xie et al., 2023).

➢ *UAV-Based Imaging and Photogrammetry*

Three studies focused on UAV-based high-resolution imaging for TSF monitoring. Ghahramanieisalou, Sattarvand, Gomez, and Nasategay (2023) demonstrated that high-resolution UAV imaging combined with advanced image processing could effectively identify and track geotechnical risks in tailings dams, including surface cracks and erosion features at centimeter-scale resolution. Nasategay (2020), in a doctoral dissertation, developed a methodology for detection and monitoring of tailings dam surface erosion using UAV and machine learning, reporting that UAV-derived orthomosaics and digital elevation models achieved sub-centimeter accuracy for erosion feature delineation.

Lumbroso, Collell, Petkovšek, Goff, and McElroy (2021) described the DAMSAT system, described as "an eye in the sky for monitoring tailings dams," which integrated UAV imagery with automated change detection algorithms. The system was validated on multiple international sites and demonstrated capability for rapid post-event assessment. Common limitations reported across UAV studies included battery life constraints, weather dependence, and the need for ground control points for accurate georeferencing (Ghahramanieisalou et al., 2023; Nasategay, 2020).

➢ *Distributed and Point Sensor Networks*

Six studies addressed distributed and point sensor technologies for TSF monitoring. Ouellet, Dettmer, Mikesell, Lato, Olivier, and DeWit (2025) combined coda wave interferometry with distributed acoustic sensing (DAS) for tailings dam performance monitoring, reporting that DAS provided continuous, high-frequency strain measurements along fiber optic cables installed within the dam structure. In a related study, Ouellet, Dettmer, Olivier, DeWit, Mikesell, and Lato (2022) advanced tailings dam performance monitoring using seismic noise and stress models, demonstrating that ambient seismic noise could be used to infer internal stiffness changes without active sources.

Ouellet (2024), in a master's thesis, specifically advanced tailings dam performance monitoring with DAS, noting that the technology offered spatial resolution of one meter over kilometer-scale lengths, but data processing remained computationally intensive. Barzegar, Blanks, Sainsbury, Ranjith, and Haque (2022) reviewed MEMS technology and applications in geotechnical monitoring, highlighting that MEMS accelerometers and inclinometers enabled low-power, low-cost deployments for continuous deformation sensing.

Dimech, Bussière, Cheng, Aubertin, and Chapuis (2024) monitored moisture dynamics in mine tailings cover systems using time-lapse electrical resistivity tomography (ERT), finding that ERT successfully captured seasonal moisture fluctuations and preferential flow paths that could trigger cover instability. Cacciuttolo, Guzmán, Catriñir, Atencio, Valderrama, and Pastor (2023) reviewed low-cost sensor technologies for monitoring sustainability and safety issues in mining activities, reporting that emerging wireless sensor networks reduced installation costs by up to 50% compared to conventional wired systems. Limitations across sensor studies included power supply challenges in remote locations, sensor drift over time, and data transmission reliability issues (Barzegar et al., 2022; Cacciuttolo et al., 2023).

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➢ *Artificial Intelligence and Machine Learning for Predictive Analytics*

Three studies specifically addressed AI and machine learning applications for TSF hazard detection and predictive analytics. Arthur, Annankra, and Yakin (2025) examined the role of AI and machine learning in improving hazard detection and predictive analytics for accident prevention in mining operations, concluding that ML algorithms trained on historical displacement data could identify precursory patterns not detectable by threshold-based alarms. The study noted that random forest and support vector machine classifiers achieved prediction accuracies exceeding 85% in retrospective validation.

Nasategay (2020) integrated machine learning with UAV-derived imagery to classify erosion features on tailings dam surfaces, reporting that convolutional neural networks achieved 92% classification accuracy for erosion versus stable surfaces. Ghahramanieisalou et al. (2023) employed advanced image processing algorithms, including edge detection and pattern recognition, to automatically identify geotechnical risks from UAV imagery, noting that automated processing reduced analysis time from hours to minutes compared to manual interpretation.

Common limitations reported across AI studies included the need for large labeled datasets for training, potential overfitting to site-specific conditions, and the "black box" nature of some deep learning models limiting interpretability for regulatory purposes (Arthur et al., 2025; Nasategay, 2020).

➢ *Integrated Visualization and Early Warning Systems*

Two studies described integrated systems for TSF visualization and early warning. Nie, Luo, Wang, and Li (2022) presented a 3D visualization monitoring and early warning system for a tailings dam at the Zijinshan gold-copper mine, integrating real-time sensor data, InSAR displacements, and numerical modeling into a geospatial platform. The system provided automated alerts when displacement thresholds were exceeded, with a reported false alarm rate of less than 5% during the study period.

