minerals

MDPI

Systematic Review

Sensor Technologies for Safety Monitoring in Mine Tailings Storage Facilities: Solutions in the Industry 4.0 Era

Carlos Cacciuttolo [1,2,*], Valentina Guzmán [1], Patricio Catriñir [1] and Edison Atencio [2,3]

[1] Department of Civil Works and Geology, Catholic University of Temuco, Temuco 4780000, Chile; vguzman2015@alu.uct.cl (V.G.); pcatrinir2016@alu.uct.cl (P.C.)
[2] Department of Civil Engineering, Universidad de Castilla-La Mancha, Av. Camilo Jose Cela s/n, 13071 Ciudad Real, Spain; edison.atencio@pucv.cl
[3] School of Civil Engineering, Pontificia Universidad Católica de Valparaíso, Av. Brasil 2147, Valparaíso 2340000, Chile
* Correspondence: ccacciuttolo@uct.cl

Abstract: The recent tailings storage facility (TSF) dam failures recorded around the world have concerned society in general, forcing the mining industry to improve its operating standards, invest greater economic resources, and implement the best available technologies (BATs) to control TSFs for safety purposes and avoid spills, accidents, and collapses. In this context, and as the era of digitalization and Industry 4.0 continues, monitoring technologies based on sensors have become increasingly common in the mining industry. This article studies the state of the art of implementing sensor technologies to monitor structural health and safety management issues in TSFs, highlighting advances and experiences through a review of the scientific literature on the topic. The methodology applied in this article adheres to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines and utilizes scientific maps for data visualization. To do so, three steps were implemented: (i) a quantitative bibliometric analysis, (ii) a qualitative systematic review of the literature, and (iii) a mixed review to integrate the findings from (i) and (ii). As a result, this article presents the main advances, gaps, and future trends regarding the main characteristics of the sensor technologies applied to monitor TSF structural health and safety management in the era of digitalization. According to the results, the existing research predominantly investigates certain TSF sensor technologies, such as wireless real-time monitoring, remote sensors (RS), unmanned aerial vehicles (UAVs), unmanned survey vessels (USVs), artificial intelligence (AI), cloud computing (CC), and Internet of Things (IoT) approaches, among others. These technologies stand out for their potential to improve the safety management monitoring of mine tailings, which is particularly significant in the context of climate change-related hazards, and to reduce the risk of TSF failures. They are recognized as emerging smart mining solutions with reliable, simple, scalable, secure, and competitive characteristics.

Keywords: mine tailings; safety; risks; sensors; remote sensing; real-time monitoring; wireless; Internet of Things; Industry 4.0

Citation: Cacciuttolo, C.; Guzmán, V.; Catriñir, P.; Atencio, E. Sensor Technologies for Safety Monitoring in Mine Tailings Storage Facilities: Solutions in the Industry 4.0 Era. *Minerals* **2024**, *14*, 446. https://doi.org/10.3390/min14050446

Academic Editors: Masoud Zare-Naghadehi and Javad Sattarvand

Received: 2 March 2024
Revised: 15 April 2024
Accepted: 19 April 2024
Published: 24 April 2024

1. Introduction

1.1. Mine Tailings Storage Facility Dam Failures: Geotechnical Human Errors or Unavoidable Accidents

The dam failures of mine tailings storage facilities (TSFs) recorded in recent decades in Los Frailes Aznalcóllar, Spain, 1998; Ajka Alumina Plant, Kolontár, Hungary, 2010; Mount Polley, Canada, 2014; Samarco Fundão, Brazil, 2015; Brumadinho Feijão, Brazil, 2019; Jagersfontein, South Africa, 2022; and Williamson, Tanzania, 2022, have caused significant social, environmental, and economic effects, as well as harming the reputation and credibility of mining companies due to the loss of human lives and causing serious environmental damage [1–4]. Many studies have been conducted in recent years to understand the causes of these disasters related to mine tailings management. Some of the findings that researchers and engineers have reported include (i) inadequate dam construction procedures, (ii) the instability of the upstream construction method, (iii) inefficient management of mine TSF operations, (iv) discontinuous engineering companies in technical studies and changes in construction contractors, and (v) an increase in the generation of mine tailings due to a decrease in ore grade in mining deposits [5–12].

Considering these causes, it is important to note that the generation of mine tailings worldwide increases every year due to the increasing demand for the metals necessary to decarbonize the economy through the development of digital age information, the implementation of electromobility, and the use of renewable energies to address the global threat of climate change [13,14]. Society in general and governments worldwide demand sustainable development to leave a better world for future generations and reduce their ecological footprint. This is how the United Nations (UN) has defined its sustainable development goals (SDGs) for the year 2030; it has also established decarbonization and renewable energy plans for 2050, seeking to reduce greenhouse gas (GHG) emissions to zero to achieve carbon neutrality [15–17]. This energy transition and efforts to achieve the SDGs will demand large quantities of minerals from both metallic mining (Cu, Ag, Au, Fe, C, REEs, and others) and non-metallic mining (Li, I, B, salts, and others), which will harm mine localities due to the increase in mining waste [18–20].

For example, the demand for copper will increase in the coming decades, and the quantities of mine tailings generated in the main source countries for this metal, such as Chile, Peru, China, the USA, Australia, the Democratic Republic of the Congo, and Mexico, have been increasing commensurately [19]. This is reflected by the size of mine TSFs and their dams in these countries, which in some cases exceed 100 m in height, and in Chile and Peru, currently reach 200 m in height [21]. Considering the copper demands by 2050 to achieve the energy transition and sustainable development objectives, some TSF dams in both Chile and Peru are expected to exceed 300 m in height, something unprecedented in this type of infrastructure [21]. Furthermore, the effects of climate change on mine TSFs must be considered, as extreme hydrometeorological events will continue to occur in various territories, and intense rainfall, frost, heat waves, changes in wind generation patterns, increased evaporation rates, snowfall, etc., will make these structures vulnerable to accidents, spills, or failures [22].

In this scenario, monitoring the structural health and safety management of mine TSFs with the best available technologies (BATs) becomes crucial for the responsible management of mine tailings and the sustainability of the mining business. Therefore, sensor technologies and Industry 4.0 technologies emerge as attractive alternatives to foster safety and reduce the risks of mine TSF failure.

The Industry 4.0 paradigm corresponds to the fourth industrial revolution, which humanity is leaving now and where the digitalization of information technologies is a priority to achieve sustainable development and societal well-being. In this context, mining should engage in digital mine operations to increase production efficiency, decrease the risk of accidents, and promote sustainability.

Mining companies worldwide have demonstrated a greater commitment to communities and society in general in recent years regarding the management of mine tailings by enacting sustainability strategies that consider corporate social responsibility (CSR) and environmental, social, and governance (ESG) programs [23–25]. In addition, mine tailings dewatering technologies, such as filtered tailings and thickened tailings, have been implemented and proven to be more stable and safer than conventional tailings technologies, which bear a higher risk of failure due to their greater stored water [26–28]. These dewatering technologies are improving the sustainability issues associated with mining, and many success cases have been registered worldwide recently that foster circular economy activities and use water efficiently [29]. Unsafe dam construction techniques have also been prohibited, such as the upstream construction method (prohibited in Chile, Peru, and Brazil), which encourages the use of downstream and centerline construction methods.

In addition, the International Council on Mining and Metals (ICMM), the Principles for Responsible Investment (PRI), and the UN defined the Global Industry Standard on Tailings Management (GISTM) in August 2020, which is a milestone in the governance of mine tailings. This standard seeks to indicate and promote the use of the BATs, best available practices (BAPs), and best environmental practices (BEPs) [20]. Figure 1 shows the failure risk levels associated with mine tailings management technologies and mine tailings dam construction methods [19].

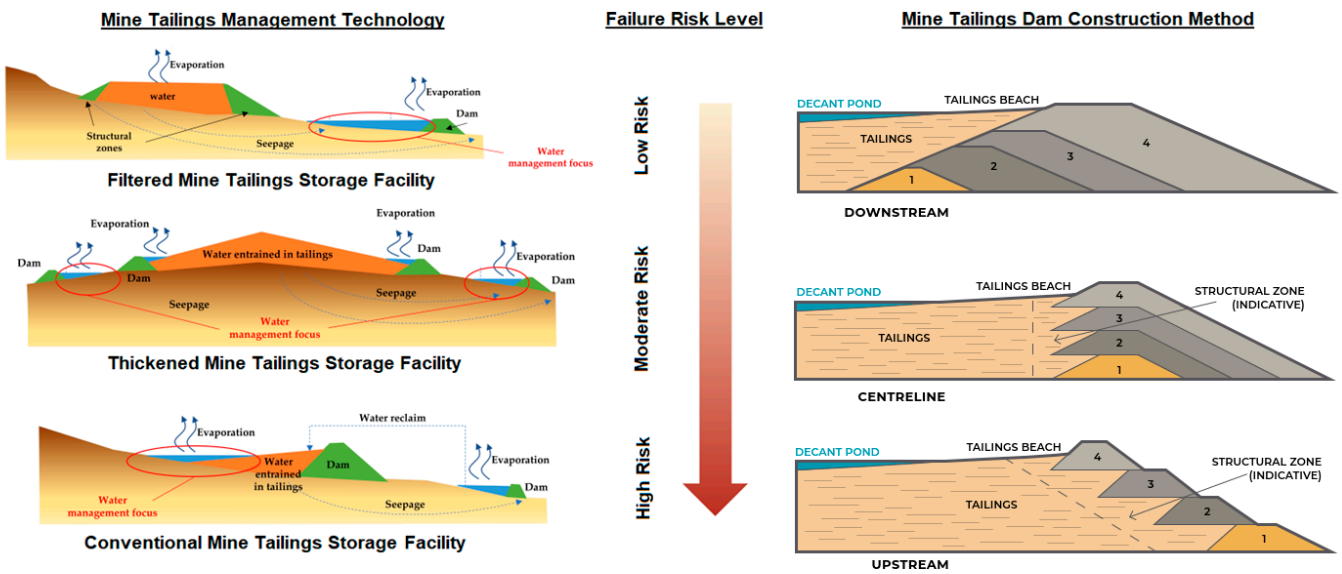

Figure 1. Mine tailings management technologies, mine tailings dam construction methods, and associated failure risk levels [19].

The monitoring systems implemented in mine TSFs for safety management must be able to track parameters that allow them to alert managers of the main failure modes. According to recent studies [7,11,28,30,31], typical TSF failure modes (FMs) and corresponding monitoring parameters (MPs) are as follows:

- FM-1, slope instability: MPs are settlement, rotation, displacement, tension cracks, and pore pressure change.
- FM-2, seepage: MPs are settlement, seepage quantity, and seepage quality.
- FM-3, foundation: MPs are rotation, displacement, and tension cracks.
- FM-4, earthquake: MPs are ground acceleration, settlement, and pore pressure change.
- FM-5, overtopping of dam crest: MP is freeboard change.
- FM-6, structural: MPs are tension cracks, displacement, and seepage.
- FM-7, internal erosion (piping): MPs are surface elevation changes, effluent quantity, and effluent quality.
- FM-8, subsidence: MPs are ground acceleration and settlement.

1.2. Smart Sensors for Structural Health and Safety Management Monitoring in Mine Tailings Storage Facilities, Considering Digitalization Technologies and the Industry 4.0 Paradigm

According to [32] “monitoring” describes the processing of signals captured by sensors for the detection and diagnosis of failures or anomalies in the TSF and understanding these phenomena as deviations of indicators of normal conditions. Consequently, a monitoring system comprises a set of components that are intended to process signals from sensors to detect and diagnose unusual operational situations.

Monitoring system complexity depends on the complexity of the data processing required by the sensors in the TSF, the components that must be incorporated, and the system’s application potential [33]. In its simplest form, a monitoring system has four basic functions: (i) acquire data from sensors, (ii) transmit those data to the cloud or a central computer or datalogger for storage, (iii) process the stored data, and (iv) display the information in a visual, graphic, or numerical form on screens called dashboards. The initial level of data processing entails filtering the noise from the signals to improve the visualization. The second level of data processing includes making predictions of how the captured signals may vary in the future [34].

The ability to compare present or future signals with predefined variation ranges and, based on this comparison, generate an alarm when these ranges are exceeded or expected to be exceeded based on the calculations can be added to these functions [35]. In all of these cases, the monitoring systems involve only signal processing, although variants of these systems incorporate image processing, or the transformation of signals and images into, for example, the frequency domain [36].

The applications of monitoring systems with the indicated characteristics are numerous; for example, in the process industry, they can be used to evaluate performance indicators (KPIs) in real-time or to detect equipment failures in advance. Many monitoring systems developed for the industry use standard industrial products, such as programmable logic controllers (PLCs), supervisory control and data acquisition (SCADA), and distributed control systems (DCS), which are marketed by companies that supply automation equipment, systems, and services [37].

Thus, mining monitoring systems that implement these technologies are transforming the productive activity of the real world into a virtual world that is also known as the metaverse, where the collection of large-volume data in real time and their processing permits better holistic and prospective decision-making [38–41]. These technological improvements are driving changes in how mine tailings governance occurs; for example, sensors are gradually changing from mostly analog to mostly digital [13]. Similarly, the implementation of the Internet of Things (IoT) allows different sensors to be connected through the Internet and offers a powerful means of connectivity and data transmission via cloud storage and computers to implement statistical and probabilistic data analysis algorithms [42–44].

TSF monitoring, along with its design, construction, and operation, is critical for maintaining safe infrastructure. In this regard, a sensor system (instrumentation), as in the example shown in Figure 2, could support data gathering and processing, enhancing related activities such as (i) evaluating performance by comparing daily expectations with data, (ii) displaying early warnings about issues that could affect the integrity of the infrastructure, (iii) increasing knowledge of infrastructure behavior, (iv) assisting in the investigation and diagnosis of abnormal phenomena, (v) understanding the behavior of tailings in the short, medium and long term, and (vi) mitigating negative environmental impacts [45–47].

Figure 2. Example of a sensor monitoring system (piezometers) in a mine tailings storage facility dam [48].

Figure 2 shows a cycloned tailings dam that needs to be monitored with sensors to study the behavior of the water pore pressure and prevent dam failure due to tailings' dynamic liquefaction phenomena in response to earthquakes.

1.3. Article Aims

This systematic review of the scientific literature on the use of sensor technologies to monitor structural health and safety management aspects in mine TSFs reviews the publications available on the Web of Science (WoS) and Scopus databases. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were used and scientific maps were generated with VOSviewer software version 1.6.20. A methodological procedure of three phases was developed: (i) a quantitative bibliometric analysis, (ii) a qualitative systematic review of the literature, and (iii) a mixed review to integrate the findings. The following research questions (RQs) guided the investigation of structural health and safety management monitoring in mine TSFs:

- RQ1: How can the sensor concepts applied to TSF be clustered and how have they evolved?
- RQ2: What are the main engineering disciplines in which sensors are applied?
- RQ3: What timescale is used to record measurements with sensor technologies?
- RQ4: Are the data measurements conducted remotely or on-site with sensor technologies?
- RQ5: What types of sensor technology are applied?
- RQ6: What connectivity technology is applied in sensors?
- RQ7: Where are sensors applied within a mine TSF?
- RQ8: What technologies related to Industry 4.0 are currently being linked to sensors?

Finally, this article is structured as follows: (i) The introduction presents the context and scope of the research; (ii) the materials and methods define the resources and materials considered in this review and the methodological procedure adopted; (iii) the results are presented in the text, graphs, figures, and tables; (iv) the discussion reviews the findings obtained; and (v) the conclusion shares the lessons learned and recommendations.

2. Methodology and Resources for the Literature Review

2.1. Materials

2.1.1. Web of Science and Scopus Scientific Databases

To conduct this systematic review, the WoS and Scopus were selected as key data sources for journals and other sources of information on sensor technologies for monitoring TSFs. For this systematic review, work published in English from 2011 to 2023 was considered, including articles, conference papers, and scientific reviews.

2.1.2. Data Processing Software

For the systematization, analysis, and processing of the data in this study, MS Excel and VOSviewer software version 1.6.20 were used. MS Excel version 18.0 was used to systematize, analyze, and process the data in tables and graphs, while VOSviewer processed the data in scientific maps.

2.2. Methodology

2.2.1. Bibliometric Analysis and Systematic Content Review

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were used in this review, and scientific maps were created with VOSviewer software [49].

The PRISMA method can be depicted with a flowchart of the screening steps, "identification, detection, eligibility, and final inclusion" [50–52]. The exclusion process is schematically shown in Figure 3.

The PRISMA method is a set of evidence-based items that researchers can use to report systematic reviews and meta-analyses [50–52]. These guidelines help scholars and researchers report their rationale for conducting a review transparently, fully, and accurately [50–52].

