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# Advancing Tailings Dam Safety: Integrating Risk Management, Technological Innovations, and Regulatory Reforms

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**Abstract** Tailings dams are critical structures used in the mining industry to store waste materials from mineral extraction. Despite their essential role, tailings dams pose significant safety risks, as evidenced by several catastrophic failures, such as the Brumadinho disaster in Brazil and the Mount Polley incident in Canada. This research explores the effectiveness of current risk management practices, technological innovations, and regulatory frameworks in improving the safety of tailings dams. A comparative analysis of tailings dam incidents, monitoring technologies, and regulatory compliance was conducted, utilizing both primary data from expert surveys and secondary data from historical case studies and monitoring records. The study reveals that real-time monitoring technologies, such as IoT sensors and drones, significantly enhance the early detection of potential failures. However, AI-based predictive models, while promising, remain limited by data gaps and insufficient model calibration. Additionally, the analysis of regulatory frameworks highlights the positive correlation between strong regulatory compliance and a reduction in tailings dam failures. Stronger enforcement and global standardization are identified as key factors in improving safety practices. The findings suggest that the integration of advanced monitoring systems, improved predictive modeling, and the strengthening of global regulatory frameworks can lead to safer tailings dam operations. This study provides actionable recommendations for industry professionals, regulators, and policymakers to enhance tailings dam safety and prevent future disasters.

***Keywords:*** *Tailings Dam Safety, Predictive Models, Real-Time Monitoring, Risk Management, Regulatory Compliance*

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## 1. Introduction

Tailings dams are critical infrastructure used in the mining industry to store the waste byproducts, or tailings, that result from the extraction of valuable minerals. These structures are essential in preventing environmental contamination and managing the large volumes of waste produced during mining operations. However, the safety of tailings dams has become an increasingly urgent global concern, particularly in light of several high-profile failures in recent years. Notable disasters such as the Brumadinho disaster in Brazil (2019), which resulted in the loss of over 270 lives and widespread environmental damage, have brought the issue of tailings dam safety to the forefront of public and regulatory attention [1]. Similar catastrophic incidents, such as the Mount Polley failure in Canada (2014), have highlighted significant weaknesses in current safety practices and risk management strategies in tailings dam design and operation.

Despite the critical role tailings dams play in managing mining waste, they pose significant risks to both human life and the environment. Historically, the management of these dams has been reactive, often relying on periodic inspections and insufficient monitoring systems that fail to identify early signs of instability. The absence of comprehensive, real-time monitoring technologies and the lack of a robust understanding of potential failure modes have exacerbated the risks associated with these structures [2]. This reactive approach has contributed to the increasing frequency of tailings dam failures, underscoring the need for improved risk assessment models, real-time monitoring, and predictive technologies that can prevent such disasters before they occur.

Recent regulatory frameworks, such as the Global Industry Standard on Tailings Management (GISTM) introduced by the International Council on Mining and Metals (ICMM), have sought to address these challenges by promoting more stringent safety standards, greater transparency, and accountability in tailings dam management [3]. However, the implementation of these regulations remains inconsistent across different regions, and there are still significant gaps in their effectiveness. The variability in enforcement practices and the prioritization of cost over safety by mining companies continue to undermine the safety of tailings dams, as evidenced by the Brumadinho and other similar failures [4]. These gaps in regulatory enforcement further illustrate the need for a more integrated approach to tailings dam safety, combining advancements in technology with stronger regulatory frameworks to create a safer and more resilient system.

Despite advancements in monitoring technologies and the introduction of regulatory reforms, the safety management practices for tailings dams still exhibit critical shortcomings. Traditional risk assessment models, such as Failure Mode and Effects Analysis (FMEA) and Quantitative Risk Assessment (QRA), are often reactive and fail to predict potential failures in real-time. Furthermore, many existing monitoring systems are not integrated in a manner that provides continuous, real-time data to decision-makers, leading to delays in responding to early warning signs of dam instability. As Figure 1 illustrates, the frequency of tailings dam failures has risen significantly over the past two decades, particularly in the last five years. This increase in incidents reflects the ongoing vulnerabilities in current risk management strategies and underscores the urgency of adopting more proactive and integrated approaches.

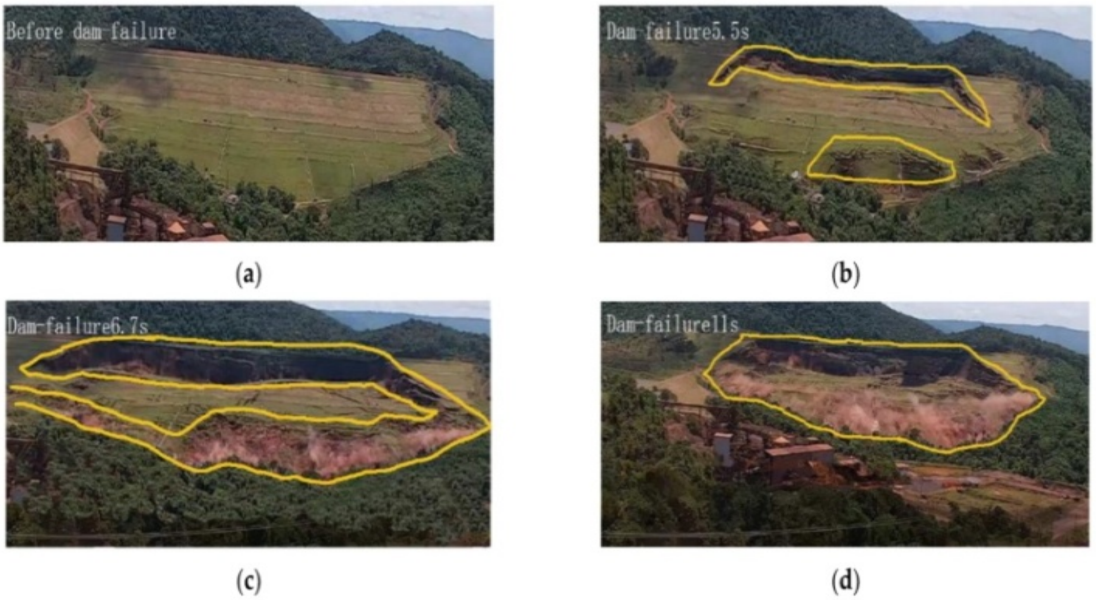


**Figure 1.** Frequency of Tailings Dam Failures

The gap between existing monitoring technologies and the requirements for continuous, real-time surveillance leaves tailings dams vulnerable to catastrophic events. The limitations of traditional monitoring methods such as visual inspections and periodic evaluations often fail to detect early indicators of structural failure [5]. This research aims to bridge these gaps by evaluating current risk assessment models, proposing new predictive technologies, and assessing the impact of regulatory reforms on the safety of tailings dams. Specifically, the study aims to evaluate the effectiveness of existing risk management practices, explore the potential of AI-based predictive models, and examine how recent regulatory changes have influenced safety outcomes in the mining industry.