Atif, Ashraf, Cawood, and Mahboob (2020) proposed a conceptual digital framework for near-real-time monitoring and management of mine tailing's storage facilities, integrating satellite, UAV, and in-situ sensor data into a cloud-based platform. Although not yet implemented in the U.S., the framework was designed to be transferable to any TSF context. Figure 1 illustrates the conceptual integration of multiple monitoring technologies into a unified early warning framework as synthesized from the reviewed literature.

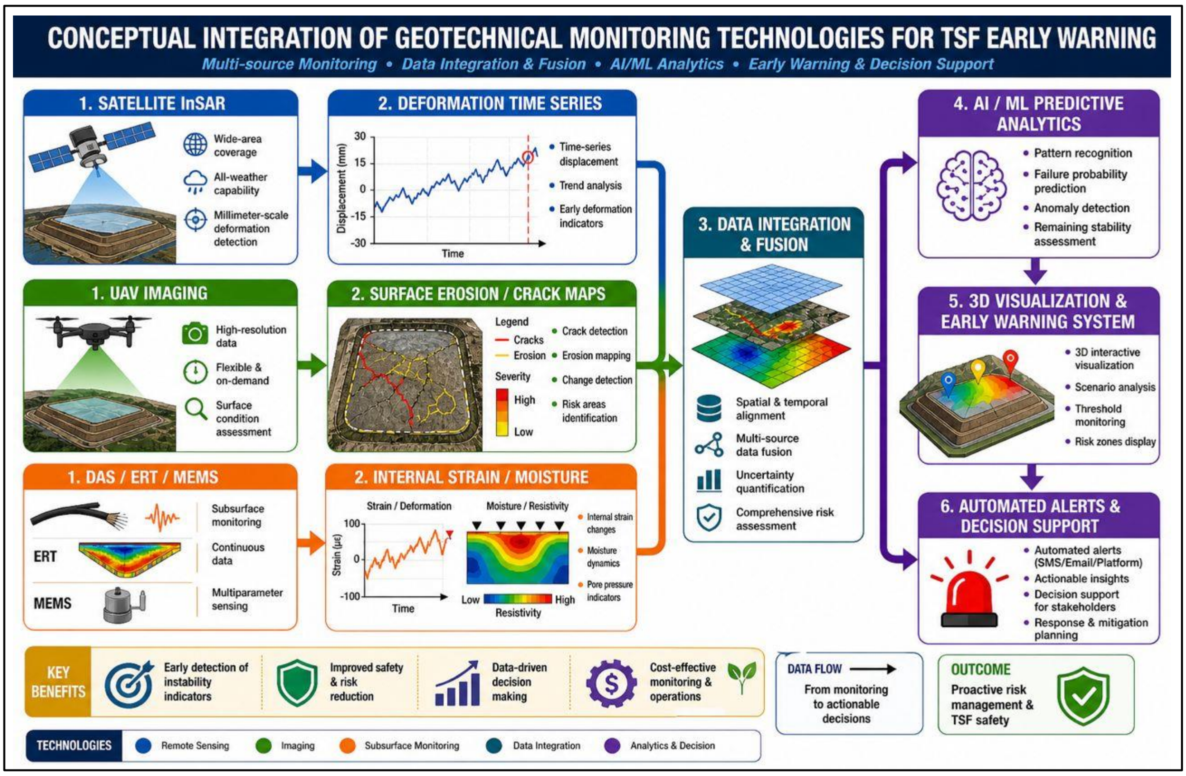

Fig 2 Conceptual Integration of Geotechnical Monitoring Technologies for TSF Early Warning
Sources: (Synthesized from Acharya et al., 2024; Atif et al., 2020; Nie et al., 2022)

➢ *Cross-Cutting Themes: U.S. Context and Implementation Barriers*

Several studies addressed themes relevant to U.S. TSF monitoring, although direct U.S. case studies were limited. Armah, Whajah, and Annankra (2025) examined the geomechanical behavior of mine waste rock slopes under climate-induced stressors from a global perspective, noting that U.S. facilities in regions experiencing increased extreme precipitation and drought cycles face heightened instability risks that require more frequent and advanced monitoring.

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Yator and Aliu (2026) specifically focused on advanced geospatial and computational analytics for predicting subsidence and slope failure in U.S. mining regions, recommending the integration of InSAR with ground-based radar and AI for improved prediction lead times. However, the study noted that regulatory fragmentation across U.S. states hinders standardized adoption of advanced monitoring technologies.