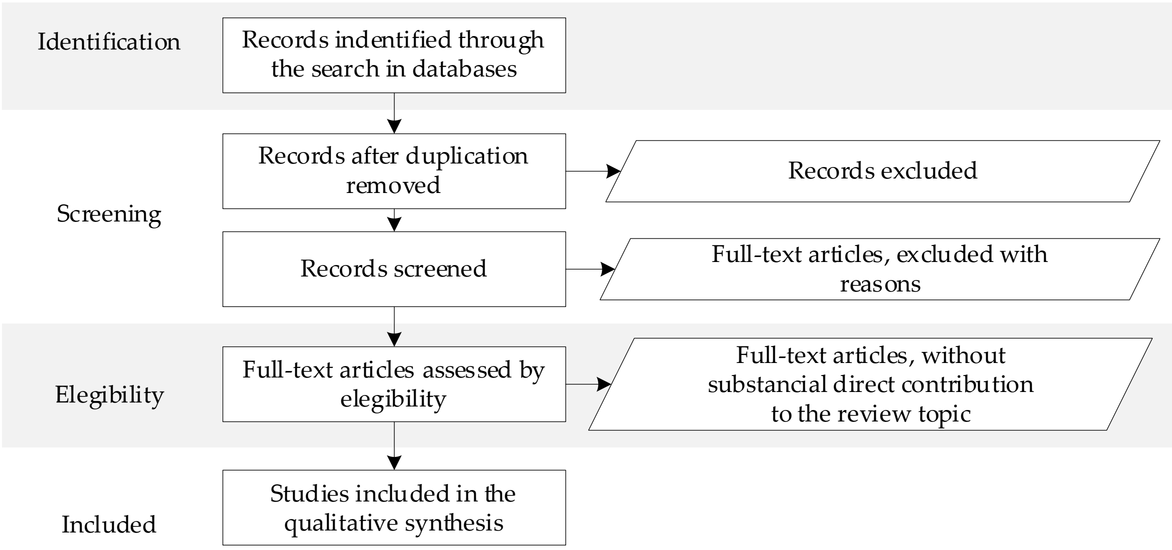

Figure 3. The PRISMA flow diagram of the search process for the highlighted and reviewed publications from the WoS and Scopus databases. Adapted from [53].

The procedure for this review is shown in Figure 4: (i) bibliometric analysis, (ii) systematic review of the literature, and (iii) mixed review to integrate the findings [53–55].

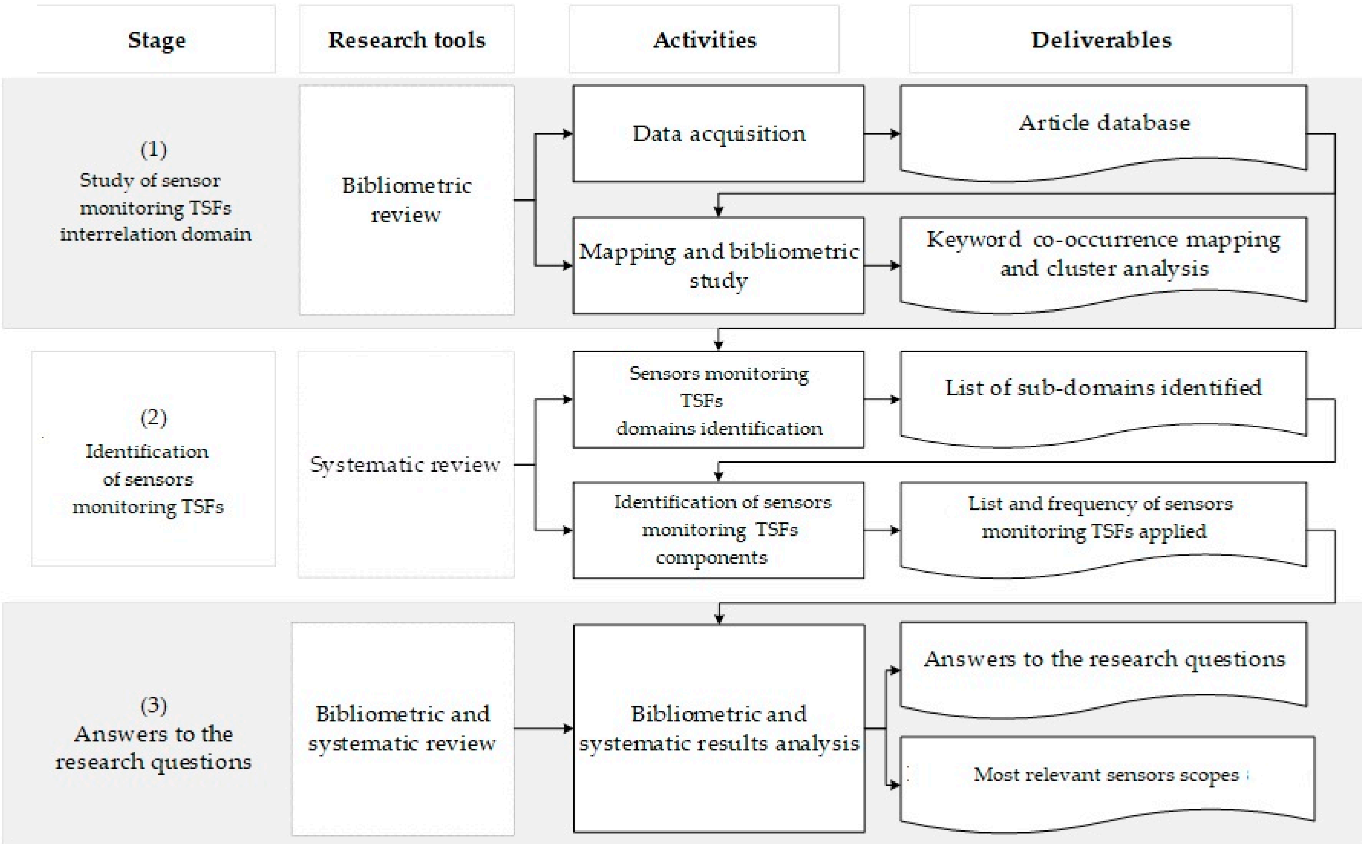

Figure 4. Summary of the methodological procedure used in this review. Adapted from [53].

Figure 4 shows the phases, research tools, activities, and deliverables developed through the methods applied in this systematic review. The three major phases of the methodological procedure implemented in this research are (i) identify interrelated sensor monitoring studies in the mine TSF domain through information acquisition, mapping, and bibliometric study, to later obtain a database of publications and map the co-occurrence of keywords for cluster analysis; (ii) identify the smart sensors used for health structural and safety management monitoring in mine TSFs through a systematic review, also identifying the monitoring domains of smart sensors and their subdomains; and (iii) answer the RQs by interpreting the integrated systematic review through bibliometric methods and describing the most relevant application scopes for sensor monitoring.

Co-occurrence is the occurrence of two or more very similar keywords. Co-occurrence maps are often considered a classification signal as they can foster an understanding of the relationships between different ideas and paradigms and permit grouping them conceptually or mapping the words visually with different font sizes and colors [56–58]. Therefore, co-occurrence maps focus on visualizing distance-based bibliometric networks that support substantial metadata [56–58]. The main purpose of a co-occurrence map in this type of work is to identify the conceptual structure of a certain scientific domain [49].

2.2.2. Scientific Publication Selection Process

To select the scientific publications to be studied in this systematic review, a search was developed with a set of keywords and Boolean operators and applied to the WoS and Scopus [49]. Therefore, a series of key concepts within the topic has to be defined for analysis in this systematic review. The selected keywords for this study were "sensor", "safety", "risks", "monitoring", and "tailings". After the keywords were chosen, four combinations of keywords were created using the Boolean AND operator, as shown in Table 1.

Table 1. Keywords and Boolean operators used to search the Scopus and WoS databases.

Keywords	Boolean Operator	Keywords	Boolean Operator	Keywords
Sensor Safety Risks	AND	Monitoring	AND	Tailings

From the results obtained with this search strategy, the scientific articles that met the search criteria were grouped and selected.

Finally, to study the scientific publications selected, a data extraction form based on [53] was used to obtain data from the metadata analysis perspective (DEM, data extracted from metadata) and the content analysis perspective (DEC, data extracted from content), as shown in Table 2.

Table 2. Data extraction form used in this review. Adapted from [53].

ID	Approach	Field	Question	Value
DEM 1	Metadata perspective	Keywords	Which are the keywords?	Keywords
DEM 2	Metadata perspective	Title	What is the title?	Name
DEM 3	Metadata perspective	Authors	Who are the authors?	Author List
DEM 4	Metadata perspective	Year	What is the publication year?	Year
DEM 5	Metadata perspective	Country	What is the first author's country of residence?	Country
DEM 6	Metadata perspective	Document Type	What is the name of the type of document?	e.g., conference paper, article, review, or other
DEC7	Content-based perspective	Popular Clusters	RQ1: How can the sensor concepts applied to TSF be clustered and how have they evolved?	e.g., sensors, safety, risks, monitoring, tailings, among others
DEC8	Content-based perspective	Engineering Disciplines	RQ2: What are the main engineering disciplines in which sensors are applied?	e.g., environmental, geotechnical, and civil, among others

Table 2. *Cont.*

ID	Approach	Field	Question	Value
DEC9	Content-based perspective	Measurement Timescale	RQ3: What timescale is used to record measurements with sensor technologies?	e.g., manual measurements (not in real-time), and/or automatic measurements (in real time)
DEC10	Content-based perspective	Measurement Spatial Scale	RQ4: Are the data measurements conducted remotely or on-site with sensor technologies?	e.g., on-site measurements (in place), and/or remote measurements (using remote sensors)
DEC11	Content-based perspective	Sensor Technology	RQ5: What types of sensor technology are applied?	e.g., piezometer sensor, deformation sensor, air quality sensor, among others
DEC12	Content-based perspective	Sensor Connectivity	RQ6: What connectivity technology is applied in sensors?	e.g., using cables, fiber optics, or wireless methods such as WiFi, Zigbee, Bluetooth, Xbee, or LoRa, among others
DEC13	Content-based perspective	TSF Area Application	RQ7: Where are sensors applied within a mine TSF?	e.g., tailings transport area, TSF dam area, and TSF reservoir area, among others
DEC14	Content-based perspective	Technologies in Industry 4.0	RQ8: What technologies related to Industry 4.0 are currently being linked to sensors?	e.g., data analytics, machine learning (ML), Internet of Things (IoT), and artificial intelligence (AI), among others

3. Results

The results obtained in this investigation are presented below.

3.1. Article Screening Process

To select the scientific publications to be analyzed in this systematic review, the articles identified in the initial search were passed through a series of exclusion criteria (EC) [49]. Figure 5 shows the procedure and its results at each stage.

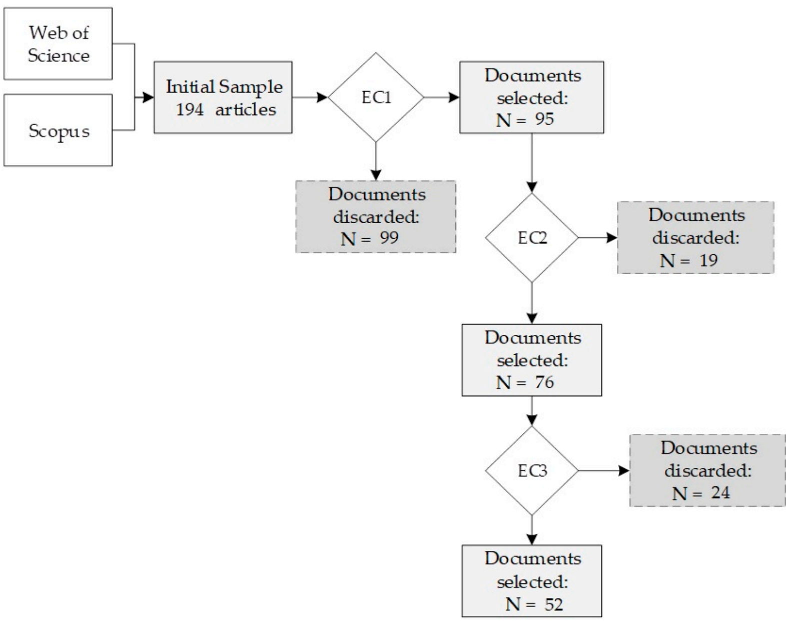

Figure 5. Scientific publication selection flowchart.

Figure 5 shows the extraction of publications from the WoS and Scopus databases with the combinations of keywords described above, which resulted in 194 articles. A first filter or exclusion criterion 1 (EC1) was used on these publications to eliminate duplicate documents, leaving 95 articles. Then, a second filter or exclusion criterion 2 (EC2) was used, which consisted of analyzing the publications' titles to determine which were related to sensors used to monitor mine TSFs, resulting in 76 articles. Finally, the last filter or exclusion criterion 3 (EC3) was applied, in which the full text of the abstracts was assessed, leaving 52 articles for analysis. These 52 selected publications deal specifically with sensors used for health, structural, and safety management monitoring in mine TSFs.

3.2. Bibliometric Analysis Results for Sensors Monitoring Mine Tailings Storage Facilities

3.2.1. Annual Quantitative Distribution of Literature

Figure 6 presents the publication year statistics for the 52 selected articles.

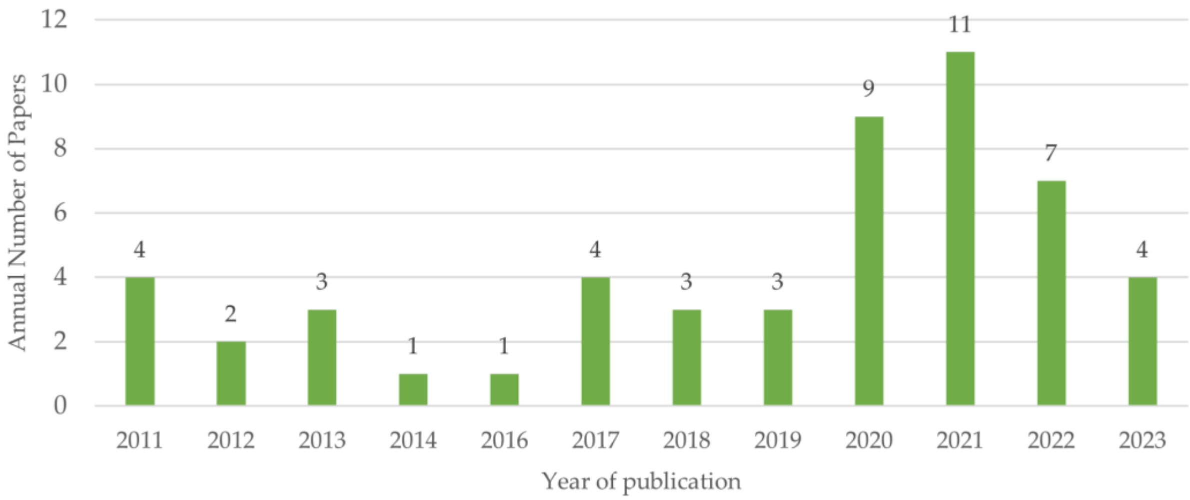

Figure 6. The number of articles published per year of the 52 selected articles, from 2011 to 2023.

Figure 6 depicts the number of articles related to sensors monitoring TSFs that were published per year out of the sample of 52 articles. 2021 was the most productive year (11 articles) and the peak of a growing trend of publications. From that year, the number of publications per year has decreased.

3.2.2. Country and Global Hemisphere Distribution of Selected Articles

Figure 7 shows the frequency of contributions by country for the 52 articles selected.

Figure 7 shows the 14 countries with the largest number of publications on the subject. By country, China, Australia, and South Africa, which represent approximately 69% of the 52 articles, lead in the number of publications, while Spain, Poland, Chile, the United Kingdom, the United States, Sweden, Brazil, Austria, Canada, Italy, and Germany have each published relatively few articles. Figure 8 shows the geographical distribution of the number of publications by country around the world. The countries that have published the most scientific articles on the topic are also the most productive countries from a mining standpoint, such as China.

Figure 9 presents the frequency of contributions to the research topic from countries belonging to the Global North and the Global South among the 52 selected articles.

Figure 9 shows that the Global North has made major contributions to this research topic, producing 79% of the selected publications while the Global South published 21%. This suggests that the main universities and research and development R&D centers for promoting sustainable innovation regarding the sensor technologies applied to TSF management are in the Global North.

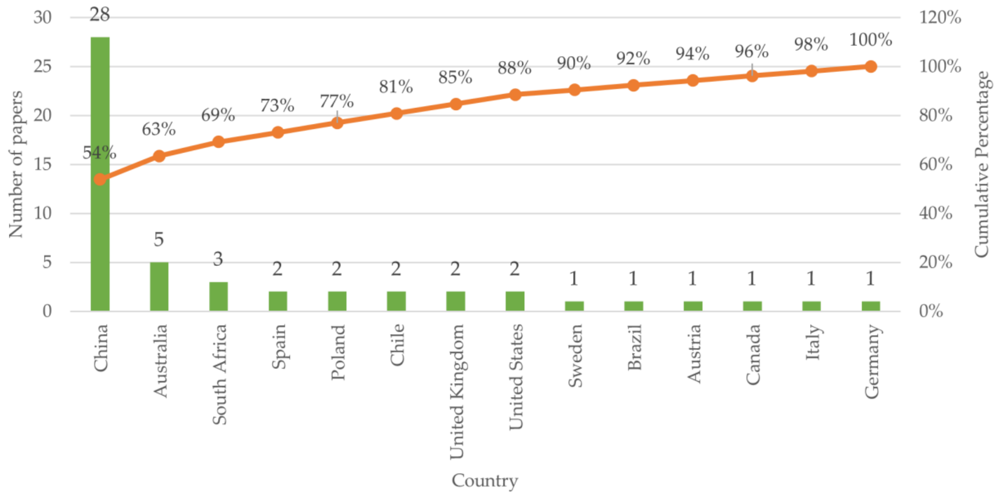

Figure 7. Productivity by country: The number of papers per country of the 52 selected articles.