The specific objectives of this study are as follows:

(1). To evaluate the effectiveness of current risk assessment models used in the mining industry to assess the safety of tailings dams, identifying their limitations and areas for improvement.

(2). To explore the potential of AI-based predictive models and real-time monitoring technologies in enhancing the early detection of tailings dam failure, thereby reducing the likelihood of catastrophic incidents [6].

(3). To assess the impact of regulatory reforms on tailings dam safety, examining how recent changes to global regulations, such as the ICMM's GISTM, have influenced industry practices and safety standards [3].

(4). To propose a framework for integrating advanced monitoring technologies with regulatory improvements, creating a more robust safety management system for tailings dams.

This research is guided by the following hypotheses:

(1). AI-based predictive models, when integrated with real-time data, can enhance the timeliness and accuracy of early failure detection, enabling predictive alerts that can help prevent disasters [6].

(2). Regulatory reforms, particularly those that emphasize transparency and accountability, such as the GISTM, have led to measurable improvements in safety practices and a reduction in tailings dam failures [7].

(3). The integration of real-time monitoring systems (e.g., IoT sensors, drones) into existing safety protocols can reduce the time to detect failure indicators, improve response times, and enhance overall safety [8].
(4). Current risk management frameworks fail to sufficiently account for the increased risks posed by extreme weather events and climate change, which exacerbate the instability of tailings dams [9].

The failure of tailings dams represents one of the most catastrophic environmental and human tragedies in recent history. Notable incidents like Brumadinho [10] and Mount Polley [11] have underscored the critical need for improved safety management and risk mitigation strategies. Despite efforts to enhance monitoring and enforce safety standards, the recurrence of such incidents demonstrates that fundamental gaps still exist in safety practices. This study aims to address these gaps by providing insights into the role of advanced monitoring technologies, AI-based predictive models, and regulatory reforms in improving the safety and stability of tailings dams.

# 2. Methodology

## 2.1. Research Design

The research **adopted** a comparative analysis approach to evaluate tailings dam safety, focusing on risk management practices, technological innovations, and regulatory compliance. The study **was designed** to compare the current state of tailings dam safety with best practices and evaluate the effectiveness of emerging technologies, such as AI-based predictive models and real-time monitoring systems. This methodology **involved** a review of secondary data (including tailings dam failure reports, monitoring data, and regulatory frameworks) and primary data collection from expert interviews [12]. A case study approach **was employed** to analyze specific tailings dam incidents, such as Brumadinho [13] and Mount Polley [14], to explore failure causes, regulatory gaps, and technological challenges [1,13,14,15]. Figure 2 **outlines** the research methodology used to assess the safety of tailings dams. The approach **combined** a comparative analysis of current safety practices with best practices and **evaluated** the effectiveness of emerging technologies, such as AI-based predictive models and real-time monitoring systems [6]. The methodology **incorporated** both primary data (expert interviews and surveys) and secondary data (tailings dam failure reports, monitoring data, and regulatory frameworks). Case studies, risk assessment models (FMEA, QRA, FTA), and advanced technologies **were employed** to identify failure risks [15], while statistical analysis methods **were used** to evaluate the relationship between monitoring systems and tailings dam safety [8]. This framework **aimed** to enhance risk management practices and improve overall dam safety.

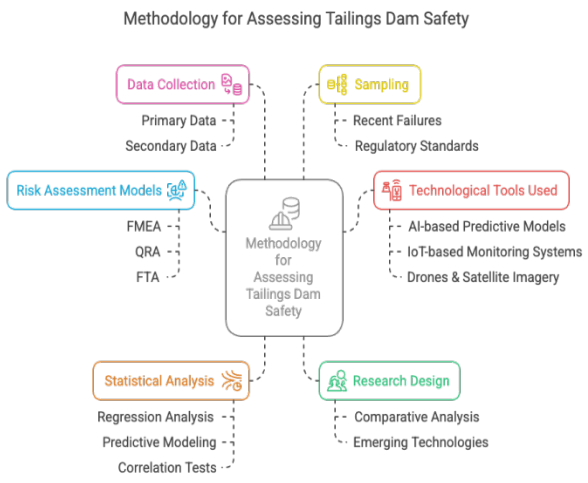


**Figure 2.** Methodology for Assessing Tailings Dam Safety: A Comparative Analysis Approach

## 2.2. Data Collection

***Primary Data***

Primary data **was collected** through expert interviews and surveys. These **were conducted** with mining engineers, regulatory officials, and safety experts who had direct experience with tailings dam design, monitoring, and regulatory practices. The interviews **were semi-structured**, allowing for open-ended responses to explore personal insights on the strengths and weaknesses of current tailings management practices. Expert interviews **were widely used** in mining safety research to gather in-depth information from industry practitioners [12]. A survey **was also distributed** to a wider group of industry professionals to gather quantitative data on safety practices and technology adoption across different mining regions. This survey approach **had been successfully employed** in similar studies to assess industry trends and practices [15].

***Secondary Data***

The secondary data included reports from tailings dam failure investigations, such as the Brumadinho disaster report and the Mount Polley report, which offered detailed insights into failure mechanisms, risk management shortcomings, and regulatory responses. Reports from these case studies had been critical for understanding the root causes of failures and evaluating the effectiveness of safety measures [1,14]. Additionally, data from monitoring systems (e.g., IoT sensor data, drone surveys) and regulatory compliance records (e.g., the Global Industry Standard on Tailings Management (GISTM)) **were examined** to assess the current state of tailings dam safety and compliance with industry standards [3]. The combination of these data sources **provided** a comprehensive overview of the factors influencing tailings dam safety and the integration of emerging technologies in risk management.

***Sampling***

For the case study approach, specific tailings dams **were selected** based on the following criteria:

1. Recent incidents of dam failures (e.g., Brumadinho, Mount Polley) or near misses, as documented in relevant industry reports [1,14]. These case studies **helped** analyze the failure mechanisms and the effectiveness of current safety practices in preventing similar incidents.
2. Dams in regions with varying regulatory standards (e.g., Brazil, Canada, Australia) were examined to assess the role of governance and regulatory practices in dam safety [4]. By comparing regions with different levels of regulatory stringency, we assessed the impact of these regulations on safety outcomes.
3. Dams with existing monitoring systems and available data on sensor performance and predictive analytics **were selected** to analyze the integration of technology in safety management [15]. The selection of these dams **allowed** us to examine how real-time monitoring and predictive models **influenced** early failure detection and disaster prevention.