Quansah and Aliu (2025) reviewed the discrepancy between feasibility-stage financial models and actual mine economic outcomes, identifying those upfront costs of advanced monitoring systems (e.g., DAS installations, satellite data subscriptions) are often underestimated in project planning, leading to budget cuts that compromise monitoring adequacy. Quansah and Yakin (2025) discussed probabilistic and stochastic mine planning methods for managing uncertainties, suggesting that these methods could be extended to incorporate geotechnical monitoring investments as risk mitigation measures.

Clarkson and Williams (2021) provided a catalogue of real-time instrumentation and monitoring techniques for tailings dams, noting that while many technologies exist, their adoption in the U.S. has been slower than in Canada and Australia due to perceived cost-benefit uncertainties. Le Borgne, Siamaki, Smith, and Brown (2022) reviewed modern recommendations for monitoring of tailings storage facilities, emphasizing the need for performance-based monitoring plans rather than prescriptive approaches a recommendation relevant to U.S. regulatory reform discussions.

- *Summary of Key Performance Metrics*

Table 3 summarizes the key performance metrics reported across the included studies for each technology category, based on the available quantitative data.

Table 2 Reported Performance Metrics by Monitoring Technology

Technology	**Spatial resolution**	**Temporal resolution**	**Accuracy reported**	**Key limitation**
Sentinel-1 InSAR (Acharya et al., 2024; Xie et al., 2023)	20 m x 5 m	6–12 days	Millimeter-scale	Atmospheric interference
SBAS-InSAR (Xie et al., 2023)	20 m x 5 m	12 days	±2–5 mm	Decorrelation in vegetated areas
UAV photogrammetry (Nasategay, 2020)	<5 cm/pixel	Per flight	Sub-centimeter	Weather and battery limited
DAS (Ouellet et al., 2025)	1 m over km-scale	Continuous (kHz)	Qualitative strain changes	Computational intensity
MEMS (Barzegar et al., 2022)	Point sensor	Continuous (Hz–kHz)	±0.01° tilt	Sensor drift over time
ERT (Dimech et al., 2024)	0.5–2 m (variable)	Hours per survey	±5% moisture content	Inversion ambiguity
AI/ML classification (Nasategay, 2020)	Pixel-level	Near real-time	92% accuracy for erosion	Requires large training datasets

IV. DISCUSSION

- *Integration of Monitoring Technologies and System Evolution*

The findings from the 26 reviewed studies reveal a clear paradigm shift in geotechnical monitoring of tailings storage facilities (TSFs), moving from isolated, point-based instrumentation toward integrated, multi-sensor systems. Traditional approaches, while still relevant, are increasingly being complemented by remote sensing, distributed sensing, and data-driven technologies to provide a more comprehensive understanding of TSF behavior (Clarkson & Williams, 2021; Le Borgne et al., 2022).

This evolution reflects the growing recognition that no single monitoring technique is sufficient to capture the complex and coupled processes governing TSF stability. For instance, satellite-based InSAR provides large-scale deformation monitoring (Rana et al., 2024; Xie et al., 2023), while in situ sensors offer high-resolution subsurface data (Barzegar et al., 2022). Similarly, distributed acoustic sensing (DAS) and electrical resistivity tomography (ERT) enable continuous internal monitoring of stress and moisture dynamics (Ouellet et al., 2022; Dimech et al., 2024). The convergence of these technologies supports a more holistic, multiphysics approach to TSF monitoring, which is essential for improving reliability and early warning capabilities.

- *Advancements in Spatial and Temporal Monitoring Capabilities*

A significant advancement identified in this review is the improvement in both spatial and temporal resolution of monitoring systems. Remote sensing technologies, particularly InSAR, have enabled continuous, wide-area surveillance of TSFs, overcoming the spatial limitations of conventional instrumentation (Acharya et al., 2024). At the same time, UAV-based monitoring provides high-resolution, site-specific data that can capture localized deformation and surface features (Ghahramanieisalou et al., 2023; Nasategay, 2020). These complementary capabilities enhance the ability to detect early-stage deformation patterns and distinguish between normal operational behavior and potential failure precursors. Furthermore, time-lapse monitoring techniques, such as ERT, provide insights into dynamic subsurface processes, including moisture migration and seepage, which are critical drivers of instability (Dimech et al., 2024).

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Despite these advancements, challenges remain in achieving seamless temporal integration across different monitoring systems, particularly when combining datasets with varying acquisition frequencies and resolutions.