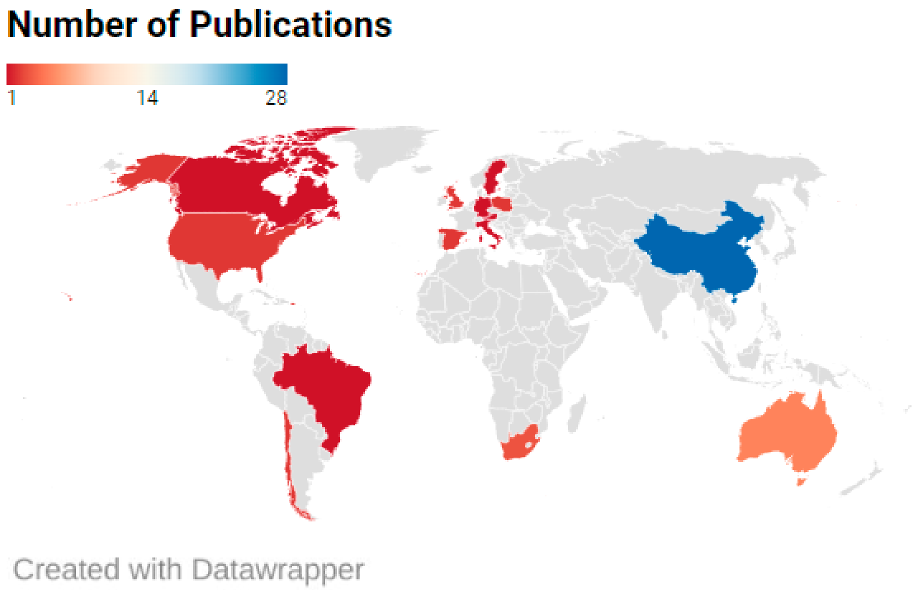

Figure 8. Geographical distribution of publications.

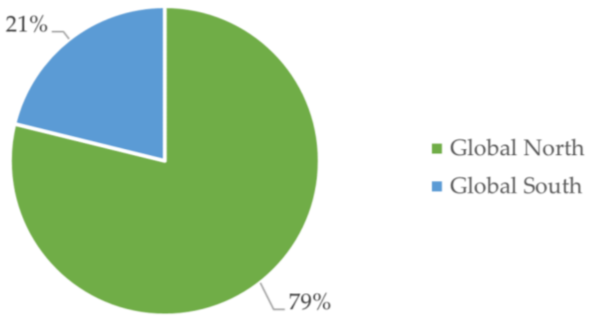

Figure 9. Productivity by global hemisphere: The number of papers by hemisphere.

3.2.3. Quantitative Analysis of Document Type

Figure 10 presents the distribution of document types of the 52 selected articles.

The pie chart in Figure 10 shows the distribution of the 52 selected articles by type: scientific articles predominate (33 total), followed by conference papers (15), and four review-type papers. This means that knowledge about the sensors used to monitor TSFs is being published primarily at the scientific level rather than at the level of advances in the state of mining industry practices presented at conferences.

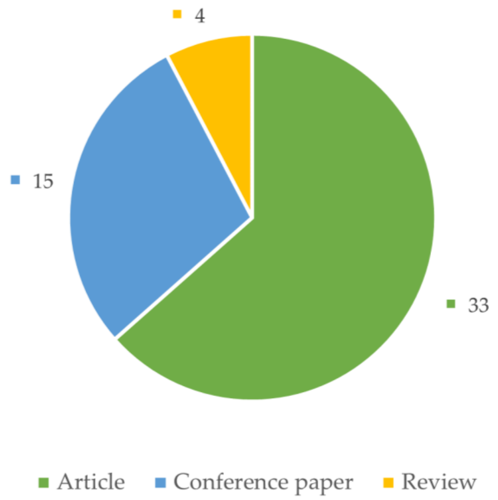

Figure 10. Distribution of documents by type.

3.2.4. Keyword Co-Occurrence Analysis

The bibliometric metadata obtained from the search for the 52 selected articles were processed in VOSviewer to produce a co-occurrence map without considering the timescale. The minimum occurrence value was two keywords; in other words, a keyword appears on the map when two articles use it. The resulting map shows four clusters, which are represented in green, blue, red, and yellow in Figure 11.

In the co-occurrence map in Figure 11, four clusters appear, which are represented by different colors. Among the keywords, the most prominent are "monitoring", "tailings dam", and "safety". Table 3 presents an interpretive summary of Figure 11, clarifying the themes of each cluster and the prominent keywords identified through the co-occurrence analysis.

Table 3. VOSviewer clusters without the time dimension.

Cluster Identification	Keywords from Co-Occurrence Analysis	Cluster Interpretation
Yellow	On-line monitoring, safety engineering, failure	Monitoring
Blue	Early warning, tailings pond, accidents	Safety management
Red	Real-time monitoring, alarm systems, dam deformation	Wireless sensor networks
Green	Deep learning, remote sensing, digital storage	Digital technologies

According to the cluster interpretations presented in Table 3, the development of sensor applications strongly trends toward their use in TSFs for monitoring, safety management, and the development of advances in sustainability monitoring.

The bibliometric metadata resulting from the search for the 52 selected articles were processed in VOSviewer to produce a co-occurrence map considering the timescale as well. The resulting map shows three clusters (represented in green, blue, and yellow) by publication year (Figure 12).

In the co-occurrence map presented in Figure 12, the timescale on which these concepts were generated can be appreciated; the most recent topics are risk management, remote sensing, and deep learning, while the oldest include disasters, alarm systems, and dam deformation. Table 4 presents an interpretive summary of Figure 12 to elucidate the themes that appear by cluster and the prominent keywords identified by the co-occurrence analysis.

The cluster interpretation presented in Table 4 shows the evolution over time of the application of sensors for monitoring safety trends, starting with issues of accidents and disasters, then evolving to consider the development of means of powerful wireless monitoring systems, and, finally, the development of technologies to support the total digitalization of information.

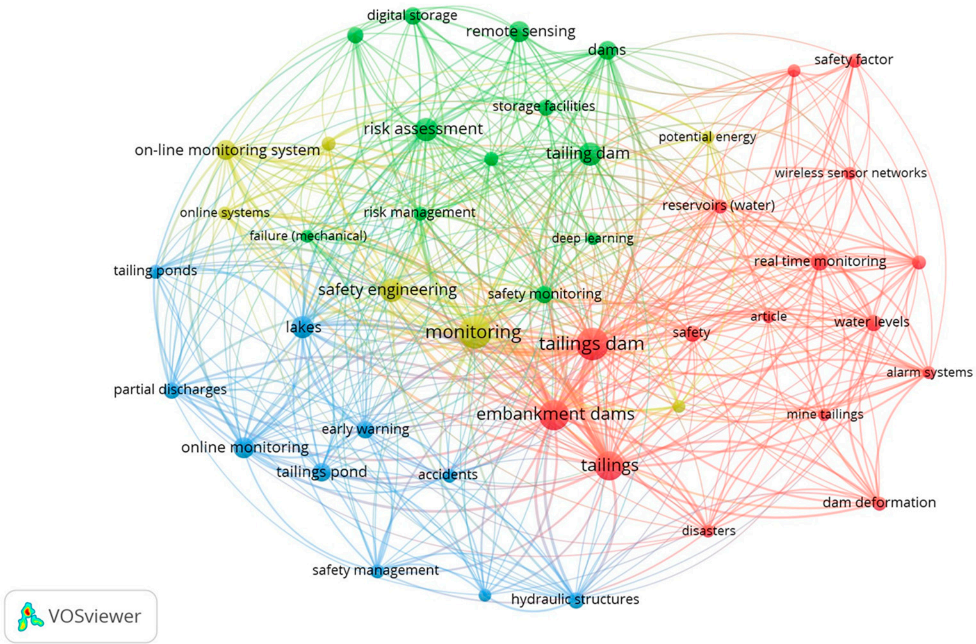

Figure 11. Keyword co-occurrence map without the time dimension.

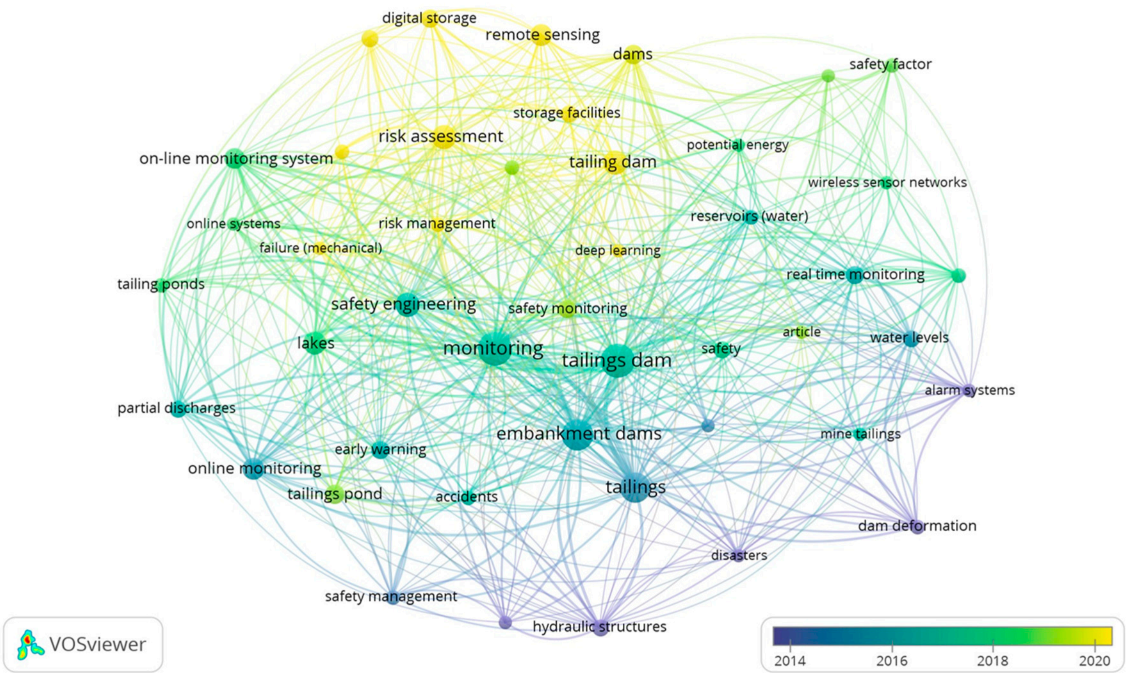

Figure 12. Keyword co-occurrence map with the time dimension.

Table 4. VOSviewer clusters with the timescale dimension.

Cluster Identification	Keywords	Average Year of Publication	Cluster Interpretation
Blue	Safety management, alarm systems, dam deformation, water levels.	2014–2016	Prevention of accidents and disasters
Green	Real-time monitoring, online monitoring, safety engineering	2016–2018	Advances in monitoring systems
Yellow	Risk management, deep learning, remote sensing, digital storage	2018–2020	Digital monitoring with the use of Industry 4.0 technologies

3.3. Systematic Content Review Results for Sensors Monitoring Mine Tailings Storage Facilities

3.3.1. Content-Based Data Perspective Analysis

In this chapter of this systematic review, the answers to the research questions, determined through an exhaustive content analysis of the 52 selected articles, are presented.

The main engineering disciplines where sensors are used to monitor TSFs are represented in Figure 13. The most prominent of these engineering disciplines are geotechnics, mining, and civil engineering, with 10, 8, and 7 documents on these topics, respectively.

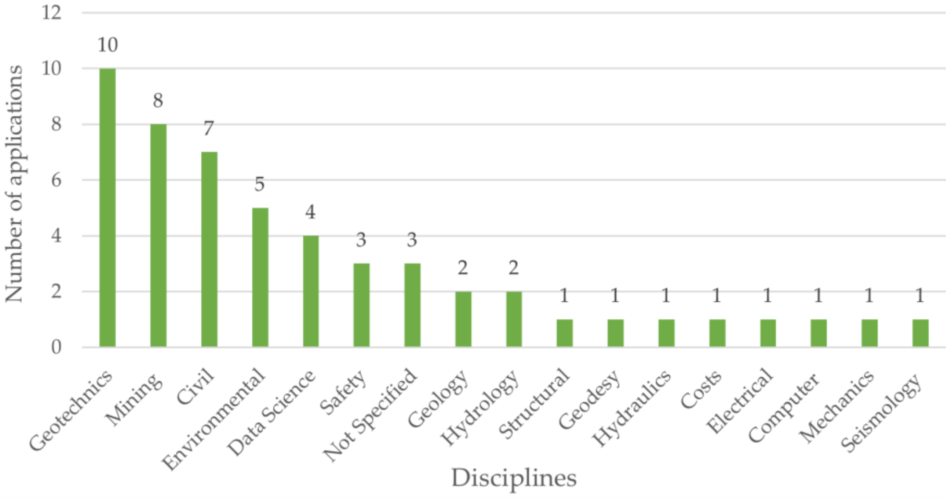

Figure 13. The main engineering disciplines where sensors are used to monitor tailings storage facilities.

As Figure 13 shows, geotechnics, mining, and civil engineering represent more than 50% of the analyzed documents. Conversely, structural engineering, geodesy, hydraulics, costs, electrical engineering, computer engineering, mechanics, and seismology each represent only one document. Three of the study documents do not specify any engineering discipline.

Figure 14 depicts the timescale of sensor data collection, considering automatic data collection as real-time and manual data collection as not real-time measurements. The graph shows that of 47 documents, the data are predominantly automatically collected in real time; only one document reports manual, non-real-time data collection, and two documents do not specify a data collection timescale.

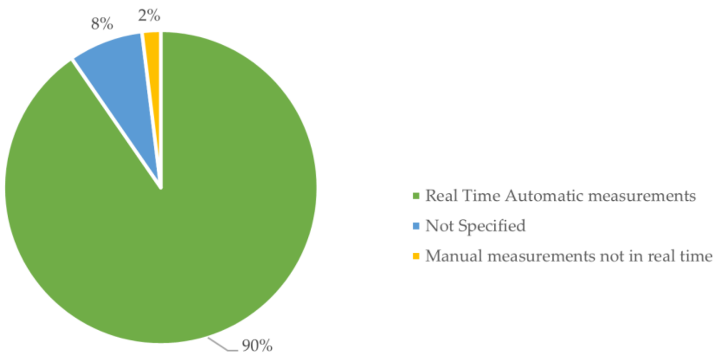

Figure 14. Timescale used to record measurements from sensor technologies used to monitor tailings storage facilities.

Figure 14 shows the main applications of sensors in TSF monitoring, highlighting the modern trend of making real-time automatic measurements (90% of sensor usage).

The space scale of data measurements performed with sensors (remote or on-site) for monitoring TSFs is represented in Figure 15, which shows that the most common method is remote measurements at 67% of the analyzed documents.

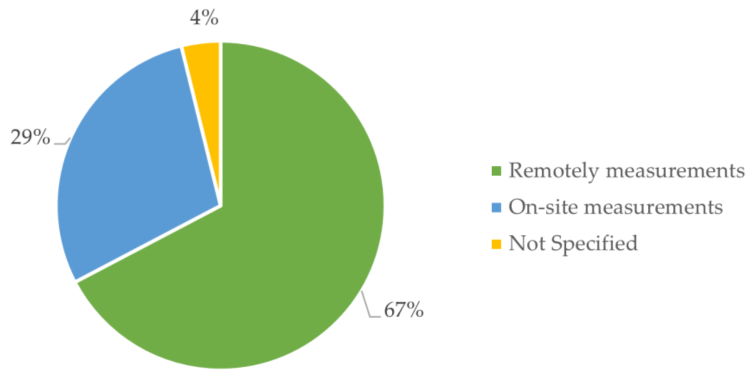

Figure 15. Space scale of data measurements performed with sensors to monitor tailings storage facilities.

Figure 15 shows the main applications of sensors for tailings storage facilities monitoring, highlighting 35 mentions of remote measurements, 15 mentions of on-site measurements, and 2 documents that do not specify.

The graph in Figure 16 depicts the different types of sensors used for monitoring tailings storage facilities according to the analyzed literature: Water level sensors (piezometers) lead the count with 8 mentions, followed by pressure sensors with six mentions and displacement sensors with 5 mentions.

According to the information presented in Figure 16, there is a tendency to monitor aspects related to dams' physical stability, such as the key infrastructure of a TSF. Only 3 documents do not mention the type of sensors used. Several types of sensors are mentioned only once, such as InSAR, radar, UAVs, air quality sensors, and others.

The type of data transmission implemented for sensor connectivity to monitor mine TSFs is shown in Figure 17. The three main types of data transmission are satellite (11 applications), Zigbee (eight applications), and 4G (mobile cellphone) with 6 applications, all wireless connection formats.

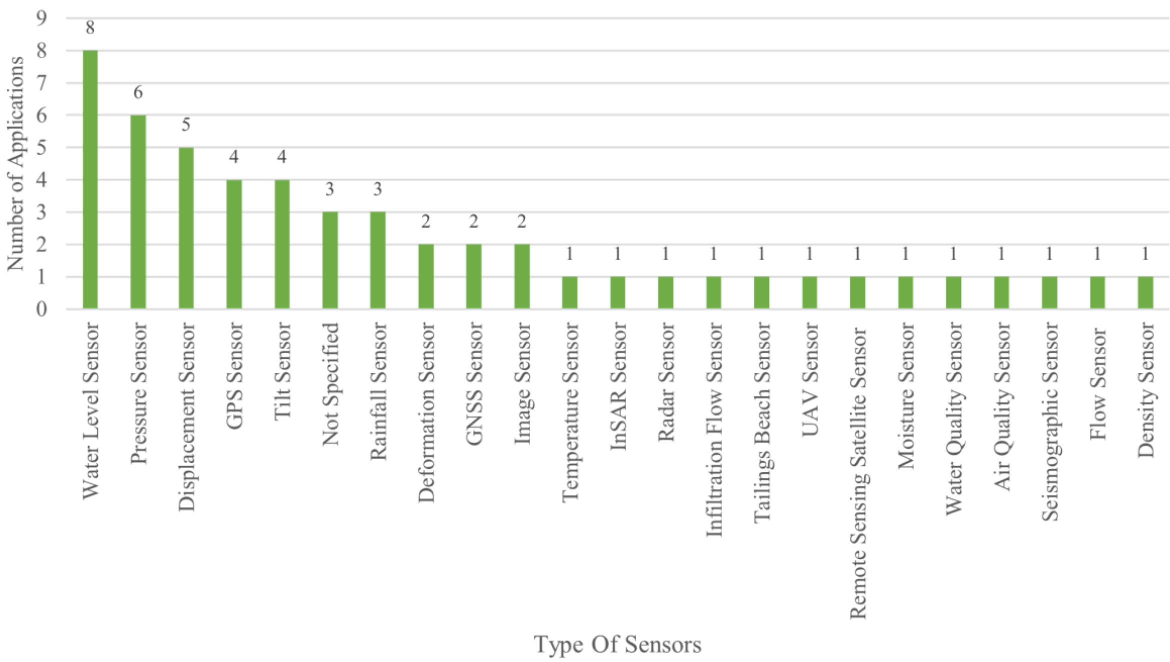

Figure 16. The type of sensor technology used to monitor tailings storage facilities.