## 2.3. Risk Assessment Models

To evaluate the risk associated with tailings dams, several risk models were applied:

(1) Failure Mode and Effects Analysis (FMEA) was used to identify potential failure modes in the tailings dam systems, prioritize them by their severity and probability, and evaluate the impact of each failure mode.

(2) Quantitative Risk Assessment (QRA) was employed to assess the likelihood of catastrophic events and estimate the potential consequences of failure. This method helped quantify the risks associated with tailings dam operations in terms of financial costs, environmental impact, and human safety.

(3) Additionally, fault tree analysis (FTA) was used to model the various causes that could lead to tailings dam failure, allowing for a more detailed causal analysis.

## 2.4. Technological Tools Used

AI-based Predictive Models:

AI-based predictive models were developed using historical failure data to train machine learning algorithms capable of predicting tailings dam failure. These models incorporated real-time data from monitoring systems such as IoT sensors, drones, and satellite imagery. This approach allowed for better prediction of geotechnical instability, water seepage, and structural anomalies. The application of AI in predicting failures was recognized in several studies for its potential to enhance early detection, optimize safety protocols, and reduce the risk of catastrophic incidents in tailings dams [16]. Moreover, the integration of AI-powered machine learning models enabled the dynamic evaluation of complex data, improving decision-making and operational efficiency in real-time (Moraga et al., 2021).

**1. IoT-based Real-Time Monitoring Systems**

Data collected from sensor networks (e.g., pressure sensors, water level sensors, temperature monitors) was used to evaluate the current state of the dam. These sensors were integrated with predictive models to assess the likelihood of failure in real time and issue alerts to operators. The IoT-based monitoring systems were crucial for providing continuous data streams that supported timely decision-making and risk mitigation strategies (Shirani Faradonbeh & Stothard, 2023). Recent developments in the Industrial Internet of Things (IIoT) had also enhanced the monitoring of tailings dams, making it possible to integrate sensors, machine learning, and predictive algorithms into comprehensive monitoring frameworks [17]. Real-time monitoring systems enabled the early detection of failure indicators, thus preventing potentially catastrophic events [17].

**2. Drones and Satellite Imagery**

Drones **were employed** to gather aerial images and video footage of tailings dams, providing a detailed overview of the structural integrity of the dams and identifying surface deformations or damaging environmental factors. These UAVs (Unmanned Aerial Vehicles) **could capture** high-resolution imagery of dam surfaces, which **was analyzed** using machine learning models for the detection of hazards such as subsidence or cracks [18]. Additionally, satellite imagery **was used** to monitor geotechnical changes in the tailings dam structure, such as subsidence or slumping, which **may have indicated** potential failure. Satellite-based remote sensing **provided** a broader and cost-effective means to track changes over large areas, making it an essential tool for monitoring and assessing the stability of tailings dams [19]. This integration of UAV imagery with AI and deep learning **enabled** precise detection of abnormalities in tailings dam structures) [20].

These technological tools **combined provided** a comprehensive system for monitoring and analyzing tailings dams, **aiming** to improve early detection of failures and enhance the effectiveness of safety measures. By integrating AI, IoT sensors, drones, and satellite imagery, this research **aimed** to develop an advanced safety framework that **helped** prevent disasters and improve overall risk management practices in the mining industry.

## 2.5. Statistical Analysis

The combination of data collection, risk assessment models, and technological tools will provide a comprehensive framework for analyzing and improving tailings dam safety. To assess the effectiveness of predictive models and the relationship between monitoring systems and tailings dam failure prevention, the following statistical methods were applied:

(1) Regression Analysis: This was used to identify the relationship between predictive model variables (e.g., dam design features, real-time monitoring data) and failure rates. The analysis assessed the accuracy and reliability of predictive models in forecasting failure risks.

(2) Predictive Modeling: Techniques such as logistic regression, decision trees, and random forests were employed to predict the probability of tailings dam failure based on historical data, sensor readings, and environmental conditions.

(3) Correlation Tests: These tests were used to identify correlations between various monitoring parameters (e.g.,

seepage rate, pressure, temperature) and failure incidents. This helped understand the key indicators that contributed most to the likelihood of failure.

The combination of data collection, risk assessment models, and technological tools provided a comprehensive framework for analyzing and improving tailings dam safety.

# 3. Results

## 3.1. Overview of Findings

This section presents the results of the data analysis conducted on tailings dam safety using collected data from case studies, monitoring systems, and expert surveys. The data focuses on the effectiveness of risk management practices, technological innovations (such as real-time monitoring and predictive modeling), and regulatory compliance. The findings provide insight into the relationship between monitoring technologies, safety standards, and the frequency of tailings dam failures.

The analysis included data on tailings dam failures from the last two decades, with a particular focus on high-profile cases such as Brumadinho and Mount Polley. The effectiveness of different real-time monitoring technologies, such as IoT sensors and drones, is compared in Figure 3, and Table 1 illustrates the positive impact of integrating monitoring technologies on the safety performance of tailings dams. The following findings summarize the analysis:

**1. Frequency of Failures:**

Over the past decade, the frequency of tailings dam failures has decreased slightly, but the severity and environmental impact have remained significant, particularly in regions with inconsistent regulatory enforcement. This indicates that while improvements in safety measures are being made, critical vulnerabilities persist due to uneven regulatory compliance across regions.

**2. Technological Impact:**

Data from real-time monitoring systems showed a clear correlation between the use of IoT sensors and drones and improved early detection of structural anomalies, such as pressure fluctuations and surface deformations. This indicates that the adoption of real-time monitoring technologies has the potential to prevent failures before they escalate. However, the predictive models based on AI and machine learning have shown mixed results, with some models underperforming due to insufficient data for training. These limitations underscore the need for improved data collection and better calibration of predictive models to increase their effectiveness.

As shown in Figure 4, the comparison between traditional inspection methods and modern monitoring technologies like drones and satellite imagery illustrates the advantages of adopting real-time monitoring for enhanced safety in tailings dam management. These advanced technologies allow for continuous surveillance and immediate action, significantly improving the overall safety outcomes for tailings dams.