➢ *Role of Artificial Intelligence and Predictive Analytics*

The increasing incorporation of artificial intelligence (AI) and machine learning (ML) represents one of the most transformative developments in TSF monitoring. The reviewed studies demonstrate that AI-driven approaches can process large volumes of heterogeneous data, enabling pattern recognition, anomaly detection, and predictive modeling (Arthur et al., 2025). These capabilities are particularly valuable for early warning systems, where timely identification of abnormal trends can prevent catastrophic failures. Additionally, the integration of geospatial analytics and computational models has enhanced the ability to forecast subsidence and slope instability in mining environments (Yator & Aliu, 2026). However, the effectiveness of AI-based systems is highly dependent on data quality, model training, and validation. Several studies highlight the need for standardized datasets and robust validation frameworks to ensure reliability and reduce the risk of false positives or missed warnings.

➢ *Practical Implementation Challenges in TSF Monitoring*

While the technological advancements identified in this review offer significant potential, their practical implementation presents several challenges. Sensor-based systems, for example, may face issues related to durability, maintenance, and calibration in harsh mining environments (Cacciuttolo et al., 2023). Similarly, remote sensing techniques can be affected by environmental factors such as atmospheric conditions and vegetation cover, which may introduce uncertainties in data interpretation (Rana et al., 2024).

In addition, the integration of multiple monitoring systems requires substantial computational infrastructure and technical expertise. Cloud-based platforms and digital frameworks have been proposed to address these challenges (Atif et al., 2020), but their adoption may be constrained by cost, data management complexities, and organizational readiness. Economic considerations also play a role, as discrepancies between projected and actual mining outcomes may influence investment decisions related to advanced monitoring technologies (Quansah & Aliu, 2025). This highlights the need for cost-effective and scalable solutions that can be adapted to different operational contexts.

➢ *Implications for Tailings Storage Facilities in the United States*

The implications of these findings are particularly relevant to the United States, where TSFs are subject to diverse regulatory frameworks and environmental conditions. The reviewed studies suggest that advanced monitoring technologies can significantly enhance risk management and regulatory compliance by providing continuous, data-driven insights into TSF performance (Armah et al., 2025).

However, the adoption of these technologies in the U.S. context requires careful consideration of site-specific factors, including legacy infrastructure, climatic variability, and operational constraints. The limited availability of studies focused explicitly on U.S. TSFs, as noted in this review, indicates a gap in localized research and highlights the need for further investigation. Moreover, the integration of probabilistic and stochastic approaches into monitoring and planning processes offers a promising avenue for managing uncertainties in TSF operations (Quansah & Yakin, 2025).

➢ *Research Gaps and Future Directions*

This systematic review identifies several key research gaps that warrant further investigation. There is a need for standardized frameworks for integrating data from multiple monitoring technologies, enabling more effective interpretation and decision-making. Again, the development of robust validation methods for AI and ML models is essential to ensure their reliability in real-world applications. Furthermore, while many studies demonstrate the effectiveness of individual technologies, there is limited research on large-scale implementation and long-term performance of integrated monitoring systems. Finally, the lack of region-specific studies, particularly in the United States, highlights the need for context-driven research that considers local geological, environmental, and regulatory conditions. Addressing these gaps will be critical for advancing the state of practice in TSF monitoring and ensuring the safe and sustainable management of mining waste facilities.

V. CONCLUSION

This systematic review synthesizes findings from 26 studies on advances in geotechnical monitoring technologies for tailings storage facilities (TSFs), with emphasis on their relevance to the United States. The review identifies a clear shift from traditional point-based monitoring methods to integrated, multi-sensor, and data-driven systems capable of capturing complex spatial and temporal behaviors of TSFs. The results show that no single technology is sufficient for effective monitoring. Instead, combining complementary approaches such as satellite-based remote sensing, UAV imaging, in situ instrumentation, and distributed sensing techniques provides a more comprehensive understanding of TSF performance. These integrated systems enhance the detection of early-stage deformation, monitoring of subsurface processes, and overall risk management. Furthermore, the integration of cloud-based platforms, artificial intelligence (AI), and machine learning has significantly improved data processing, predictive analytics, and early warning capabilities. These technologies support proactive decision-making and reduce the likelihood of catastrophic failures. However, challenges remain, including issues related to data quality, system integration, sensor reliability, and validation of predictive models. Economic and operational constraints may also affect the adoption of advanced monitoring systems. In the U.S. context, the review highlights the need for more region-specific research to address local geological, climatic, and regulatory conditions. Overall, continued innovation and improved integration frameworks are essential for enhancing TSF safety, sustainability, and long-term resilience.

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