Notably, among the data presented in Figure 17, 5 documents do not specify the connectivity technology used.

The use of cables or wireless systems for sensor connectivity is shown in a pie chart in Figure 18. Wireless systems are mentioned in 35 documents and wired systems are mentioned in 7 documents; 10 documents do not specify the system type.

To transmit the information captured by a sensor or monitoring system and make it available in real time, some communication system technologies stand out.

- Fiber optic and/or coaxial cable. Communication systems based on fiber optics and/or coaxial cable have been used routinely in the telecommunications and mining industries. These systems' advantages are (i) they allow the automatic control of variables, (ii) they allow real-time diagnosis, (iii) they offer perpetual operation without maintenance, (iv) they allow control during post-operation, (v) they can transmit data over long distances, and (vi) they can transmit large amounts of data (high transfer rate compared to other wired systems).
- Satellite communication or radio communication. These systems allow communication at any time, anywhere, and on any device. Their advantages include (i) simultaneous communication to several receivers and (ii) the capacity to transmit early community warnings.

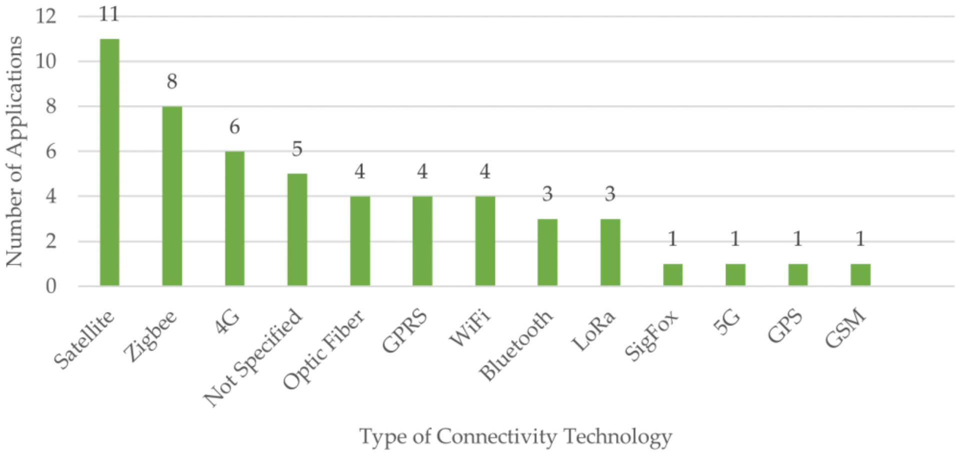

Figure 17. Types of data transmission implemented for sensor connectivity to monitor TSFs.

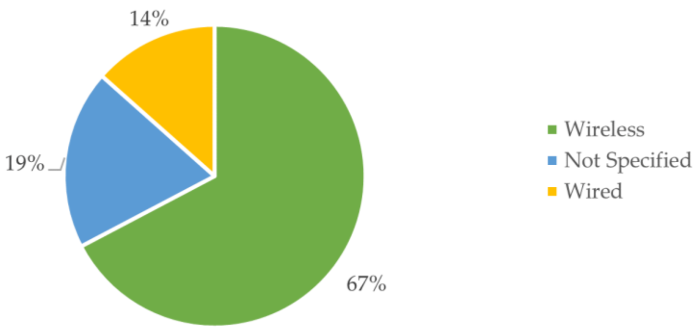

Figure 18. The use of cables or wireless systems for sensors monitoring TSFs.

The areas within a mine TSF where sensors are used to monitor structural health and safety management are shown in Figure 19.

As Figure 19 shows, the dam area is the main sensor location with 14 mentions, followed by the reservoir level area with 12 mentions; the least mentioned areas are the drainage system and cut-off trench, with only one mention each. Nine documents did not specify sensor location areas in the TSF.

The selected documents were also analyzed for the implementation of technologies related to Industry 4.0 with monitoring sensors. Figure 20 shows the percentage of mentions of different technologies in the selected papers. Artificial intelligence (AI) is the most common technology, with 30% of the total mentions, followed by the IoT with 23% of the total mentions, and cloud computing (CC) with 18% of the total mentions.

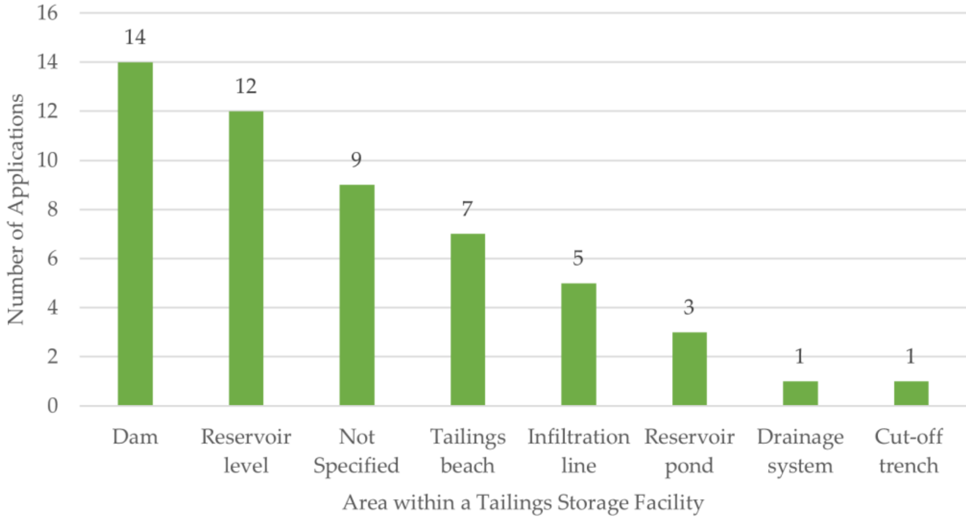

Figure 19. Areas within a TSF where sensors are used to monitor structural health and safety management.

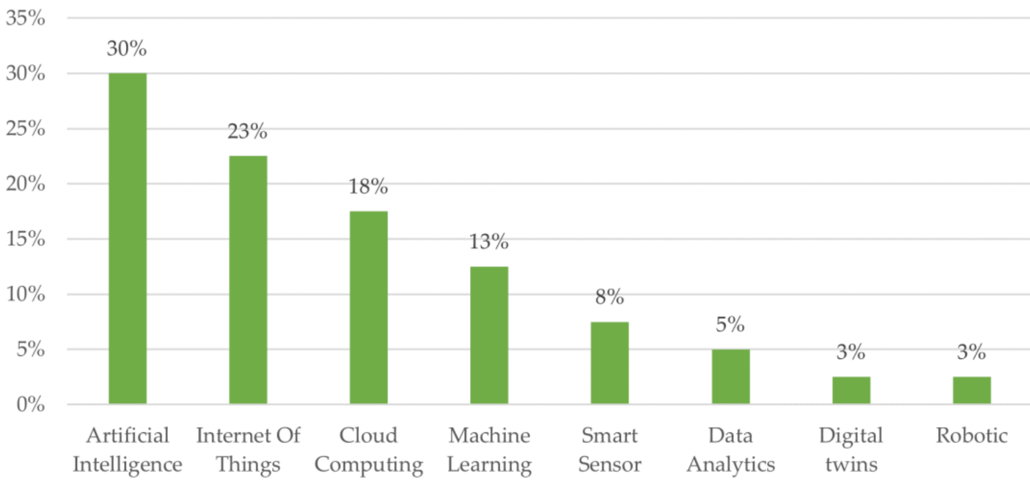

Figure 20. Technologies related to Industry 4.0 that have been applied in sensors monitoring TSFs.

3.3.2. Main Applications of Sensor Use to Monitor the Structural Health and Safety Management of TSFs

Figure 21 shows some examples of the use of sensors to monitor structural health and safety management in TSFs under an Industry 4.0 paradigm. This monitoring permits the study of key variables affecting sustainability, productivity, and safety performance.

Currently, the addition of wireless monitoring systems is trending upward via remote monitoring and the use of Industry 4.0-related technologies. As Figure 21 depicts, different sensors for structural health and safety management monitoring in mine TSFs can be used. The following sensors are displayed in Figure 21: (i) piezometer (Casagrande and vibrating wire), (ii) temperature sensor, (iii) inclinometer, (iv) pressure cell, (v) settlement cell, (vi) borehole extensometer, (vii) water quality well, (viii) V-notch weir, (ix) crack gauge, (x) vented piezometer, (xi) strain gauge load cell, (xii) rain/wind/moisture content/evaporation gauge, (xiii) central data acquisition, (xiv) drone, (xv) satellite, InSAR and radar (remote sensing), and (xvi) bathymetry with unmanned survey vessel. Figure 22 shows some examples of typical sensors and devices used for these purposes.

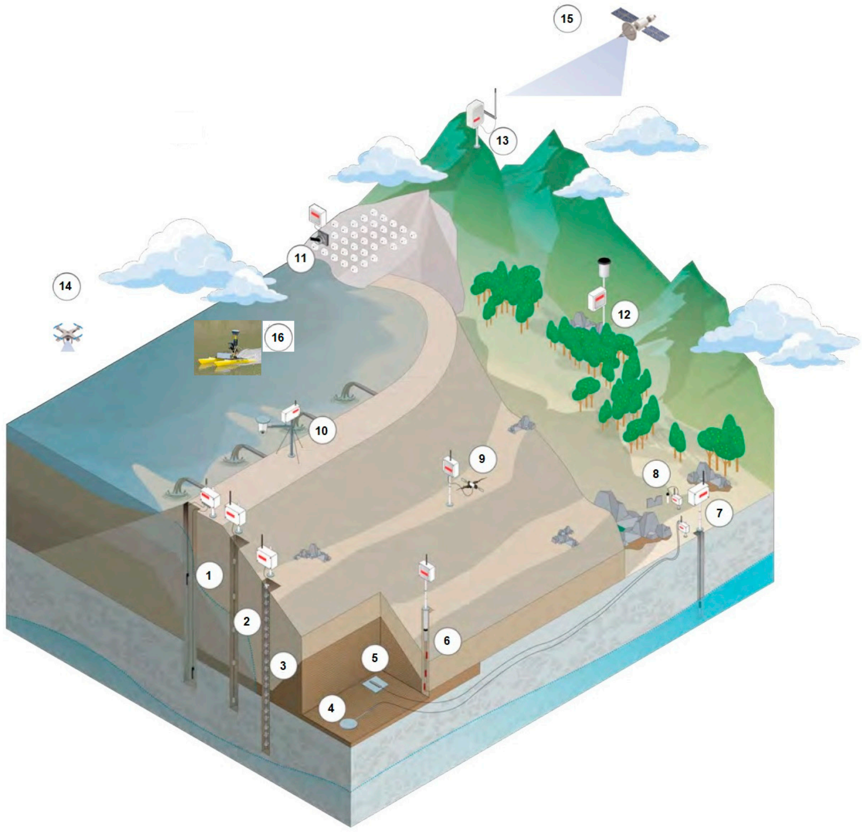

Figure 21. Examples of the use of different sensors for structural health and safety management monitoring in mine TSFs. Adapted from [59]. The following sensors are displayed in the figure: (1) piezometer, (2) temperature sensor, (3) inclinometer, (4) pressure cell, (5) settlement cell, (6) borehole extensometer, (7) water quality well, (8) V-notch weir, (9) crack gauge, (10) vented piezometer, (11) strain gauge load cell, (12) rain/wind/moisture content/evaporation gauge, (13) central data acquisition (gateways and nodes), (14) drone, (15) satellite, InSAR and radar (remote sensing), and (16) bathymetry with unmanned survey vessel.

Figure 22. Examples of sensors used for mine TSF monitoring.

The wireless configuration of the data acquisition system eliminates the need for expensive cabling and manual monitoring in mine TSFs. Laying cables in a mine tailings dam requires trenches and cable protection against issues such as embankment settlements. New sensors must be added as the site grows, again requiring expensive cable installation. A wireless system provides data from sensors in near-real time, versus manually collected readings with a more sporadic periodicity and vulnerability to human error.

3.3.3. Comparision of the Main Characteristics of the Articles Selected Dealing with Sensors Monitoring Mine Tailings Storage Facilities

A comparison of the main characteristics of the 52 selected articles is summarized in Table 5. This table includes (i) the space scale of data measurement, (ii) the type of operation, (iii) data connectivity, (iv) TSF area, (v) engineering discipline, (vi) the use of cables or wireless, (vii) Industry 4.0 technology, and (viii) the cost in USD.

Table 5. Comparison of the main characteristics of the 52 selected articles on the use of sensors to monitor TSFs. The following abbreviations are used for various elements: (i) the space scale of data measurement (Remote, R; On-site, OS; or Not specified, NS), (ii) operation (Real-time automatic, RTA; Not real-time/manual, NRTM; or Not specified, NS), (iii) connectivity (Satellite, S; Zigbee, Z; 4G, 4G; SigFox, SF; Other, O; or Not specified, NS), (iv) TSF area (Dam, D; Reservoir level, RL; Tailings beach, TB; or Not specified, NS), (v) engineering discipline (Geotechnics, G; Mining, M; Civil, C; Other, O; or Not specified), (vi) use of cables or wireless (Cables, C; Wireless, W; or Not specified, NS), (vii) Industry 4.0 technology (Internet of Things, IoT; Cloud computing, CC; Artificial intelligence, AI; Unmanned aerial vehicles, UAVs; Other, O; or Not specified, NS), and (viii) cost (USD) (Yes, Y, or Not specified, NS).

#	Reference	Year of Publication	Space Scale Data Measurements	Operation	Connectivity	TSF Area	Engineering Discipline	Use of Cables or Wireless	Industry 4.0 Technology	Cost (USD)
1	Jeong and Kim [60]	2019	R	RTA	4G	TB	C	W	AI	NS
2	Basson et al. [61]	2021	OS	RTA	SF	TB	G	C	UAVs	Y
3	Wu et al. [62]	2017	OS	RTA	4G	D	C	W	AI	NS
4	Guan and Yang [63]	2020	NS	RTA	NS	D	G	W	AI	NS
5	Ma et al. [64]	2023	R	RTA	4G	D	G	W	AI	NS
6	Dong et al. [65]	2022	OS	RTA	NS	D	G	C	AI	NS
7	Wang et al. [47]	2021	OS	RTA	S	D	G	C	CC	NS
8	Zhang et al. [66]	2023	R	RTA	S	D	M	W	UAVs	NS
9	Yu et al. [67]	2011	OS	RTA	4G	D	G	C	NS	NS
10	Clarkson and Williams [68]	2021a	R	RTA	4G	D	G	W	NS	NS
11	Clarkson and Williams [37]	2021b	R	RTA	4G	D	G	W	NS	NS
12	López-Vinielles et al. [69]	2021	R	RTA	S	D	M	W	NS	NS
13	Lumbroso et al. [70]	2020	R	RTA	S	D	M	W	NS	Y
14	Hu and Liu [71]	2011	R	RTA	S	D	G	W	NS	NS
15	He et al. [72]	2013	R	RTA	Z	D	M	W	IoT	NS
16	Li et al. [73]	2020	R	RTA	S	D	M	W	AI	NS
17	Sarker et al. [74]	2022	R	RTA	S	D	M	W	NS	NS
18	Yang et al. [75]	2020	OS	RTA	4G	D	G	C	AI	NS
19	Villavicencio et al. [76]	2021	R	RTA	S	D	G	W	AI	NS
20	Li and Wang [77]	2011	R	RTA	S	D	M	W	NS	NS
21	Zhen et al. [78]	2020	NS	RTA	NS	D	M	NS	AI	NS
22	Yang et al. [79]	2019	OS	RTA	4G	TB	C	C	AI	NS
23	Cacciuttolo and Atencio [13]	2023	R	RTA	Z	RL	C	W	IoT	NS
24	Balaniuk et al. [80]	2020	R	RTA	S	RL	C	W	AI	NS
25	Wu et al. [81]	2018	NS	NRTM	NS	D	C	NS	AI	NS
26	Mura et al. [82]	2018	R	RTA	S	D	G	W	NS	NS
27	Jing and Gao [83]	2022	OS	RTA	4G	D	G	C	AI	NS
28	Stefaniak and Wróżyńska [84]	2018	OS	NRTM	NS	RL	G	C	NS	NS
29	Chalkley et al. [85]	2023	R	RTA	S	D	M	W	NS	NS
30	Dong et al. [36]	2018	OS	RTA	4G	D	G	W	IoT	NS
31	Ruan et al. [86]	2023	OS	RTA	4G	D	G	C	AI	NS
32	Donovan et al. [87]	2022	R	RTA	S	RL	M	W	NS	NS
33	Zhen et al. [88]	2022	OS	NRTM	NS	NS	M	NS	AI	NS