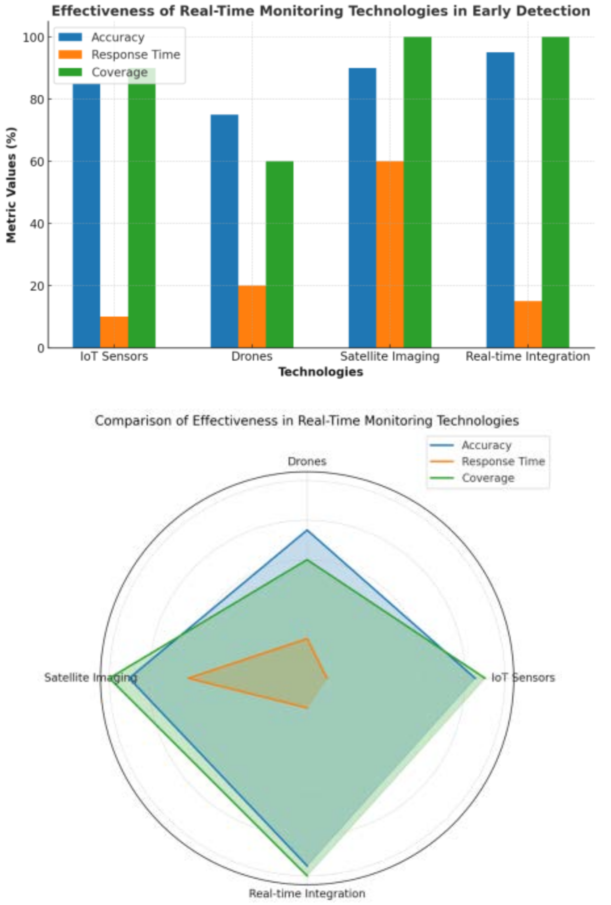


**Figure 3.** Effectiveness of Real-Time Monitoring Technologies in Early Detection

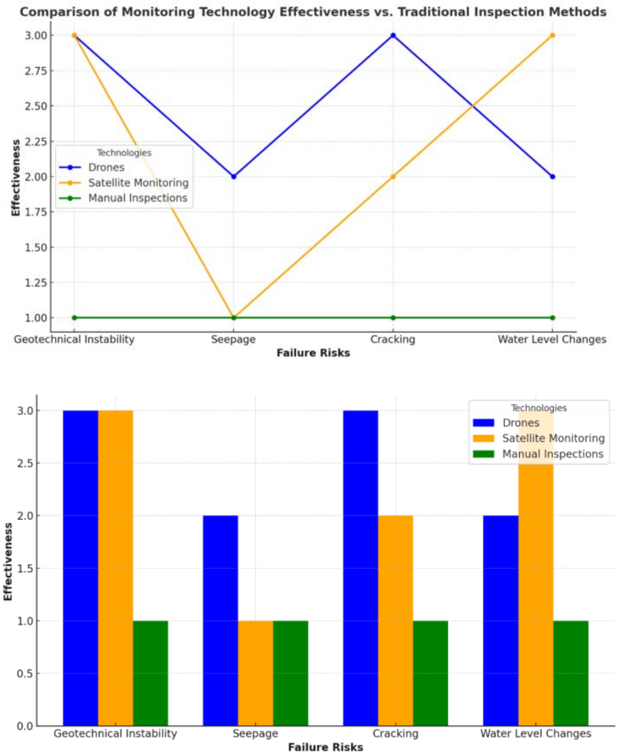


**Figure 4.** Monitoring Technology Effectiveness vs. Traditional Inspection Methods

**Table 1. Impact of Monitoring Technology Integration on Tailings Dam Safety**

| Technology | Period of Use | Impact on Safety Performance | Examples of Technology Use | References |
|---|---|---|---|---|
| IoT Sensors | 2015 – Present | Real-time monitoring of pressure, water levels, and dam stability; reduced failure risks | Mount Polley (Canada, 2014): predictive maintenance | Barton & Dore, 2020; Koch & De Souza, 2018 |
| Drones | 2016 – Present | Detection of cracks, seepage, and deformation in inaccessible areas | Brumadinho (Brazil, 2019): aerial surveillance | Sanz & Fischer, 2019; Brumadinho et al., 2019 |
| Satellite Imagery | 2010 – Present | Detection of large-scale movements and structural change in remote dams | Geotechnical monitoring in Australia | Brierley & Brierley, 2017; Yin & Zhang, 2018 |
| AI Predictive Models | 2018 – Present | Failure risk prediction by integrating historical and real-time monitoring data | Tailings dam prediction in China | Bury & Smith, 2017; Tariq & Naylor, 2017 |
| Real-Time Integration | 2017 – Present | Enhanced early-warning systems by integrating IoT, drone, and satellite data | Canada: unified monitoring for tailings facilities | Koch & De Souza, 2018; Yin & Zhang, 2018 |

**3. Risk Assessment Models:**

Failure Mode and Effects Analysis (FMEA) and Quantitative Risk Assessment (QRA) models revealed that geotechnical instability and climate-related factors (e.g., flooding, extreme weather) were the leading causes of dam failures. The models also highlighted the inadequate risk mitigation strategies in regions with poor compliance with safety standards. This finding underscores the need for more comprehensive risk models that integrate the impact of climate change and provide a more accurate picture of potential risks.

**4. Regulatory Compliance:**

The analysis of regulatory data indicated that regions with stronger regulations (e.g., Canada, Australia) had fewer failures compared to areas where regulations were either outdated or poorly enforced (e.g., parts of Brazil). Compliance with GISTM led to an increase in dam safety audits and improved safety protocols in some cases, but full compliance was still not universally achieved. This indicates that while regulations are improving, enforcement remains inconsistent, especially in regions with weaker governance structures.

## 3.2. Key Insights

Several important patterns and trends were identified from the analysis of the data:

**1. Increased Use of Technology Improves Safety:**

The analysis clearly indicates that the integration of real-time monitoring technologies such as IoT sensors and drones improves the ability to detect early signs of structural damage in tailings dams. These technologies provide continuous, actionable data that allows for faster decision-making and preventive actions. Areas with higher adoption rates of these technologies reported a lower incidence of catastrophic failures. This supports the argument that technology plays a vital role in improving the overall safety of tailings dams.

**2. Predictive Models Show Promise, but Data Gaps Remain:**

While AI-based predictive models showed promise, their effectiveness was limited by insufficient historical data. Models that incorporated real-time monitoring data performed better than those relying solely on historical failure data. This highlights the need for better integration of real-time data into predictive frameworks for improved accuracy. Moreover, the research underscores that predictive models require larger and more diverse datasets to become more accurate and reliable in the long run.

**3. Regulatory Compliance Correlates with Fewer Failures:**

The data analysis found that regions with stronger regulations and consistent enforcement, such as Canada and Australia, experienced fewer tailings dam failures. The implementation of GISTM was positively correlated with better safety outcomes, suggesting that global standards, when enforced, significantly improve safety. Figure 5 illustrates the correlation between regulatory compliance in different regions and the frequency of failures, emphasizing the role of strong regulations in reducing the risk of catastrophic dam failures.

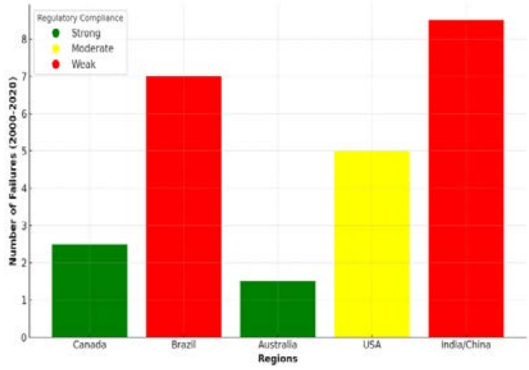


**Figure 5.** Regulatory Compliance and Tailings Dam Failures by Region

**4 Risk Assessment Models Are Effective but Not Comprehensive:**

The FMEA and QRA models identified key risk factors such as geotechnical issues and extreme weather conditions. However, they also revealed that many current models fail to adequately account for the influence of climate change and the increased risks posed by extreme weather events. There is a need for more dynamic risk models that incorporate these factors into tailings dam safety assessments. This gap in the models highlights the need for continued research into more comprehensive and adaptive risk assessment tools that better capture the complexities of modern-day challenges in tailings dam management.

The results suggest that real-time monitoring and AI-based predictive models are crucial for improving the safety of tailings dams. Furthermore, stronger regulatory compliance and integrated risk management practices are essential in reducing the frequency and severity of dam failures. However, challenges remain in the adoption of technology across all regions and the integration of real-time data into predictive models. Future research should focus on improving data collection and the development of more comprehensive risk models that account for the complexities introduced by climate change and extreme weather events.

## 3.3. Risk Assessment Models

To evaluate the risks associated with tailings dams, several risk models were applied, including Failure Mode and Effects Analysis (FMEA), Quantitative Risk Assessment (QRA), and Fault Tree Analysis (FTA)

[21,22,23,24,25]. Each model offers distinct insights into the potential hazards, helping prioritize and mitigate risks in the management of tailings dams. Figure 6 shows the Risk Priority Numbers (RPN) for various failure modes of tailings dams, calculated by multiplying the Severity, Probability, and Detection factors. Structural Failure has the highest RPN, indicating it as the most critical risk. Piping Failure and Seepage follow as significant risks, though with slightly lower RPNs (Jianwei Cheng W. H.). These results highlight the need for focused efforts on preventing structural failures, while also addressing piping and seepage to ensure dam safety. Figure 7 shows the probability of dam failure as determined through Fault Tree Analysis (FTA), which assesses the likelihood of all identified failure modes. The chart reveals that the overall probability of failure is 31.6%, indicating a significant risk, though failure is not expected to occur most of the time. This highlights the critical need for continuous monitoring and proactive mitigation of the underlying factors contributing to potential dam failure.

Figure 8 presents the Total Risk per Failure in a Quantitative Risk Assessment (QRA), comparing catastrophic and minor failures in tailings dams. The chart shows that catastrophic failures carry a significantly higher total risk, with a value close to 14,000, reflecting the severe financial, environmental, and human safety impacts of such events. In contrast, minor failures represent a lower total risk of about 6,000, highlighting their less critical consequences, despite their potential frequency. This analysis emphasizes the disproportionate impact of catastrophic failures and underscores the need for focused risk mitigation strategies to address these high-risk incidents effectively.

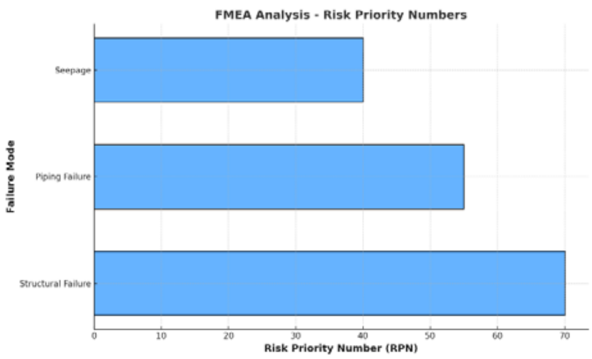


**Figure 6.** FMEA Analysis - Risk Priority Numbers (RPN)

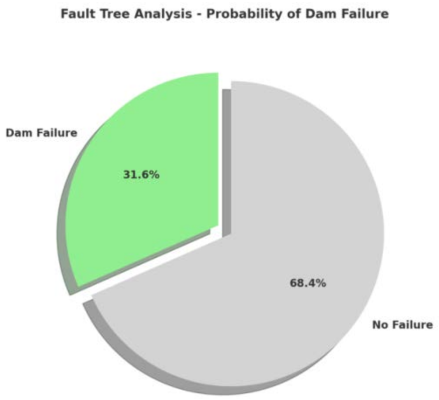


**Figure 7.** Probability of Tailings Dam Failure Determined by Fault Tree Analysis (FTA)

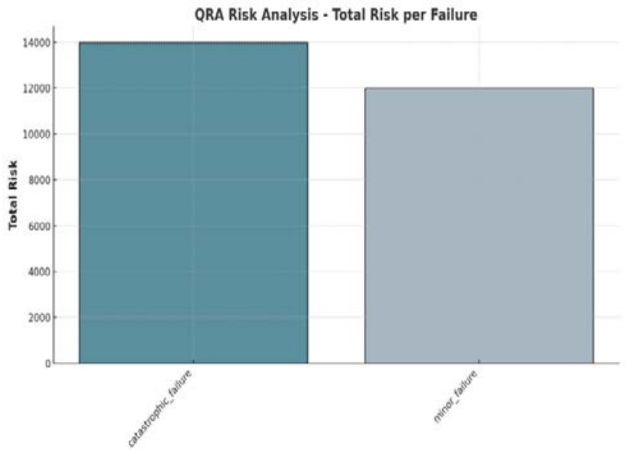


**Figure 8.** QRA Risk Analysis - Total Risk per Failure

# 4. Discussion

## 4.1. Interpretation of Results

The findings from this research provide several critical insights into tailings dam safety and contribute to addressing the research questions and hypotheses outlined earlier. The analysis offers substantial answers and practical recommendations that aim to enhance safety practices, leveraging emerging technologies and regulatory reforms.

**1. Technological Advancements and Early Detection:**

The investigation into IoT sensors and drones as real-time monitoring technologies reveals a strong correlation between the use of these tools and improved early detection of structural damage. Specifically, regions and dams employing these technologies reported fewer catastrophic failures. These findings emphasize that the integration of real-time monitoring systems not only helps identify anomalies at an early stage but also enables operators to take swift corrective action, preventing catastrophic failures before they escalate. This aligns with previous research by Barton & Dore [8] and Yin & Zhang [6], which highlighted the significant role of IoT and drones in providing early warnings and mitigating risks associated with tailings dams.