Table 5. *Cont.*

#	Reference	Year of Publication	Space Scale Data Measurements	Operation	Connectivity	TSF Area	Engineering Discipline	Use of Cables or Wireless	Industry 4.0 Technology	Cost (USD)
34	Hu et al. [89]	2013	OS	RTA	4G	RL	C	C	NS	NS
35	Hui et al. [46]	2017	R	RTA	S	D	G	W	IoT	NS
36	Clarkson et al. [34]	2020	R	RTA	Z	D	G	W	IoT	Y
37	Hao et al. [90]	2019	R	RTA	S	D	G	W	NS	NS
38	Chen et al. [91]	2019	OS	RTA	4G	RL	M	W	AI	NS
39	Wan et al. [45]	2012	R	RTA	S	D	G	W	CC	NS
40	Zhang et al. [92]	2014	OS	RTA	Z	D	M	W	IoT	NS
41	Lu [33]	2020	OS	RTA	NS	RL	M	NS	AI	NS
42	Du et al. [93]	2020	R	RTA	S	D	G	W	NS	NS
43	Li et al. [94]	2020	OS	RTA	4G	D	G	W	IoT	NS
44	Cacciuttolo and Cano [4]	2023	R	RTA	S	RL	C	W	CC	NS
45	Haiming and Jing [95]	2013	R	RTA	4G	D	C	NS	NS	NS
46	Li et al. [96]	2011	OS	RTA	4G	D	G	C	NS	NS
47	Sun et al. [35]	2012	OS	RTA	4G	D	C	W	IoT	NS
48	Lumbroso et al. [97]	2019	R	RTA	S	D	M	W	NS	Y
49	Koperska et al. [98]	2022	OS	RTA	4G	D	M	W	IoT	NS
50	Morton [99]	2021	R	RTA	S	D	G	W	IoT	NS
51	Mazzanti et al. [100]	2021	R	RTA	S	D	M	W	NS	NS
52	Cacciuttolo et al. [32]	2023	R	RTA	Z	RL	C	W	IoT	NS

Based on the analysis summarized in Table 5, the following findings emerge:

- Regarding the space scale of data measurements, 67% of the cases involve remote measurements, while 29% utilize on-site measurements, and the remaining 4% of the documents do not specify. There is a clear tendency toward remote systems with sensors (telemetry technologies) for mine TSF monitoring.
- When studying the type of operation of sensor systems, 90% of the studies mention automatic applications with real-time data collection, and 2% indicate manual non-real-time data collection. Finally, 8% of the documents do not specify the operation information. This shows that monitoring mine TSF activities in real time is preferred.
- Regarding the connectivity of sensor systems, 21% of the documents mention satellite, 15% mention Zigbee, 17% mention 4G, 10% do not specify a connectivity method, and 42% mention other applications. This shows a tendency to use wireless sensor connections in mine TSF monitoring applications.
- Analyzing the area of the mine TSF where sensor systems are applied reveals that 27% are applied in the dam area, 23% in the reservoir level area, 13% in the tailings beach area, 17% in unspecified areas, and 19% in other areas of the TSF. This affirms that the current monitoring emphasis in TSFs with sensor systems is on the dam and reservoir areas.
- Regarding engineering disciplines, the discipline mentioned most often is geotechnics, at 19%, then mining at 15%, civil engineering at 13%, and others at 52%, including the emerging discipline of data science. This shows that structural stability aspects are a priority in the use of sensor systems in mining.
- Considering the use of sensors with wired or wireless connections, 67% of the cases indicate wireless connections, while 13% correspond to cable connections, and 19% are unspecified. This demonstrates a clear trend toward the use of wireless sensor systems, reflecting the application of IoT and Industry 4.0 technologies.

- Regarding the technologies linked to Industry 4.0, 23% of the cases are not specified. However, 21% of the cases mention AI, 17% mention the IoT, 13% mention CC, and 25% mention other technologies. This shows that sensor systems are often linked to AI and IoT approaches, but massive integration with other Industry 4.0 technologies such as digital twins (DT) remains lacking.
- The cost analysis reveals that, although all applications claim to reduce costs, this characteristic is rarely documented in the scientific literature.

TSF monitoring processes have varied from manually measuring dams and the installation of downhole instrumentation to measuring pore pressures or monitoring crack structures. Typically, these activities are periodically undertaken via manual techniques that require humans in the field, increasing the risk of fatigue or injury [34]. Furthermore, as mining projects grow, surveying crews are inevitably placed under more operational pressure and routine monitoring tasks can bear the risk of accidents [32].

Alternatives to manual methods include the application of a wireless, autonomous, near-real-time monitoring system with sensors that avert the need to manually measure relevant parameters [37]. Furthermore, the cost to the operation, whilst higher in the short term with CAPEX, is rapidly offset by the minimal labor and data transfer effort required.

The benefits of wireless systems are primarily associated with the ease of installation. New communication technologies preserve the data pathways between the sensors, and only part of the system must be able to see the gateway [101]. Once installed, work activities around the system are facilitated by the absence of cabling, and temporary obstructions can be resolved by the system's ability to self-heal data pathways from the instruments to the gateway [101].

Near-real-time systems can alert key personnel when TSF thresholds are exceeded or sensors have been disconnected from the gateway for a short time. For example, tilt systems can be integrated with other geotechnical and downhole instrumentation, allowing the entire system to report to a dashboard. In situ, pore pressures within a dam can be measured with a vibrating wire piezometer and the data can be wirelessly collected by a single gateway in the field. Instruments that are further afield, such as crack sensors and displacement sensors, can also be integrated. Although TSF dam monitoring can be undertaken in many ways, only an autonomous near-real-time system can both reduce the risk of failure and enhance productivity [68].

A data logger is an electronic device that is integrated on-site and records data over time from geotechnical instruments and its own or externally connected sensors. The main advantage of geotechnical data loggers is that they can operate independently, making them effective for conducting counts and generating a traceable database over time to record the trends in the physical and chemical parameters monitored. Data loggers are essential for the management of a TSF to guarantee compliance with regulations according to the projected engineering thresholds and with ICMM global standards [34,37,68].

For example, vibrating wire piezometers, which are water pressure sensors installed in the dam and foundation of a TSF, are connected to data loggers that can transmit piezometric information wirelessly to a web-based platform that is tailored to the mining operation. This information can be uploaded and automatically entered into a database to enable various functions, including sending automatic alerts via email or mobile platforms and allowing data viewing, recording, and downloading [72]. Other facilities that monitor and evaluate seismic activity and rainfall events can also be integrated into an automated monitoring system.

The types of sensors that are used to monitor structural health and safety management aspects of mine TSFs in the selected articles are summarized in Table 6. This table includes (i) sensor typology, (ii) data obtained/variable measured, (iii) monitoring results, (iv) monitoring frequency, and (v) real-time monitoring.

Table 6. Comparison of different monitoring technologies for structural health and safety management monitoring in TSFs.

Sensor Name	Sensor Typology	Data Obtained/ Variable Measured	Monitoring Results	Monitoring Frequency	Real-Time Monitoring
Visual inspection by miners	Photographic inspection (observational method)	Dam performance	Interior/exterior, medium reliability, low cost	1/week	No
Visual inspection by EoR		Dam performance	Interior/exterior, medium reliability, low cost	1/month	No
DSR inspection		Dam performance	Interior/exterior, high reliability, high cost	1/year	No
ITRB inspection		Dam performance	Interior/exterior, high reliability, high cost	1/3 years	No
Closed-circuit television camera (CCTV)		Dam performance	Interior/exterior, high reliability, low cost	Every minute	Yes
Meteorological station		Rain/wind/ evaporation/solar radiation	Interior/exterior, high reliability, low cost	Every minute	Yes
Accelerometer	Geotechnical instrumentation	1D/2D/3D seismic accelerations	Interior/exterior, point, high reliability, medium cost	On event	Yes
Slope indicator/inclinometer		1D/2D displacement/slope	Interior/exterior, point, high reliability, low cost, achievable accuracy: 3 mm/10 m	4/month	Yes
Extensometer		1D displacement	Interior/exterior, point, high reliability, low cost, achievable accuracy: 0.05 mm/10 m	4/month	Yes
Casagrande piezometer		Hydraulic head/pore water pressure	Interior, point, high reliability, low cost	1/week 1/month	No
Vibrating wire piezometer		Hydraulic head/pore water pressure	Interior, point, high reliability, medium cost	Real time	Yes
Tiltmeter		2D displacement	Interior/exterior, point, high reliability, low cost	4/month	Yes
Settlement cell		1D displacement (vertical)	Interior/exterior, point, high reliability, low cost	2/month	Yes
Distributed optical fiber strain sensors		1D displacement (strain), acoustics	Interior/exterior, feature, high initial cost for permanent monitoring, achievable accuracy: 10–5 mm/m		
Distributed optical fiber temperature sensors		1D temperature	Interior/exterior, leak and seepage detection/localization		
Monitoring wells	Hydraulic instrumentation	Phreatic level	Leak and seepage detection/localization	1/week	No
Seepage with weir or flume		Seepage flow	Seepage condition	Real time	Yes
Water quality		Metals content	Leak and seepage detection/localization	4/month	Yes
Surveying (optical)	Topographical/ bathymetrical/ geodetic devices (remote sensing)	3D displacement	Exterior, point/ feature, e.g., level profile surveys, labor-intensive	6/year	No
Automated total stations (ATS)		3D displacement	Exterior, point/ feature, high accuracy, lower labor costs, sub-cm accuracy for distances <1 km	12/year	No
Global positioning system (GPS)/Global navigation satellite system (GNSS)		3D displacement	Exterior, point/ feature, real-time kinematics (RTK) can be used to enhance GPS/GNSS measurements	1/day	Yes
Secondary surveillance radar (SSR)		3D displacement	Exterior, feature	1/day	Yes

Table 6. *Cont.*

Sensor Name	Sensor Typology	Data Obtained/ Variable Measured	Monitoring Results	Monitoring Frequency	Real-Time Monitoring
Light detection and ranging (LiDAR)		3D displacement, beach crest height	Exterior, feature, high accuracy, point cloud data, high data processing cost	1/day	Yes
Unmanned aerial vehicles (UAVs)/drones		Mine tailings storage facility panoramic view, dry beach length	Interior/exterior, point, high reliability, medium cost	1/month	Yes
Unmanned survey vessel (USV)		Mine tailings water pond bathymetry	Interior/exterior, point, high reliability, medium cost	1/month	Yes
Aerial imaging analysis		2D/3D displacement	Exterior, feature, stereographic need for vertical displacement	1/day	Yes
Satellite data analysis		2D/3D displacement	Exterior, feature, measurement interval limited by satellite return time and atmospheric conditions	1/day	Yes
Interferometric synthetic aperture radar (InSAR)		3D displacement	Exterior, feature, ground-based or satellite-borne, sub-centimeter accuracy	1/day	Yes

The sensor instrumentation reviewed in Table 6 is classified as either invasive instrumentation, which breaks into a location and destroys or modifies the measured object, or non-invasive instrumentation, which does not break into a location and, therefore, does not destroy or modify the measured object.

Figure 23 shows an example of the typical location and installation of invasive sensor instrumentation in a TSF dam.

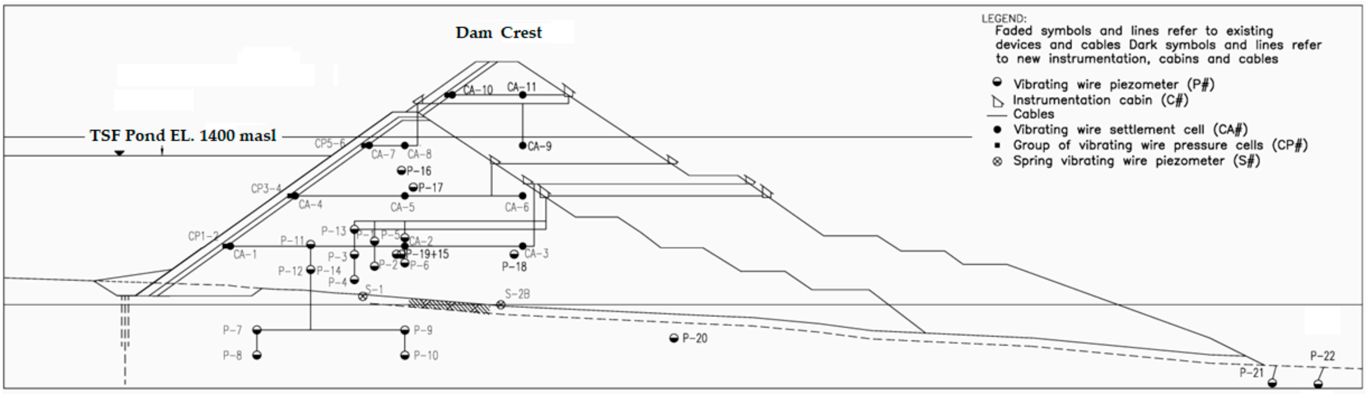

Figure 23. Example of the implementation of an invasive sensor instrumentation system in a mine TSF.

Due to their extensive application and the availability of information, the details of the most traditional invasive instrumentation types are not presented in this review, as they are already described in other articles in the literature.

Considering their relatively recent usage in TSFs, of the options presented in Table 6, the non-invasive instrumentation sensor tools are presented below, including satellite images and interferometry, among others. The modern technologies applied in recent years include UAVs or drones to collect aerial photos or conduct analyses with photogrammetry or LiDAR systems, satellite and radar technologies (InSAR) to analyze the subsidence or displacement of soils or dams, and satellite images, which are visual representations captured by sensors mounted on artificial satellites in space. Satellite images may be purchased or higher-resolution images may be generated with drones. There are several alternatives for purchasing these images; for example, an online platform to acquire images allows images with resolutions of up to 0.30 m per pixel to be obtained. Additional modern technologies include GNSS, a global satellite navigation system that is used to support any satellite navigation system with global coverage, which transmits highly precise geolocation information to GNSS devices and receivers to determine an object's current location and movements in 3D, and USVs to conduct bathymetry in the process water ponds of TSFs [102].

4. Discussion

4.1. Advances

The remote geotechnical monitoring of TSFs around the world involves the use of remote monitoring technologies and systems to evaluate and control these structures' stability and structural behavior [30,31,103]. These technologies are used to prevent and mitigate geotechnical risks, such as spillages or dam collapses. Some of the common technologies used in the remote geotechnical monitoring of this infrastructure include the following [34,37]:

- Geotechnical instrumentation: Sensors and measurement devices used to monitor parameters such as pore pressure, soil deformation, water pressure, inclination, and vibration. These sensors can provide real-time data on TSFs' structural behavior.
- Telemetry systems: Data collected by sensors can be transmitted wirelessly or through wired communication networks for remote analysis and monitoring. This allows experts to assess TSFs' physical stability and make informed decisions.
- Data modeling and analysis: The collected data can be used to create geotechnical models and perform risk analyses. These models help predict future structural behavior and enable data-driven decision-making.
- Satellite monitoring: Satellite images can be used to monitor changes in the surfaces of dams and reservoir areas, such as movements or deformations. These provide an overview of the state of the infrastructure over time.

According to the literature [32], the instrumentation must comply with the principle that "Each instrument must respond to a variable that I want to control, then quantity neither generates quality nor increases the level of safety".

The use of telemetry has allowed mining sites to record, transmit, and store data in real time, which permits precise analyses and the development of operational algorithms that can be implemented by advanced control systems, as shown in Figure 24. The data collected have been transformed into vital information to improve safety, efficiency, and prediction value, as well as to control and reduce operational costs as the margin for errors and improvisation is controlled [71].

Cloud computing, the on-demand use of computer system resources—especially their data storage and processing capacity—without the user's direct active management, has also been implemented in these systems [35]. This technology has generally been implemented to make data centers available from anywhere to many Internet users from any mobile or fixed device [36]. Positioning the real-time monitoring of TSFs in the cloud allows any authorized user to access the information from any device [35].

Thermal and optical remote sensing (visible and infrared) can be used to monitor the humidity of natural soils and mining infrastructure that handles contained water. For example, the use of the normalized difference vegetation index (NDVI) has shown promise in differentiating the dry and wet areas of tailings beaches in the reservoir areas of mine TSFs. As some studies have already demonstrated, the use of remote sensors for these purposes is an accurate and cost-efficient method to estimate the water content in stored mine tailings, permitting the study of other key variables, such as water balance, evaporation rates, and the risk of liquefaction [104].

According to the experience gained from several mining operations that manage their TSFs, simple data collection is insufficient [71,95,96,98]. Mining operations must understand from the outset that the management and analysis of their data depend on a developed corporate strategy that considers how to obtain value from the data. Then, they can implement efficient processing, storage, and validation systems, as well as effective analysis strategies, such as advanced data analytics.

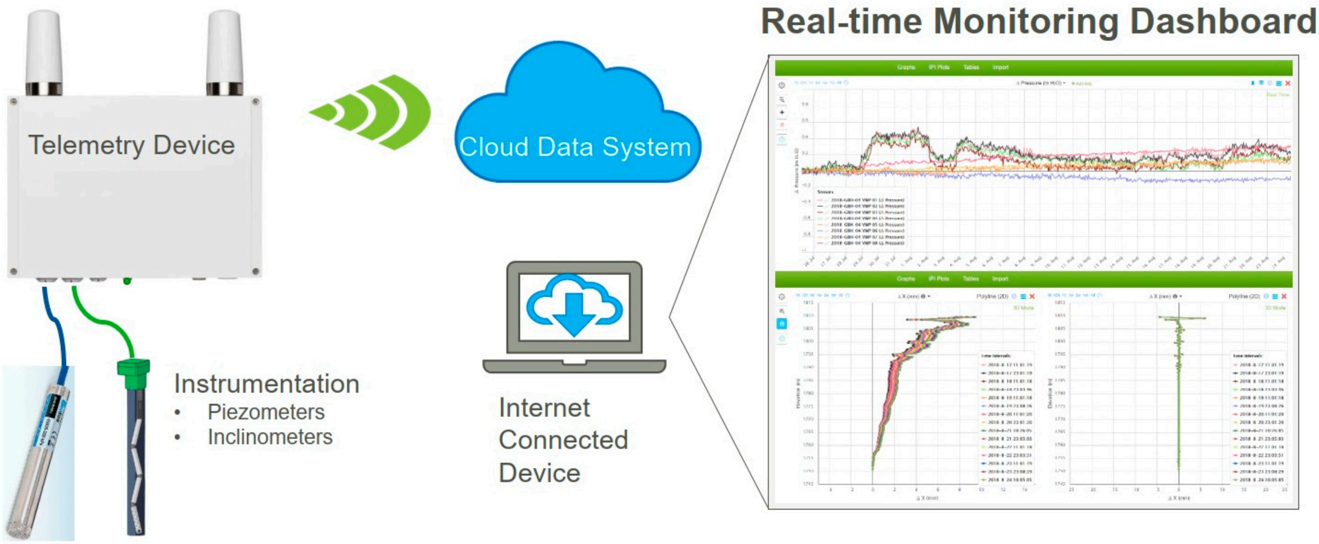

Figure 24. An example of the implementation of telemetry technology in mine TSF monitoring.

4.2. Gaps

Although progress has been made on issues related to the implementation of a monitoring and early warning system to study the physical and chemical stability of TSFs, knowledge gaps remain in the mining sector concerning how to provide quality, reliable, real-time information to mining companies, communities, and authorities through an intuitive, stable platform to avoid the risks of failure and socio-environmental harm [105–107]. This must be addressed in the coming years to strengthen operational management, promote a culture of risk reduction, and improve communication between the responsible parties and emergency responders [108,109].

Although TSF monitoring systems apply Industry 4.0 tools in the initial stage, there are relevant advances that could be adopted from related mineral processing facilities. Souza et al. [110] address the issue of severe variability in the fresh feed ore flow rate in a crushing circuit, which can lead to operational problems such as conveyor belt and sieve overload, interlocked crushers, early equipment wear, and silo overflow. This work presents a digital twin approach, where a digital model interacts with a physical asset. A numerical simulation is performed to evaluate the effectiveness of simultaneously regulating feeder speed and gate aperture. Similarly, Aldrich et al. [111] present a review of machine vision applications for monitoring froth flotation plants, specifically focusing on enhancing their automated control systems through the analysis of froth images. These AI-related applications are mainly based on convolutional neural networks (CNNs) and transfer learning, for which GoogleNet and MobileNet are highlighted architectures. Concerning flotation processes, Matos et al. [112] developed an intelligent online instrument to recognize ore type and degree of fragmentation on conveyor belts. They did so by utilizing a 2D LiDAR sensor combined with machine learning (ML) techniques. Five ML models' performances were compared in a random forest (RF) analysis to identify the one that performed best.

Insufficient information about advances in sensor issues for TSFs is available, leaving a knowledge gap in scientific databases. Information and communication technologies are part of the Industry 4.0 paradigm when they are applied by mining companies worldwide, but much of the knowledge, experience, and lessons learned from this usage are published or shared in technical conferences rather than scientific journals and academic conferences. Although there are advances and publications in the field of TSF management that consider linking sensors with AI, IoT, and CC tools, there are still not enough results reported from case studies on the synergy of sensors with DT technology. Identifying synergies between sensor technologies with DTs to monitor the safety of TSFs is an initial stage for such research; more studies of this approach are needed to generate models and simulations of different TSF construction and operation scenarios to identify the possible risks [39,113,114]. Cost information about using sensors to monitor TSFs is also scarce [32].

In addition, there are gaps regarding data centralization, i.e., the idea that all of the data generated by a mining operation could be made available on a centralized platform for interested stakeholders, which contrasts with the reality of some mining operations, where data are dispersed and stored on several computers and servers. Integrating and synchronizing data from different sources into a single control platform would allow them to be leveraged cleanly and directly from mining operators, construction contractors, engineering contractors, equipment and materials suppliers, authorities, and communities, as well as integrated with the operational data on all of the processes associated with the value chain. This is of great importance due to the complexity of the information handled in mining operations, which reinforces the urgent need to adopt data interoperability standards at the industry level [115].

When IoT approaches are applied to industrial automation and control systems, the concept of the industrial IoT (IIoT) arises [116]. Therefore, IoT applications for TSF management could be considered within the IIoT field. In the IIoT, security vulnerabilities could affect systems. These vulnerabilities are categorized into several groups, including inadequate authentication and authorization, broken access controls, network vulnerabilities, a lack of encryption, device firmware and software vulnerabilities, and insufficient logging and monitoring. The prevention and detection of these problems are crucial for IIoT security and should cover various aspects, such as authentication, access controls, intrusion detection systems, vulnerability analysis, and device certification [116]. Barrie et al. [117] highlight that IIoT cybersecurity in mining activities still remains a challenge, and the main issues to be addressed are related to the lack of clear standards, interoperability fears, and security issues related to identity, authentication, access control, protocol and network security, privacy, and technological governance.

Considering the experiences recorded worldwide regarding the on-site monitoring of mine TSFs, the specific conditions of these structures limit and condition the use of several existing on-site and online sensors and monitoring techniques. This is why the water quality in TSFs constitutes a critical factor for the use of existing measurement sensors, as incrustations and deposits of solids on them can affect electrode or sensor sensitivity.

Furthermore, only real-time monitoring provides an updated table of parameter variations over time; therefore, making information regarding the presence of inorganic traces (metals, metalloids such as arsenic, and ions such as sulfate) and the physical–chemical parameters of water quality available online is practical due to the importance of these parameters, and will help in identifying anomalous situations early or define environmental effects that may harm the health of mining workers or nearby communities. Sensor systems must also be implemented to monitor the performance of TSF drainage systems and cut off trench infrastructure to manage seepage or leaks and preserve groundwater quality [21]. A further knowledge gap exists regarding the real-time monitoring of the emission of particulate matter in the environment of a TSF and mitigating air pollution [118,119].

Finally, although important advances have been made in monitoring the safety of operational TSFs, monitoring the safety of abandoned and post-closure TSFs in abandonment remains under-researched [120,121].

4.3. Future Trends

Digitalization is a fundamental requirement for the mining industry's continued growth. Any mining company seeking to integrate into the current dynamic economic system and remain competitive must apply digital thinking to all of its processes, including mine tailings management [122]. To achieve this digital transformation, mining operations must know where they are and where they want to be; this will allow them to align their strategies with overall market trends and the mining sector. The incorporation of digital technologies is a priority to improve mining productivity and sustainability [123]. We also understand that this transformation process, which entails immersion in an environment of constant change and high uncertainty, is complex both culturally and technologically. This uncertainty can be managed through collaborative processes that allow the industry to address common problems and indicate how to foster the innovation ecosystem [124].

Mine tailings storage facilities are vulnerable to extreme hydrometeorological events resulting from global climate change, such as intense precipitation, frost, heat waves, snowfalls, and other events. This demonstrates how the implementation of sensor systems in TSF infrastructure allows for the real-time and online monitoring of various key operating parameters, granting operators greater safety control. Climate uncertainty and its effects on mine tailings storage facilities require these infrastructures to be resilient and have redundant monitoring systems to avoid failures, collapses, or spills of mine tailings. Adaptive measures to respond to climate change must be implemented, and solutions that incorporate digitalization technologies can help reduce the associated risks [22].

Sensors take two main types of measurements in mine TSFs, point measurements and spatial measurements, and there are currently uses for both types in the mining industry. Therefore, it is essential to define each of these types of measurements and the associated sensors that make them. For example, specific measurements that correspond to the local or specific study of the temporal variation in a particular parameter to be studied in a TSF are point measurements; these include (i) the water table (Casagrande and vibrating wire piezometers), (ii) the magnitude of precipitation (rain gauge), (iii) the flow rate of leaks from the TSF (dam drainage system gauge), and (iv) topographic surveying to enable the georeferencing of characteristic points of the terrain (drone with LiDAR system), among others. Spatial measurements are taken in an area of two or three dimensional space and consider the temporal variation in a specific parameter in a TSF, such as (i) the generation of a 3D model of the TSF with photogrammetry (drone with multispectral camera system), (ii) the estimation of 2D moisture content maps of TSF tailings (satellite image indices and processing), and (iii) 2D estimation of deformation and subsidence maps of the TSF dam (satellite images processed with InSAR), among others. Currently, the mining industry uses both types of measurements, mainly to achieve different purposes depending on the instrument's degree of precision, reliability, and cost-efficiency. Technological solutions that provide confidence are prioritized due to years of experience, and low-cost measures are preferred. Although important developments and advances have been made in sensors that take spatial measurements to monitor TSFs, there are still knowledge gaps and a lack of large-scale experiences that would increase these tools' precision, security, and reliability. In the coming decades, digital twins, augmented reality, computer vision, and AI technologies linked to the Industry 4.0 paradigm are expected to drive disruptive changes that will encourage the use of new spatial monitoring sensors that will replace existing point-measurement sensors.

The conception of a smart mining business model that manages the safety of mine tailings must revolve around the integration of its entire value chain and implies migration to a production model associated with Industry 4.0, in which technologies and tools such as the IoT, advanced data analytics such as big data, DT approaches, CC, robotics, ML, and the use of AI are essential to achieving better products and more efficient processes in addition to generating new business opportunities [40,115,123]. Considering the digitalization of information, data visualization is expected to occur in dashboards through applications for mobile phones, tablets, computers, and laptops that deliver documents, photos, and text information in different formats and languages. Many of these tools are known and available at low cost for academic and research use, so their incorporation into industrial monitoring systems is feasible for experienced users [32].

In this context, developing an online TSF monitoring system that makes the monitored information available through a web information platform and permits different levels of users (e.g., companies mining companies, authorities, and communities) to have different access to information for editing, visualization, etc., is crucial.

Such a system will be powered by instrumentation and sensors that allow parameters related to the physical and chemical stability of the TSF to be measured, as well as, for example, being supported by the installation of video and closed-circuit television cameras (CCTV) to visualize the dam, the reservoir, and other ancillary infrastructure online, allowing the community, authorities, and the mining company to access these data. Data processing on the platform will not only allow the system to support decision-making and operations management but also support an alert system for parameters that threaten the stability of the TSFs (Figure 25).

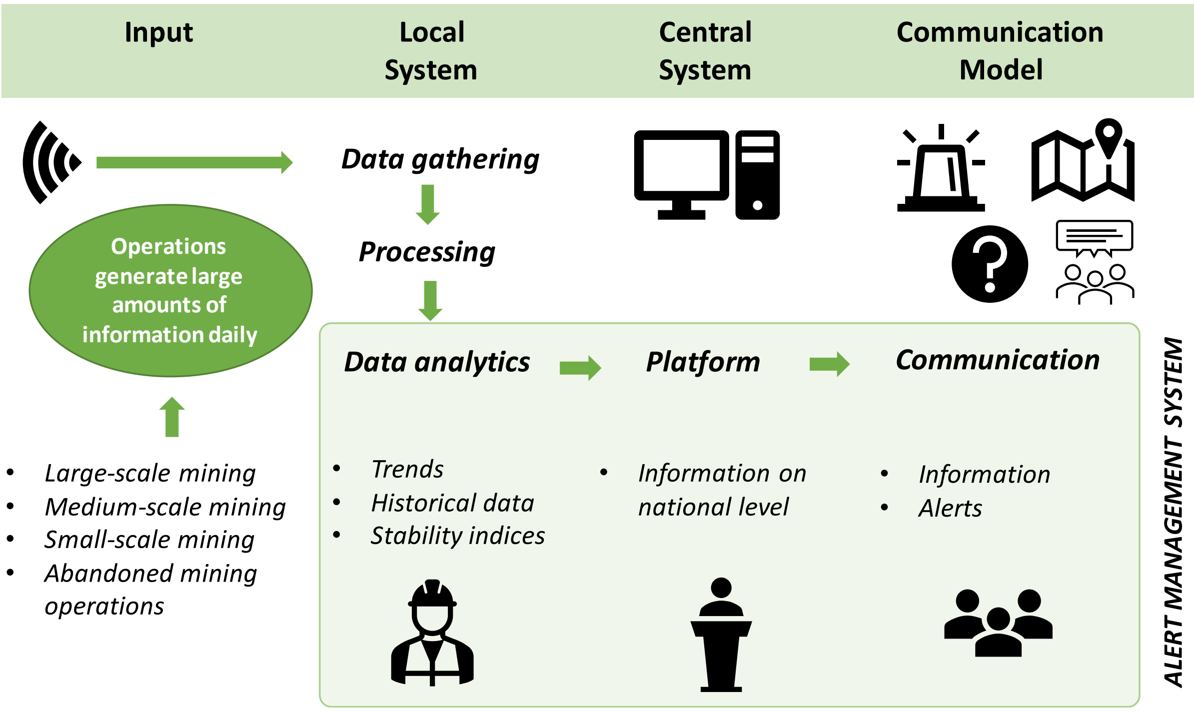

Figure 25. Examples of online monitoring systems for TSFs.

At the same time, to maintain the physical stability of TSFs, it is advisable for monitoring systems to incorporate (i) signal sensors that are not available on the market; (ii) sensors that process images captured by cameras or satellite images corresponding to study areas; and (iii) virtual sensors that use software to replace measurement with physical devices. The current technology for measuring TSFs' physical stability is based on instruments that transform deformations or temperature readings into electrical signals; these tools include strain gauges, vibrating ropes, extensometers, inclinometers, and the deformation of a coaxial cable or optical fiber. These measurements must be complemented with new tools, such as laser distance meters and local radar used in topography, which must be adapted to measure displacements and large deformations in TSFs.

The TSF monitoring system should have at least the following tools:

- A tool for monitoring critical parameters with different instrumentation systems via sensors, the verification of threshold values, and the simulation of the most common failure scenarios.
- A tool to periodically verify the status of the TSF that considers elements of vulnerability and deviations from the design and analyzes the occurrence of adverse triggering events.
- An integrative and predictive tool that relates the information from the monitoring system and the verification system through fault trees and predictive models that use AI and ML approaches.

Many mining countries around the world have begun to implement risk assessments for the TSFs in their territories regarding socio-environmental issues, but more efforts are needed, as well as strategies to disclose risks to society [125–127]. A sustainable alternative future technological trend of the Industry 4.0 paradigm could involve the application of smart sensor monitoring systems to monitor mine tailings and help reduce the risk of failures as low as reasonably practicable (ALARP).

5. Conclusions

Although various solutions exist in the current market to monitor parameters related to the physical and chemical stability of TSFs, some mining operations remain characterized by manual, low-level monitoring techniques, limited technological innovation, insufficient data, and inadequate data processing and integration, as well as lacking early warning and communications systems for surrounding communities.

Mining operations generate large volumes of data to monitor operational processes and the physical and chemical performance of equipment and processes, but only a fraction of these data are used to improve decision-making regarding the management of TSFs. However, with the adoption of new sensor types and IoT approaches, the volume of data handled is expected to significantly exceed that generated today. Recent advances in AI, ML, CC, and data analytics will allow mining operations to take advantage of data from different sources within and outside the value chain to provide real-time decision support and insights into the probability of future events that cannot be predicted with traditional analysis methods. All of these technologies will allow sensor data to be converted into practical metrics and then automate complex calculations to deliver a uniform interpretation of the data. In addition, data can be monitored in real time, allowing management to escalate when necessary and receive alerts to prevent problems early.

An online, real-time monitoring system for mine TSFs would allow the visualization of physical and chemical stability indices, which can be constructed by processing the information derived from monitoring the relevant parameters and variables related to these structures' stability and security. This monitoring, depending on each parameter and current and future technological developments affecting monitoring techniques, may include direct monitoring information of parameters that can be measured online and in real-time, while those that require further analysis are achieved either by processing the data through specific models or software or via laboratory analysis. The stability indices should include an analysis based on the risk associated with the variables' behavior.

Without digitalization in the sense of changing the data format from analog to digital, data exchange would be cumbersome, and changing the current operating model to one based on the use of digital technologies would also be impossible to achieve. Similarly, without interoperability, mining equipment and computer systems would remain bound to current data structures, which have hindered initiatives to improve mining processes for years.

To achieve a smart monitoring model for mine TSFs, from an Industry 4.0 paradigm, a permanent technological surveillance program must be established to identify emerging technologies and channel relevant information to key parties. The acquisition of these technologies must be supported according to their potential effects on mining processes. Technological surveillance can reduce the time that elapses between the occurrence of technological advances and their detection by industry by analyzing technological suppliers, patents, and publications. The identification and use of external sources of knowledge is especially relevant today, given the growing complexity that globalization entails.

The mining industry's potential to evolve toward becoming a benchmark industry for the adoption of Industry 4.0 technologies requires support from all stakeholders and interest groups in the mining ecosystem. The fourth industrial revolution, like its predecessors, has brought a fierce debate regarding its benefits and potential threats, particularly the fear of job loss and replacement with technology. Therefore, these impacts must first be understood and measured, and then susceptible interest groups must be properly informed and educated.

Finally, considering the above context, challenges, and opportunities, citizen participation is increasing and communities' demands to participate in decisions that affect their environment and quality of life are linked to mine tailings management. These stakeholders pose a challenge for the mining industry in terms of responsible and safety management, which would facilitate the industry in obtaining the socio-environmental license to operate, ensure the operational continuity of TSFs, and, consequently, support the sustainability of the mining industry overall.