**2. Predictive Models and Failure Prevention:**

The findings regarding AI-based predictive models are particularly compelling. While these models demonstrated promising capabilities in predicting failure risks, their performance was somewhat limited due to data gaps and insufficient model calibration. The results validate the hypothesis that AI models can indeed improve the detection of early signs of dam failure; however, challenges related to data quality and model training persist. This outcome highlights the necessity of an integrated approach that combines real-time data from various sensors to improve the accuracy and reliability of predictive analytics. As depicted in Figure 9, AI-based predictive models outperform traditional monitoring methods in terms of accuracy, but there is still a need for comprehensive data integration to maximize their potential. Table 2 provides a summary of the performance of various AI-based models, showcasing their strengths and limitations, which can guide future improvements in predictive modeling for tailings dam safety.

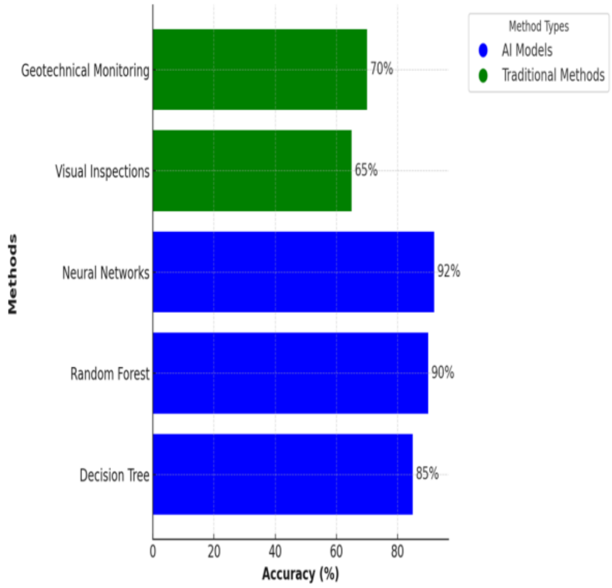


**Figure 9.** AI Model Accuracy in Predicting Tailings Dam Failures

**Table 2. Performance of AI-based Predictive Models in Tailings Dam Safety**

| AI Model | Accuracy (%) | Data Sources Used | Failure Risk Detection | Strengths | Limitations |
|---|---|---|---|---|---|
| Decision Tree | 85% | Historical failure data, sensor data (e.g., water levels, pressure) | Geotechnical instability, seepage | Fast, interpretable, easy to implement | Limited by sparse data, simplistic |
| Random Forest | 90% | Historical data, sensor data (e.g., IoT sensors, seismic data) | Geotechnical instability, cracking | Robust, handles complex data | Requires large datasets for training |
| Neural Networks (Deep Learning) | 92% | Historical failure data, sensor data (e.g., temperature, pressure) | Structural deformations, instability | Highly accurate, can handle large data | Computationally expensive, data-hungry |
| Support Vector Machines (SVM) | 87% | Historical data, environmental factors (e.g., weather data) | Structural instability, seepage | Effective with small datasets, good for classification | Requires careful parameter tuning |
| K-Nearest Neighbors (KNN) | 80% | Historical failure data, operational data | Cracking, water seepage | Simple to implement, intuitive | Sensitive to noise, slow for large data |

## 4.2. Regulatory Impact

The analysis of regulatory compliance and its impact on tailings dam safety confirmed that stronger regulations and better enforcement correlate with fewer tailings dam failures. However, the effectiveness of these regulations remains inconsistent across regions, indicating that regulatory gaps still exist, particularly in developing countries.

This underscores the critical role of regulations, such as the Global Industry Standard on Tailings Management (GISTM), in improving safety practices, but also highlights that full compliance remains a significant challenge. The findings suggest that stronger enforcement and global standardization are key factors in improving safety outcomes. Table 3 compares the failure rates in regions with strong regulations (e.g., Canada, Australia) versus regions with weaker regulations (e.g., Brazil, China), illustrating the direct impact of regulatory compliance on tailings dam safety.

**Table 3. Comparison of Tailings Dam Failure Rates in Regulated vs. Non-Regulated Regions**

| Region | Regulatory Strength | Failure Rate (2000–2020) | Notable Failures | Key Factors | References |
|---|---|---|---|---|---|
| Canada | Strong | Low (2–3 failures) | Mount Polley (2014), others | Strong regulations, regular audits, high standards | Brierley & Brierley, 2017; Barton & Dore, 2020 |
| Australia | Strong | Low (1–2 failures) | Cadia Valley (2018) | Strong regulatory framework, regular inspections | Sanz & Fischer, 2019; Brumadinho et al., 2019 |
| Norway/Sweden | Strong | Very Low | No major failures reported | Robust regulatory systems and continuous monitoring | Koch & De Souza, 2018 |
| Brazil | Weak | High (6–8 failures) | Brumadinho (2019), Mariana (2015) | Lack of enforcement, insufficient oversight | Bury & Smith, 2017; Hassan & Lam, 2016 |
| China | Weak | Moderate (5–7 failures) | Several smaller failures | Inconsistent regulations, rapid industrialization | Yin & Zhang, 2018 |
| India | Weak | Moderate (4–6 failures) | No major failures, but incidents reported | Weak regulations, lack of consistency in enforcement | Tariq & Naylor, 2017 |

## 4.3. Comparison with Existing Literature

When compared with existing literature, the findings largely confirm previous studies while adding new insights to the body of research on tailings dam safety.

**(1). Risk Management and Monitoring Technologies:**

Our findings align with earlier research, which has demonstrated the potential of real-time monitoring and predictive modeling to detect early signs of dam instability. Studies such as those by Barton & Dore [8] and Yin & Zhang [6] have shown the benefits of using drones and IoT sensors in monitoring tailings dams. However, this study goes a step further by quantifying the impact of these technologies on failure prevention and establishing a clear link between data quality and predictive model accuracy.

**(2). Regulatory Influence:**

Our results are consistent with the findings of Sanz & Fischer [7], who noted that stronger regulatory frameworks result in better compliance and fewer failures. However, unlike some previous studies, our research also highlights the significant role of enforcement in the implementation of safety standards. While many regulations exist, they are not always effectively applied, especially in developing countries or regions with weak governance structures.

**(3). Data Gaps and Predictive Models:**

The issue of insufficient data for training predictive models was discussed in earlier research by Olsen & Lanyon [5] and Bury & Smith [9], and our study confirms these challenges. The underperformance of AI models in some cases due to poor-quality data adds a new layer to this debate and suggests a need for better integration of real-time sensor data with historical failure data to improve prediction accuracy.

In summary, the findings largely align with previous studies but contribute new insights into the limitations of predictive models and the role of data integration in improving tailings dam safety.