Author Contributions: Conceptualization, C.C.; formal analysis, C.C. and E.A.; investigation, C.C., V.G., P.C. and E.A.; resources, C.C., V.G., P.C. and E.A.; writing—original draft preparation, C.C.; writing—review and editing, C.C., V.G., P.C. and E.A.; visualization, C.C., V.G., P.C. and E.A.; supervision, E.A. All authors have read and agreed to the published version of the manuscript.

Funding: The research is funded by the Research Department of Catholic University of Temuco, Chile, and Pontificia Universidad Católica de Valparaíso, Chile.

Data Availability Statement: The data presented in this study are available on request from the corresponding author due to internal privacy.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

TSFs	Tailings Storage Facilities
BATs	Best Available Technologies
BAPs	Best Applicable Practices
BEPs	Best Environmental Practices
REEs	Rare Earth Elements
RQs	Research Questions
FM	Failure Modes
MP	Monitoring Parameters
WoS	Web of Science
DEM	Data Extraction from Metadata
DEC	Data Extraction from Content
EC	Exclusion Criteria
ICTs	Information and Communication Technologies
AI	Artificial Intelligence
IoT	Internet of Things
IIoT	Industrial Internet of Things
CC	Cloud Computing
ML	Machine Learning
DT	Digital Twins
CNNs	Convolutional Neural Networks
RF	Random Forest
EoR	Engineer of Record
ATS	Automated Total Stations
GPS	Global Positioning System
GNSS	Global Navigation Satellite System
SSR	Secondary Surveillance RADAR
InSAR	Interferometric Synthetic Aperture RADAR
LIDAR	Light Detection and Ranging
UAV	Unmanned Aerial Vehicles
USV	Unmanned Survey Vessels
DSR	Dam Safety Review
ITRB	Independent Tailings Review Board
4G	Internet of high velocity of 4th generation
RM	Remote Sensor

CCTV	Closed-Circuit Television Camera
PLC	Programmable Logic Controllers
SCADA	Supervisory Control and Data Acquisition
DCS	Distributed Control Systems
PCA	Principal Component Analysis
KPI	Key Performance Indicator
CSR	Corporate Social Responsibility
ESG	Environmental Social and Governance
SDGs	Sustainable Development Goals
UN	United Nations
PRI	Principles for Responsible Investment
ICMM	International Council on Mining and Metals
GISTM	Global Industry Standard on Tailings Management
ALARP	As Low As Reasonably Practicable
APPs	Software Applications
masl	Meters above sea level

References

1. Dong, L.; Deng, S.; Wang, F. Some developments and new insights for environmental sustainability and disaster control of tailings dam. *J. Clean. Prod.* **2020**, *269*, 122270. [CrossRef]
2. Rana, N.M.; Ghahramani, N.; Evans, S.G.; Small, A.; Skermer, N.; McDougall, S.; Andy Take, W. Global magnitude-frequency statistics of the failures and impacts of large water-retention dams and mine tailings impoundments. *Earth-Sci. Rev.* **2022**, *232*, 104144. [CrossRef]
3. Piciullo, L.; Storrøsten, E.B.; Liu, Z.; Nadim, F.; Lacasse, S. A new look at the statistics of tailings dam failures. *Eng. Geol.* **2022**, *303*, 106657. [CrossRef]
4. Cacciuttolo, C.; Cano, D. Spatial and Temporal Study of Supernatant Process Water Pond in Tailings Storage Facilities: Use of Remote Sensing Techniques for Preventing Mine Tailings Dam Failures. *Sustainability* **2023**, *15*, 4984. [CrossRef]
5. Silva Rotta, L.H.; Alcântara, E.; Park, E.; Negri, R.G.; Lin, Y.N.; Bernardo, N.; Mendes, T.S.G.; Filho, C.R.S. The 2019 Brumadinho tailings dam collapse: Possible cause and impacts of the worst human and environmental disaster in Brazil. *Int. J. Appl. Earth Obs. Geoinf.* **2020**, *90*, 102119. [CrossRef]
6. dos Santos Vergilio, C.; Lacerda, D.; da Silva Souza, T.; de Oliveira, B.C.V.; Fioresi, V.S.; de Souza, V.V.; da Rocha Rodrigues, G.; de Araujo Moreira Barbosa, M.K.; Sartori, E.; Rangel, T.P.; et al. Immediate and long-term impacts of one of the worst mining tailing dam failure worldwide (Bento Rodrigues, Minas Gerais, Brazil). *Sci. Total Environ.* **2021**, *756*, 143697. [CrossRef] [PubMed]
7. Armstrong, M.; Petter, R.; Petter, C. Why have so many tailings dams failed in recent years? *Resour. Policy* **2019**, *63*, 101412. [CrossRef]
8. Cheng, D.; Cui, Y.; Li, Z.; Iqbal, J. Watch out for the tailings pond, a sharp edge hanging over our heads: Lessons learned and perceptions from the brumadinho tailings dam failure disaster. *Remote Sens.* **2021**, *13*, 1775. [CrossRef]
9. Kemp, D.; Owen, J.R.; Lèbre, É. Tailings facility failures in the global mining industry: Will a 'transparency turn' drive change? *Bus. Strategy Environ.* **2021**, *30*, 122–134. [CrossRef]
10. Hatje, V.; Pedreira, R.M.A.; De Rezende, C.E.; Schettini, C.A.F.; De Souza, G.C.; Marin, D.C.; Hackspacher, P.C. The environmental impacts of one of the largest tailing dam failures worldwide. *Sci. Rep.* **2017**, *7*, 10706. [CrossRef]
11. Islam, K.; Murakami, S. Global-scale impact analysis of mine tailings dam failures: 1915–2020. *Glob. Environ. Chang.* **2021**, *70*, 102361. [CrossRef]
12. Owen, J.R.; Kemp, D.; Lèbre Svobodova, K.; Pérez Murillo, G. Catastrophic tailings dam failures and disaster risk disclosure. *Int. J. Disaster Risk Reduct.* **2020**, *42*, 101361. [CrossRef]
13. Cacciuttolo, C.; Atencio, E. Dry Stacking of Filtered Tailings for Large-Scale Production Rates over 100,000 Metric Tons per Day: Envisioning the Sustainable Future of Mine Tailings Storage Facilities. *Minerals* **2023**, *13*, 1445. [CrossRef]
14. Agusdinata, D.B.; Liu, W. Global sustainability of electric vehicles minerals: A critical review of news media. *Extr. Ind. Soc.* **2023**, *13*, 101231. [CrossRef]
15. Solé, J. Climate and Energy Crises from the Perspective of the Intergovernmental Panel on Climate Change: Trade-Offs between Systemic Transition and Societal Collapse? *Sustainability* **2023**, *15*, 2231. [CrossRef]
16. Holechek, J.L.; Geli, H.M.E.; Sawalhah, M.N.; Valdez, R. A Global Assessment: Can Renewable Energy Replace Fossil Fuels by 2050? *Sustainability* **2022**, *14*, 4792. [CrossRef]
17. Araya, N.; Mamani Quiñonez, O.; Cisternas, L.A.; Kraslawski, A. Sustainable Development Goals in Mine Tailings Management: Targets and Indicators. *Mater. Proc.* **2021**, *5*, 82. [CrossRef]
18. Lim, B.; Alorro, R.D. Technospheric Mining of Mine Wastes: A Review of Applications and Challenges. *Sustain. Chem.* **2021**, *2*, 686–706. [CrossRef]
19. Cacciuttolo, C.; Atencio, E. Past, Present, and Future of Copper Mine Tailings Governance in Chile (1905–2022): A Review in One of the Leading Mining Countries in the World. *Int. J. Environ. Res. Public Health* **2022**, *19*, 13060. [CrossRef]

20. Cacciuttolo, C.; Cano, D.; Custodio, M. Socio-Environmental Risks Linked with Mine Tailings Chemical Composition: Promoting Responsible and Safe Mine Tailings Management Considering Copper and Gold Mining Experiences from Chile and Peru. *Toxics* **2023**, *11*, 462. [CrossRef]
21. Cacciuttolo, C.; Pastor, A.; Valderrama, P.; Atencio, E. Process Water Management and Seepage Control in Tailings Storage Facilities: Engineered Environmental Solutions Applied in Chile and Peru. *Water* **2023**, *15*, 196. [CrossRef]
22. Labonté-Raymond, P.L.; Pabst, T.; Bussière, B.; Bresson, É. Impact of climate change on extreme rainfall events and surface water management at mine waste storage facilities. *J. Hydrol.* **2020**, *590*, 125383. [CrossRef]
23. Innis, S.; Kunz, N.C. The role of institutional mining investors in driving responsible tailings management. *Extr. Ind. Soc.* **2020**, *7*, 1377–1384. [CrossRef]
24. Schoenberger, E. Environmentally sustainable mining: The case of tailings storage facilities. *Resour. Policy* **2016**, *49*, 119–128. [CrossRef]
25. Adiansyah, J.S.; Rosano, M.; Vink, S.; Keir, G. A framework for a sustainable approach to mine tailings management: Disposal strategies. *J. Clean. Prod.* **2015**, *108*, 1050–1062. [CrossRef]
26. Cacciuttolo Vargas, C.; Marinovic Pulido, A. Sustainable Management of Thickened Tailings in Chile and Peru: A Review of Practical Experience and Socio-Environmental Acceptance. *Sustainability* **2022**, *14*, 10901. [CrossRef]
27. Cacciuttolo Vargas, C.; Pérez Campomanes, G. Practical Experience of Filtered Tailings Technology in Chile and Peru: An Environmentally Friendly Solution. *Minerals* **2022**, *12*, 889. [CrossRef]
28. Ledesma, O.; Sfriso, A.; Manzanal, D. Procedure for assessing the liquefaction vulnerability of tailings dams. *Comput. Geotech.* **2022**, *144*, 104632. [CrossRef]
29. Hamraoui, L.; Bergani, A.; Ettoumi, M.; Aboulaich, A.; Taha, Y.; Khalil, A.; Neculita, C.M.; Benzaazoua, M. Towards a Circular Economy in the Mining Industry: Possible Solutions for Water Recovery through Advanced Mineral Tailings Dewatering. *Minerals* **2024**, *14*, 319. Available online: https://www.mdpi.com/2075-163X/14/3/319 (accessed on 30 March 2024). [CrossRef]
30. Kossoff, D.; Dubbin, W.E.; Alfredsson, M.; Edwards, S.J.; Macklin, M.G.; Hudson-Edwards, K.A. Mine tailings dams: Characteristics, failure, environmental impacts, and remediation. *Appl. Geochem.* **2014**, *51*, 229–245. [CrossRef]
31. Hancock, G.R. A method for assessing the long-term integrity of tailings dams. *Sci. Total Environ.* **2021**, *779*, 146083. [CrossRef] [PubMed]
32. Cacciuttolo, C.; Guzmán, V.; Catriñir, P.; Atencio, E.; Komarizadehasl, S.; Lozano-Galant, J.A. Low-Cost Sensors Technologies for Monitoring Sustainability and Safety Issues in Mining Activities: Advances, Gaps, and Future Directions in the Digitalization for Smart Mining. *Sensors* **2023**, *23*, 6846. [CrossRef] [PubMed]
33. Lu, Z. Research on the optimization analysis and monitoring elements of tailings pond. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *558*, 022082. [CrossRef]
34. Clarkson, L.; Williams, D.; Seppälä, J. Real-time monitoring of tailings dams. *Georisk* **2021**, *15*, 113–127. [CrossRef]
35. Sun, E.; Zhang, X.; Li, Z. The internet of things (IOT) and cloud computing (CC) based tailings dam monitoring and pre-alarm system in mines. *Saf. Sci.* **2012**, *50*, 811–815. [CrossRef]
36. Dong, L.; Shu, W.; Sun, D.; Li, X.; Zhang, L. Pre-Alarm System Based on Real-Time Monitoring and Numerical Simulation Using Internet of Things and Cloud Computing for Tailings Dam in Mines. *IEEE Access* **2017**, *5*, 21080–21089. [CrossRef]
37. Clarkson, L.; Williams, D. Catalogue of real-time instrumentation and monitoring techniques for tailings dams. *Min. Technol. Trans. Inst. Min. Metall.* **2021**, *130*, 52–59. [CrossRef]
38. Zhironkin, S.; Ezdina, N. Review of Transition from Mining 4.0 to Mining 5.0 Innovative Technologies. *Appl. Sci.* **2023**, *13*, 4917. [CrossRef]
39. Barnewold, L.; Lottermoser, B.G. Identification of digital technologies and digitalisation trends in the mining industry. *Int. J. Min. Sci. Technol.* **2020**, *30*, 747–757. [CrossRef]
40. Zhironkin, S.; Gasanov, M.; Suslova, Y. Orderliness in Mining 4.0. *Energies* **2022**, *15*, 8153. [CrossRef]
41. Smith, K.; Sepasgozar, S. Governance, Standards and Regulation: What Construction and Mining Need to Commit to Industry 4.0. *Buildings* **2022**, *12*, 1064. [CrossRef]
42. Yaqub, M.Z.; Alsabban, A. Industry-4.0-Enabled Digital Transformation: Prospects, Instruments, Challenges, and Implications for Business Strategies. *Sustainability* **2023**, *15*, 8553. [CrossRef]
43. Zhironkina, O.; Zhironkin, S. Technological and Intellectual Transition to Mining 4.0: A Review. *Energies* **2023**, *16*, 1427. [CrossRef]
44. Aziz, A.; Schelén, O.; Bodin, U. A Study on Industrial IoT for the Mining Industry: Synthesized Architecture and Open Research Directions. *IoT* **2020**, *1*, 529–550. [CrossRef]
45. Wan, X.; Sun, L.; Tian, H.; Huang, Z.; Yang, H. Research on 3S integration technology in the tailings pond monitoring. *Adv. Mater. Res.* **2012**, *356–360*, 688–692. [CrossRef]
46. Hui, S.; Charlebois, L.; Sun, C. Real-time monitoring for structural health, public safety, and risk management of mine tailings dams. *Can. J. Earth Sci.* **2018**, *55*, 221–229. Available online: https://mc06.manuscriptcentral.com/cjes-pubs (accessed on 22 December 2023). [CrossRef]
47. Wang, Y.; Mei, G.; Wang, S.; Li, X. Application of information technology in safety monitoring and early warning of tailings pond. *J. Phys. Conf. Ser.* **2021**, *1961*, 012018. [CrossRef]
48. International Council on Mining and Metals (ICMM). Tailings Reduction Roadmap. 2022. Available online: https://www.icmm.com/en-gb/guidance/innovation/2022/tailings-reduction-roadmap (accessed on 1 April 2024).