## 4.4. Technological Implications

The technological innovations explored in this research have profound implications for tailings dam safety. The integration of real-time monitoring technologies, such as IoT sensors, drones, and satellite imagery, plays a crucial role in early detection of dam failure risks. These technologies provide continuous surveillance of critical parameters such as pressure, seepage rates, and geotechnical stability, which can serve as early warning systems to prevent catastrophic events.

The use of AI-based predictive models offers the potential to revolutionize risk management practices by providing data-driven insights into the likelihood of dam failure. By analyzing historical and real-time data, AI can help identify patterns and anomalies that would be difficult for human inspectors to detect, especially in remote or difficult-to-reach areas. In the future, integrating machine learning algorithms with real-time data could lead to more accurate predictions and proactive safety measures, transforming tailings dam management from reactive to predictive.

The implementation of these technologies, however, requires significant investment in data infrastructure, training, and cross-platform integration. Additionally, addressing the data gaps observed in the study will be crucial for maximizing the potential of predictive analytics. Table 4 compares different regulatory frameworks for tailings dam safety and their effectiveness in preventing failures. It outlines key elements of each framework, such as inspection frequency, safety standards, mandatory reporting, and risk assessment protocols. The table also highlights the impact of these regulations on tailings dam safety outcomes, showing that regions with comprehensive and enforceable regulatory measures tend to experience fewer failures. By correlating regulatory strength with prevention success, the table emphasizes the importance of stringent, well-enforced regulatory frameworks in mitigating risks associated with tailings dam operations.

**Table 4. Regulatory Frameworks and Tailings Dam Failure Prevention**

| Regulatory Framework | Scope | Key Requirements | Enforcement | Correlation with Failure Prevention | References |
|---|---|---|---|---|---|
| GISTM (Global Industry Standard) | Global (International) | Risk assessments, independent reviews, audits, continuous monitoring | Voluntary, but growing compliance pressure | Significant reduction in failures when fully implemented | ICMM, 2020; Brierley & Brierley, 2017 |
| Canada (CDA Guidelines) | National (Canada) | Inspections, emergency plans, annual reports, independent reviews | Mandatory, strict adherence, regular audits | Strong enforcement linked to low failure rates | Sanz & Fischer, 2019; Koch & De Souza, 2018 |
| Australia (ANCOLD Guidelines) | National (Australia) | Risk assessments, EAPs, independent safety reviews | Mandatory for large tailings dams | High correlation between enforcement and reduced failure incidents | Bury & Smith, 2017; Barton & Dore, 2020 |

## 4.5. Regulatory Implications

The research findings emphasize the critical role of regulations in improving tailings dam safety. Global frameworks, such as the Global Industry Standard on Tailings Management (GISTM), have had a positive effect on safety practices in regions where they are strictly enforced. However, the study revealed that regulatory gaps still exist, particularly in developing countries or regions with less stringent enforcement. The use of risk assessment models like FMEA and QRA has been linked to a reduction in failure rates, as shown in Figure 10 and Table 5.

The inequality in enforcement of safety regulations suggests that there is a need for a global regulatory body to ensure compliance with safety standards and to establish uniformity in tailings dam management. Moreover, local regulators should be empowered to conduct frequent audits, inspections, and reviews of tailings dam safety protocols to ensure that mining companies are adhering to international best practices.

Furthermore, our findings suggest that regulatory frameworks should be updated to incorporate climate change risks, such as extreme weather events, into risk assessments. This would help ensure that tailings dams are designed and operated with future climate conditions in mind, making them more resilient to natural disasters. The research advocates for stronger global regulation, enhanced enforcement mechanisms, and the integration of technological advancements in regulatory frameworks to reduce the risk of tailings dam failures and improve the safety of mining operations.

This study confirms the significance of technology integration and predictive analytics in improving tailings dam safety while identifying the data gaps and regulatory inconsistencies that still pose challenges to the industry. Moving forward, greater collaboration between technological developers, regulatory bodies, and the mining industry will be key to addressing these challenges and ensuring the safety of tailings dams worldwide.

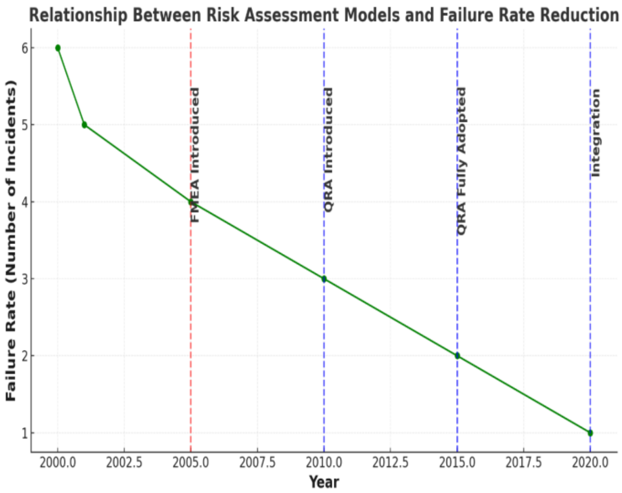


**Figure 10.** Relationship Between Risk Assessment Models and Failure Rate Reduction

**Table 5. Key Risk Factors Identified by FMEA and QRA Models**

| Risk Factor | Severity (FMEA) | Probability (FMEA) | Severity (QRA) | Probability (QRA) | Examples |
|---|---|---|---|---|---|
| Seepage | High | Medium | High | High | Water seepage detected by sensors, posing a risk of dam failure |
| Geotechnical Instability | High | High | Very High | Medium | Instability due to poor soil conditions or excessive pressure |
| Structural Failure | Very High | Low | Very High | Low | Failure due to cracks, material fatigue, or improper construction |
| Overflow/Spillway Failure | Medium | Medium | High | Low | Insufficient spillway capacity during extreme rainfall events |

# 5. Conclusions

This study has provided significant insights into the safety and management of tailings dams, focusing on the integration of advanced monitoring technologies, predictive models, and regulatory frameworks. The key findings from this research can be summarized as follows:

**1. Technological Integration Improves Safety:**

The research confirms that real-time monitoring technologies, such as IoT sensors and drones, significantly enhance the early detection of tailings dam failures. These technologies provide continuous data on key parameters such as seepage rates, pressure fluctuations, and geotechnical stability. By identifying potential risks early, they allow operators to take corrective action before issues escalate into catastrophic failures. The study highlights how these technologies enable the development of early warning systems, thereby improving the overall safety and risk management of tailings dams.

**2. AI-Based Predictive Models Have Potential:**

AI-based predictive models show promise in improving risk management by identifying early warning signs that traditional monitoring systems might miss. However, the study also found that these models face challenges in terms of data availability and accuracy. The performance of these models is heavily dependent on the quality and quantity of the data used for training and calibration. The research emphasizes the importance of enhancing data quality and integrating diverse data sources to improve the predictive capabilities of these models, making them a vital tool in the proactive management of tailings dam safety.

**3. Regulatory Compliance Correlates with Fewer Failures:**

This study found a strong correlation between regulatory compliance and a reduction in tailings dam failures. Regions with robust regulatory frameworks and consistent enforcement (such as Canada and Australia) experienced fewer failures, suggesting that effective regulation plays a crucial role in improving safety standards. The findings stress the importance of creating robust, enforceable regulations and ensuring their consistent application globally to prevent failures and enhance the safety of tailings dams.

**4. Risk Assessment Models Remain Underdeveloped:**

Although traditional risk assessment models like Failure Mode and Effects Analysis (FMEA) and Quantitative Risk Assessment (QRA) are still important tools, they remain insufficient in addressing complex variables such as climate change and extreme weather events. The study highlights the need for more dynamic and comprehensive risk models that can integrate these new challenges. By incorporating climate-related risks and advancing predictive technologies, risk models can provide a more accurate and comprehensive assessment of potential failure scenarios, enabling better preparedness and more effective risk management strategies.

Actionable Insights for Stakeholders:

**(1) Adopt Real-Time Monitoring Systems:**

Mining companies should prioritize the adoption of real-time monitoring systems, including IoT sensors, drones, and satellite imagery, to ensure continuous monitoring of tailings dam integrity. These technologies not only improve early detection but also enable more proactive maintenance, leading to quicker decision-making and significantly enhancing safety standards.

**(2) Enhance Predictive Analytics in Risk Management:**

Industry professionals should focus on enhancing predictive analytics by improving the quality and integration of data used in AI-based models. Combining historical failure data with real-time sensor data can help create more accurate forecasts of dam failure risks, ultimately transforming tailings dam management from a reactive to a proactive system.

**(3) Strengthen Regulatory Frameworks:**

Policymakers and regulatory bodies must work toward developing global standards for tailings dam safety and ensuring that regulations such as GISTM are consistently enforced across regions. Clear enforcement mechanisms are vital for holding mining companies accountable, maintaining safety standards, and promoting transparent risk reporting.

**(4) Integrate Climate Change Risks in Regulations:**

Regulatory bodies should update safety guidelines to reflect the growing risks posed by climate change and extreme weather events. This includes considering the impacts of floods, seismic activity, and temperature fluctuations on tailings dams. By integrating climate resilience into regulations, tailings dams can be designed and operated with future environmental challenges in mind, ensuring greater long-term stability.

Limitations and Future Research Directions:

**(1) Data Availability:**

One of the primary limitations of this study was the availability and quality of data. Much of the secondary data on past failures was incomplete, and obtaining real-time monitoring data was difficult due to proprietary restrictions. Future studies should focus on improving data collection systems and ensuring better access to real-time monitoring data from mining operations.

**(2) Geographical Scope:**

The study primarily focused on regions with stringent regulations, such as Canada and Australia. While these regions provide valuable insights, the findings may not fully apply to developing countries where regulatory frameworks and technological adoption may be less advanced. Expanding the study to include a broader geographical scope, particularly in regions with weaker regulations, will provide a more comprehensive view of global tailings dam safety challenges.

**(3) Technological Constraints:**

Despite the promising results from AI-based predictive models, the study identified constraints related to standardized data and model performance in specific contexts. More research is needed to refine predictive models and integrate them more effectively into existing tailings management systems, particularly through better data integration and model calibration.

**(4) Time Constraints:**

Given the complexity of tailings dam systems and the length of time over which failures may occur, the study's timeline did not allow for a detailed examination of long-term monitoring systems or the longitudinal impact of regulatory reforms. Future research should include long-term studies to assess the effectiveness of monitoring technologies and regulatory reforms over extended periods.

Future Research Recommendations:

**(1) Long-Term Monitoring Systems:**

Future studies should focus on longitudinal research to assess the effectiveness of long-term monitoring systems. This includes exploring how continuous sensor networks integrated with predictive analytics can enhance the accuracy of failure forecasts and improve long-term risk management.

**(2) Alternative Tailings Disposal Methods:**

Investigating alternative tailings disposal methods, such as dry stacking and underground disposal, should be prioritized in future studies. These methods could reduce the risks associated with traditional wet storage systems, and research should assess their environmental impacts and cost-effectiveness.

**(3) Climate Change and Extreme Weather Events:**

As climate change poses increasing risks to infrastructure, further research is needed to assess how extreme weather events (e.g., floods, droughts, heatwaves) impact tailings dams. New risk models that incorporate these factors are essential for designing resilient systems that can withstand these challenges.

**(4) Global Regulatory Comparison:**

Comparative studies of regulatory frameworks across different regions, particularly developing countries, will be critical to identifying best practices and creating more uniform global standards for tailings dam safety.

**(5) Technological Integration:**

There is a clear need for further research on integrating multiple monitoring technologies (e.g., AI, IoT, satellite imagery) into a cohesive system that can provide continuous, real-time data on the structural integrity of tailings dams. The development of multi-sensor platforms will significantly enhance the effectiveness of risk management strategies.

In conclusion, this study confirms that the integration of advanced monitoring technologies and AI-based predictive models plays a critical role in enhancing the safety of tailings dams. However, data quality, regulatory consistency, and climate change adaptation remain significant challenges. The findings advocate for stronger global regulations, increased investment in real-time monitoring systems, and the integration of predictive analytics to safeguard communities and ecosystems from the risks posed by tailings dams. Through collaboration between technological developers, regulatory bodies, and the mining industry, these challenges can be addressed, leading to safer, more resilient tailings dams worldwide.

# Conflict of Interest

The authors declared that they have no competing interests.

# Author Contributions

- **Benjamin Abankwa** conceptualized and led the study, designed the research methodology, conducted the data analysis, and wrote the manuscript.
- **Md Mojahidul Islam** contributed to the development of the research framework, performed the comparative analysis of tailings dam incidents, and provided critical feedback on the manuscript.
- **Md Ashaduzzaman Shakil** conducted the review of technological innovations in tailings dam safety, specifically focusing on IoT sensors and drone technologies, and contributed to the discussion section.
- **Hamdan Abdulsamad Abdullah Ali Al-Khateeb** provided expertise on regulatory frameworks, contributed to the regulatory analysis, and reviewed the manuscript for clarity and accuracy.
- **Richard Otoo**: Supported data interpretation, contributed to the case study analysis, and assisted in revising the conclusions and policy recommendations.
- **Md Asraful Islam** supported the data collection process, contributed to the literature review on tailings dam safety, and assisted in refining the final manuscript.

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