49. Donthu, N.; Kumar, S.; Mukherjee, D.; Pandey, N.; Lim, W.M. How to conduct a bibliometric analysis: An overview and guidelines. *J. Bus. Res.* **2021**, *133*, 285–296. [CrossRef]
50. Oláh, J.; Krisán, E.; Kiss, A.; Lakner, Z.; Popp, J. PRISMA statement for reporting literature searches in systematic reviews of the bioethanol sector. *Energies* **2020**, *13*, 2323. [CrossRef]
51. Boaye Belle, A.; Zhao, Y. Evidence-Based Software Engineering: A Checklist-Based Approach to Assess the Abstracts of Reviews Self-Identifying as Systematic Reviews. *Appl. Sci.* **2022**, *12*, 9017. [CrossRef]
52. Chigbu, U.E.; Atiku, S.O.; Du Plessis, C.C. The Science of Literature Reviews: Searching, Identifying, Selecting, and Synthesising. *Publications* **2023**, *11*, 2. [CrossRef]
53. Atencio, E.; Bustos, G.; Mancini, M. Enterprise Architecture Approach for Project Management and Project-Based Organizations: A Review. *Sustainability* **2022**, *14*, 9801. [CrossRef]
54. Simonsen, E.M.; Herrera, R.F.; Atencio, E. Benefits and Difficulties of the Implementation of Lean Construction in the Public Sector: A Systematic Review. *Sustainability* **2023**, *15*, 6161. [CrossRef]
55. Galaz-Delgado, E.I.; Herrera, R.F.; Atencio, E.; Rivera, F.M.L.; Biotto, C.N. Problems and challenges in the interactions of design teams of construction projects: A bibliometric study. *Buildings* **2021**, *11*, 461. [CrossRef]
56. Jia, C.; Mustafa, H. A Bibliometric Analysis and Review of Nudge Research Using VOSviewer. *Behav. Sci.* **2023**, *13*, 19. [CrossRef] [PubMed]
57. Kirby, A. Exploratory Bibliometrics: Using VOSviewer as a Preliminary Research Tool. *Publications* **2023**, *11*, 10. [CrossRef]
58. Kuzior, A.; Sira, M. A Bibliometric Analysis of Blockchain Technology Research Using VOSviewer. *Sustainability* **2022**, *14*, 8206. [CrossRef]
59. World Sensing. How Monitoring Can Help Make Tailings Dams Safer. 2019. Available online: https://www.worldsensing.com/resource/safer-monitoring-tailings-dams/ (accessed on 27 February 2024).
60. Jeong, Y.; Kim, K. A Case Study: Determination of the Optimal Tailings Beach Distance as a Guideline for Safe Water Management in an Upstream TSF. *Min. Met. Explor.* **2020**, *37*, 141–151. [CrossRef]
61. Adriaan Basson, J.; Broekman, A.; Willem Jacobsz, S. TD-DAQ: A low-cost data acquisition system monitoring the unsaturated pore pressure regime in tailings dams. *HardwareX* **2021**, *10*, 221. Available online: http://creativecommons.org/licenses/by/4.0/ (accessed on 23 December 2023).
62. Wu, T.; Zhang, C.; Zhao, Y. A study on faults diagnosis and early-warning method of tailings reservoir monitoring points based on intelligent discovery. *Int. J. Perform. Eng.* **2017**, *13*, 697–710. [CrossRef]
63. Guan, H.; Yang, P. Advance in Artificial Intelligence Method Safety on Warning of Tailings Dam Break. In *ACM International Conference Proceeding Series*; Association for Computing Machinery: New York, NY, USA, 2020; pp. 229–234.
64. Ma, W.; Zhang, L.; Zhang, S.; Liu, Y.; Wang, H. Analysis of quantitative management of online intelligent monitoring of tailing ponds based on the perspective of safety prevention and control. *Appl. Math. Nonlinear Sci.* **2023**, *9*, 15–30. [CrossRef]
65. Dong, K.; Yang, D.; Yan, J.; Sheng, J.; Mi, Z.; Lu, X.; Peng, X. Anomaly identification of monitoring data and safety evaluation method of tailings dam. *Front. Earth Sci.* **2022**, *10*, 1016458. [CrossRef]
66. Zhang, H.; Li, Q.; Wang, J.; Fu, B.; Duan, Z.; Zhao, Z. Application of Space–Sky–Earth Integration Technology with UAVs in Risk Identification of Tailings Ponds. *Drones* **2023**, *7*, 222. [CrossRef]
67. Yu, G.M.; Song, C.W.; Zou, J.B.; Wu, Y.X.; Pan, Y.Z.; Li, L.; Li, R.; Wang, P.-S.; Wang, Y.-L. Applications of online monitoring technology for tailings dam on digital mine. *Trans. Nonferrous Met. Soc. China* **2011**, *21* (Suppl. 3), s604–s609. [CrossRef]
68. Clarkson, L.; Williams, D. Catalogue of example instrumentation and monitoring systems for tailings dams in Australia. *Min. Technol. Trans. Inst. Min. Metall.* **2021**, *130*, 119–129. [CrossRef]
69. López-Vinielles, J.; Fernández-Merodo, J.A.; Ezquerro, P.; García-Davalillo, J.C.; Sarro, R.; Reyes-Carmona, C.; Barra, A.; Navarro, J.A.; Krishnakumar, V.; Alvioli, M.; et al. Combining satellite insar, slope units and finite element modeling for stability analysis in mining waste disposal areas. *Remote Sens.* **2021**, *13*, 2008. [CrossRef]
70. Lumbroso, D.; Collell, M.R.; Petkovsek, G.; Davison, M.; Liu, Y.; Goff, C.; Wetton, M. DAMSAT: An Eye in the Sky for Monitoring Tailings Dams. *Mine Water Environ.* **2021**, *40*, 113–127. [CrossRef]
71. Hu, J.; Liu, X. Design and implementation of tailings dam security monitoring system. *Procedia Eng.* **2011**, *26*, 1914–1921. [CrossRef]
72. He, X.W.; Sheng, Y.F.; Fan, K.G.; Zheng, L.P.; Cao, Q.M. Design of tungsten tailing reservoir safety monitoring and warning system based on wireless sensor networks and LabVIEW. *Appl. Mech. Mater.* **2013**, *427–429*, 1268–1271. [CrossRef]
73. Li, Q.; Chen, Z.; Zhang, B.; Li, B.; Lu, K.; Lu, L.; Guo, H. Detection of tailings dams using high-resolution satellite imagery and a single shot multibox detector in the Jing-Jin-Ji Region, China. *Remote Sens.* **2020**, *12*, 2626. [CrossRef]
74. Sarker, S.K.; Haque, N.; Bruckard, W.; Bhuiyan, M.; Pramanik, B.K. Development of a geospatial database of tailing storage facilities in Australia using satellite images. *Chemosphere* **2022**, *303*, 135139. [CrossRef]
75. Yang, J.; Sun, Y.; Li, Q.; Sun, Y. Effective risk prediction of tailings ponds using machine learning. In Proceedings of the 2020 3rd International Conference on Advanced Electronic Materials, Computers and Software Engineering, AEMCSE 2020, Shenzhen, China, 24–26 April 2020; Institute of Electrical and Electronics Engineers Inc.: Piscataway, NJ, USA, 2020; pp. 234–238.
76. Arancibia, G.V.; Bustamante, O.P.; Vigneau, G.H.; Allende-Cid, H.; Fuentelaba, G.S.; Nieto, V.A. Estimation of Moisture Content in Thickened Tailings Dams: Machine Learning Techniques Applied to Remote Sensing Images. *IEEE Access* **2021**, *9*, 16988–16998. [CrossRef]

77. Li, W.; Wang, C. GPS in the tailings dam deformation monitoring. *Procedia Eng.* **2011**, *26*, 1648–1657. [CrossRef]
78. Zhen, Z.; Li, J.; Li, Z. Hazard identification and risk decision-making system of tailings storage facilities based on complex networks. In Proceedings of the 2020 IEEE Joint International Information Technology and Artificial Intelligence Conference (ITAIC), Chongqing, China, 11–13 December 2020; pp. 2119–2123.
79. Yang, J.; Li, Q.; Sun, Y.; Qian, Z. Measure dry beach length of tailings pond using deep learning algorithm. In *ACM International Conference Proceeding Series*; Association for Computing Machinery: New York, NY, USA, 2019; pp. 503–508.
80. Balaniuk, R.; Isupova, O.; Reece, S. Mining and tailings dam detection in satellite imagery using deep learning. *Sensors* **2020**, *20*, 6936. [CrossRef]
81. Wu, T.; Zhang, C.; Zhao, Y. Monitoring and warning methods of tailings reservoir using BP neural network. *Int. J. Perform. Eng.* **2018**, *14*, 1171–1180. [CrossRef]
82. Mura, J.C.; Gama, F.F.; Paradella, W.R.; Negrão, P.; Carneiro, S.; de Oliveira, C.G.; Brandão, W.S. Monitoring the vulnerability of the dam and dikes in Germano iron mining area after the collapse of the tailings dam of fundão (Mariana-MG, Brazil) using DInSAR techniques with terraSAR-X data. *Remote Sens.* **2018**, *10*, 1507. [CrossRef]
83. Jing, Z.; Gao, X. Monitoring and early warning of a metal mine tailings pond based on a deep learning bidirectional recurrent long and short memory network. *PLoS ONE* **2022**, *17*, e0273073. [CrossRef]
84. Stefaniak, K.; Wróżyńska, M. On possibilities of using global monitoring in effective prevention of tailings storage facilities failures. *Environ. Sci. Pollut. Res.* **2018**, *25*, 5280–5297. [CrossRef]
85. Chalkley, R.; Crane, R.A.; Eyre, M.; Hicks, K.; Jackson, K.M.; Hudson-Edwards, K.A. A Multi-Scale Feasibility Study into Acid Mine Drainage (AMD) Monitoring Using Same-Day Observations. *Remote Sens.* **2023**, *15*, 76. [CrossRef]
86. Ruan, S.; Han, S.; Lu, C.W.; Gu, Q. Proactive control model for safety prediction in tailing dam management: Applying graph depth learning optimization. *Process Saf. Environ. Prot.* **2023**, *172*, 329–340. [CrossRef]
87. O'donovan, C.; Adam, E.; Torres-Cruz, L.A. Remote sensing of the decant pond of tailings dams: Insights from a South African case study. *J. S. Afr. Inst. Min. Metall.* **2022**, *122*, 10–25. Available online: https://scielo.org.za/pdf/jsaimm/v122n4/03.pdf (accessed on 10 April 2024).
88. Zhen, Z.; Wu, X.; Ma, B.; Zhao, H.; Zhang, Y. Propagation network of tailings dam failure risk and the identification of key hazards. *Sci. Rep.* **2022**, *12*, 5580. [CrossRef]
89. Hu, J.; Hu, S.; Kang, F.; Zhang, J. Real-time dry beach length monitoring for tailings dams based on visual measurement. *Math. Probl. Eng.* **2013**, *2013*, 935371. [CrossRef]
90. Hao, L.; Zhang, Z.; Yang, X. Mine tailing extraction indexes and model using remote-sensing images in southeast Hubei Province. *Environ. Earth Sci.* **2019**, *78*, 493. [CrossRef]
91. Chen, Y.; Li, Q.; Liang, Y. Research and application of data classification in risk prediction for tailings reservoirs. In *ACM International Conference Proceeding Series*; Association for Computing Machinery: New York, NY, USA, 2019.
92. Zhang, D.; Wang, L.G.; Yang, X.C. Research on tailings pond online safety monitoring system based on Zigbee sensor network. *Appl. Mech. Mater.* **2014**, *602–605*, 1728–1732. [CrossRef]
93. Du, Z.; Ge, L.; Ng, A.H.M.; Zhu, Q.; Horgan, F.G.; Zhang, Q. Risk assessment for tailings dams in Brumadinho of Brazil using InSAR time series approach. *Sci. Total Environ.* **2020**, *717*, 137125. [CrossRef]
94. Li, X.; Li, J.; Liu, C.; Chen, C. Safety monitoring system based on internet of things tailings dam. *J. Intell. Fuzzy Syst.* **2021**, *40*, 3005–3014. [CrossRef]
95. Haiming, L.; Jing, C. Study on automatic safety monitoring and management system of tailings reservoir. *Adv. Mater. Res.* **2013**, *663*, 1043–1048.
96. Li, Q.M.; Wang, Y.H.; Li, G. Tailings dam breach disaster on-line monitoring method and system realization. *Procedia Eng.* **2011**, *26*, 1674–1681. [CrossRef]
97. Lumbroso, D.; McElroy, C.; Goff, C.; Collell, M.R.; Petkovsek, G.; Wetton, M. The potential to reduce the risks posed by tailings dams using satellite-based information. *Int. J. Disaster Risk Reduct.* **2019**, *38*, 101209. [CrossRef]
98. Koperska, W.; Stachowiak, M.; Duda-Mróz, N.; Stefaniak, P.; Jachnik, B.; Bursa, B.; Koperska, B.; Stefanek, P. The Tailings Storage Facility (TSF) stability monitoring system using advanced big data analytics on the example of the Żelazny Most Facility. *Arch. Civ. Eng.* **2022**, *68*, 297–311.
99. Morton, K.L. The Use of Accurate Pore Pressure Monitoring for Risk Reduction in Tailings Dams. *Mine Water Environ.* **2021**, *40*, 42–49. [CrossRef]
100. Mazzanti, P.; Antonielli, B.; Sciortino, A.; Scancella, S.; Bozzano, F. Tracking deformation processes at the legnica glogow copper district (Poland) by satellite insar—II: Żelazny most tailings dam. *Land* **2021**, *10*, 654. [CrossRef]
101. Duarte, J.; Rodrigues, F.; Branco, J.C. Sensing Technology Applications in the Mining Industry—A Systematic Review. *Int. J. Environ. Res. Public Health* **2022**, *19*, 2334. [CrossRef]
102. Bayaraa, M.; Rossi, C.; Kalaitzis, F.; Sheil, B. Entity Embeddings in Remote Sensing: Application to Deformation Monitoring for Infrastructure. *Remote Sens.* **2023**, *15*, 4910. [CrossRef]
103. Edraki, M.; Baumgartl, T.; Manlapig, E.; Bradshaw, D.; Franks, D.M.; Moran, C.J. Designing mine tailings for better environmental, social and economic outcomes: A review of alternative approaches. *J. Clean. Prod.* **2014**, *84*, 411–420. [CrossRef]

104. Zwissler, B.; Oommen, T.; Vitton, S.; Seagren, E.A. Thermal Remote Sensing for Moisture Content Monitoring of Mine Tailings: Laboratory Study. *Environ. Eng. Geosci.* **2017**, *23*, 299–312. Available online: https://pubs.geoscienceworld.org/aeg/eeg/article-pdf/23/4/299/4046405/i1078-7275-23-4-299.pdf (accessed on 23 December 2023). [CrossRef]
105. Cacciuttolo, C.; Cano, D. Environmental Impact Assessment of Mine Tailings Spill Considering Metallurgical Processes of Gold and Copper Mining: Case Studies in the Andean Countries of Chile and Peru. *Water* **2022**, *14*, 3057. [CrossRef]
106. Soares Fortes, B.C.; Villefort Teixeira, M.C.; Pereira da Costa, S.; Wagner, M.H.; Scotti, M.R. Post-disaster recovery plan for a rural settler's community affected by the Fundão dam tailings in Brazil. *J. Rural Stud.* **2022**, *93*, 55–66. [CrossRef]
107. Blight, G. *Geotechnical Engineering for Mine Waste Storage Facilities*; CRC Press: Boca Raton, FL, USA, 2010.
108. Adiansyah, J.S.; Rosano, M.; Vink, S.; Keir, G.; Stokes, J.R. Synergising water and energy requirements to improve sustainability performance in mine tailings management. *J. Clean. Prod.* **2016**, *133*, 5–17. [CrossRef]
109. Franks, D.M.; Boger, D.V.; Côte, C.M.; Mulligan, D.R. Sustainable development principles for the disposal of mining and mineral processing wastes. *Resour. Policy* **2011**, *36*, 114–122. [CrossRef]
110. Souza LCO de Júnior, O.T.L.; Barros, J.L.; Yamashita, A.S.; Euzébio, T.A.M. Performance Analysis of a Silo-SlideGate-Feeder System to Regulate the Ore Flow by DEM Simulation. *J. Control Autom. Electr. Syst.* **2022**, *33*, 1310–1318. [CrossRef]
111. Aldrich, C.; Avelar, E.; Liu, X. Recent advances in flotation froth image analysis. *Miner. Eng.* **2022**, *188*, 107823. [CrossRef]
112. Matos, S.N.; Pinto, T.V.B.; Domingues, J.D.; Ranieri, C.M.; Albuquerque, K.S.; Moreira, V.S.; Souza, E.S.; Ueyama, J.; Euzébio, Y.; Pessin, G. An Evaluation of Iron Ore Characteristics Through Machine Learning and 2-D LiDAR Technology. *IEEE Trans. Instrum. Meas.* **2024**, *73*, 1–11. [CrossRef]
113. Hazrathosseini, A.; Moradi Afrapoli, A. The advent of digital twins in surface mining: Its time has finally arrived. *Resources Policy* **2023**, *80*, 103155. [CrossRef]
114. Kukushkin, K.; Ryabov, Y.; Borovkov, A. Digital Twins: A Systematic Literature Review Based on Data Analysis and Topic Modeling. *Data* **2022**, *7*, 173. [CrossRef]
115. Bi, L.; Wang, Z.; Wu, Z.; Zhang, Y. A New Reform of Mining Production and Management Modes under Industry 4.0: Cloud Mining Mode. *Appl. Sci.* **2022**, *12*, 2781. [CrossRef]
116. Ni, C.; Li, S.C. Machine learning enabled Industrial IoT Security: Challenges, Trends and Solutions. *J. Ind. Inf. Integr.* **2024**, *38*, 100549. [CrossRef]
117. Barrie, G.; Whyte, A.; Bell, J. IoT security: Challenges and solutions for mining. In *ACM International Conference Proceeding Series*; Association for Computing Machinery: New York, NY, USA, 2017.
118. Zanetta-Colombo, N.C.; Fleming, Z.L.; Gayo, E.M.; Manzano, C.A.; Panagi, M.; Valdés, J.; Siegmund, A. Impact of mining on the metal content of dust in indigenous villages of northern Chile. *Environ. Int.* **2022**, *169*, 107490. [CrossRef]
119. Mian, M.H.; Yanful, E.K. Tailings erosion and resuspension in two mine tailings ponds due to wind waves. *Adv. Environ. Res.* **2003**, *7*, 745–765. [CrossRef]
120. Dold, B. Sustainability in metal mining: From exploration, over processing to mine waste management. *Rev. Environ. Sci. Biotechnol.* **2008**, *7*, 275–285. [CrossRef]
121. Zine, H.; El Mansour, A.; Hakkou, R.; Papazoglou, E.G.; Benzaazoua, M. Advancements in Mine Closure and Ecological Reclamation: A Comprehensive Bibliometric Overview (1980–2023). *Mining* **2023**, *3*, 798–813. [CrossRef]
122. Majstorovic, V.; Simeunovic, V.; Miskovic, Z.; Mitrovic, R.; Stosic, D.; Dimitrijevic, S. Smart Manufacturing as a framework for Smart Mining. *Procedia CIRP* **2021**, *104*, 188–193. [CrossRef]
123. Nwaila, G.T.; Frimmel, H.E.; Zhang, S.E.; Bourdeau, J.E.; Tolmay, L.C.K.; Durrheim, R.J.; Ghorbani, Y. The minerals industry in the era of digital transition: An energy-efficient and environmentally conscious approach. *Resour. Policy* **2022**, *78*, 102851. [CrossRef]
124. Novák, P.; Vyskočil, J. Digitalized Automation Engineering of Industry 4.0 Production Systems and Their Tight Cooperation with Digital Twins. *Processes* **2022**, *10*, 404. [CrossRef]
125. Garcia, F.F.; Camilo Cotrim, C.F.; Caramori, S.S.; Bailão, E.F.L.C.; Nabout, J.C.; Junior, G.d.F.N.G.; Almeida, L.M. Mine tailings dams' failures: Serious environmental impacts, remote solutions. *Environ. Dev. Sustain.* **2024**. [CrossRef]
126. Hu, S.; Xiong, X.; Li, X.; Chang, J.; Wang, M.; Xu, D.; Pan, A.; Zhou, W. Spatial distribution characteristics, risk assessment and management strategies of tailings ponds in China. *Sci. Total Environ.* **2024**, *912*, 169069. [CrossRef]
127. Massignan, R.S.; Sánchez, L.E. Public databases of tailings storage facilities fall short of full risk disclosure. *Extr. Ind. Soc.* **2024**, *17*, 101420. [CrossRef]