

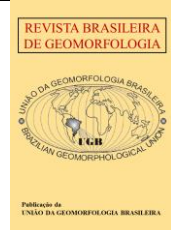


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Review Article

Low-cost sensors and intelligent systems for landslide monitoring: a systematic literature review

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Abstract: Landslides represent one of the major socio-environmental risks worldwide, with socio-economic impacts intensified by unequal urbanization and the increasing frequency of extreme events associated with climate change. In this context, monitoring and early warning systems based on low-cost sensors emerge as a strategic alternative to expand the coverage and accessibility of these technologies, particularly in areas with poor or inadequate infrastructure. This paper presents a Systematic Literature Review (SLR), conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, aiming to analyze the state of the art of such systems. The search was carried out in the Scopus and Web of Science databases, considering articles published between 2020 and 2025, resulting in a final selection of 69 studies. Bibliometric, thematic, and qualitative analyses made it possible to identify application contexts, employed technologies, and criteria adopted for defining low cost. The results indicate a predominance of studies associated with intense rainfall events, the integration of *in situ* sensors, the Internet of Things (IoT), and applications in mountainous rural areas, as well as the emerging use of digital twins as a strategy for multiscale synthesis and predictive support. It is concluded that low-cost solutions have a high potential to democratize early warning systems, although challenges related to calibration, reliability, and durability remain.

Keywords: Landslides; Low-cost sensors; Slope monitoring; Early warning systems; Internet of Things.

Resumo: Os deslizamentos de terra representam um dos principais riscos socioambientais em escala global, com impactos socioeconômicos agravados pela urbanização desigual e pela intensificação de eventos extremos associados às mudanças climáticas. Nesse contexto, sistemas de monitoramento e alerta precoce baseados em sensores de baixo custo emergem como alternativa estratégica para ampliar a cobertura e a acessibilidade dessas tecnologias, especialmente em áreas com infraestrutura precária ou inadequada. Este artigo apresenta uma Revisão Sistemática da Literatura (RSL), conduzida de acordo com as diretrizes PRISMA (*Preferred Reporting Items for Systematic Reviews and Meta-Analyses*), com o objetivo de analisar o estado da arte desses sistemas. A busca foi realizada nas bases *Scopus* e *Web of Science*, considerando artigos publicados entre 2020 e 2025, totalizando 69 estudos. As análises bibliométrica, temática e qualitativa permitiram identificar contextos de aplicação, tecnologias empregadas e critérios adotados para a definição de baixo custo. Os resultados indicam a predominância de estudos associados a eventos de chuva intensa, à integração de sensores *in situ*, à Internet das Coisas (IoT) e a aplicações em áreas rurais montanhosas, e o uso emergente de gêmeos digitais como estratégia de síntese multiescalar e de suporte à predição. Conclui-se que soluções de baixo custo apresentam elevado potencial para democratizar sistemas de alerta, embora persistam desafios relacionados à calibração, à confiabilidade e à durabilidade.

Palavras-chave: Deslizamentos de terra; Sensores de baixo custo; Monitoramento de encostas; Sistemas de alerta precoce; Internet das Coisas.

1. Introduction

Landslides represent one of the most significant socio-environmental hazards on a global scale, generating substantial socioeconomic, environmental, and human impacts, particularly in mountainous regions and urban areas characterized by precarious settlements (Dias et al., 2018; Froude; Petley, 2018; Fidan et al., 2024). The expansion of informal settlements and infrastructure on unstable terrain, combined with the increasing frequency and intensity of extreme precipitation events driven by climate change, has amplified the severity and recurrence of these events (Kumar et al., 2024).

In this context, the challenge of predicting and continuously monitoring the precursory processes of slope instability becomes evident, particularly for landslides triggered by intense rainfall, seismic events, or anthropogenic interventions. This underscores the need for systems capable of providing reliable and technically robust early warnings (Gamperl et al., 2023; Hofmann; Berger; Wimmer, 2025).

Traditionally, slope monitoring has relied on high-cost technologies. For *in situ* geotechnical monitoring, precision instruments such as inclinometers, piezometers, and robotic total stations are widely used, providing point measurements of high reliability (Smethurst et al., 2017). Complementarily, remote sensing has employed technologies such as Interferometric Synthetic Aperture Radar (InSAR) (Colesanti and Wasowski, 2006; Intrieri et al., 2012; Bianchini et al., 2013), Light Detection and Ranging (LiDAR) (Jaboyedoff et al., 2012), and Unmanned Aerial Vehicle (UAV) surveys (Casagli et al., 2017). However, the high financial cost, combined with the operational and logistical complexity of these approaches, restricts their large-scale application, particularly in informal settlements and areas with limited infrastructure.

In contrast, advances in Internet of Things (IoT)-based solutions, open-source platforms, and low-cost sensors have enabled the deployment of modular, replicable, and cost-effective systems for slope monitoring (Chu et al., 2021). The adoption of microcontrollers such as Arduino, sensors based on Micro-Electro-Mechanical Systems (MEMS), and wireless sensor networks, frequently paired with long-range communication protocols, has significantly expanded the applicability of these technologies in remote or difficult-to-access contexts (Mendrot Filho and Stringhini, 2019; Lima, 2022).

Concurrently, the integration of these technologies with the Digital Twin (DT) concept is emerging as a promising frontier in contemporary geotechnical engineering. According to Wang, Rezaei, and Hicks (2025), the adoption of DTs enables significant advances in predictive accuracy, operational efficiency, and geotechnical risk management. However, the authors note that the practical application of this approach in real-world slope monitoring environments remains limited compared to more established sectors such as manufacturing and structural engineering, revealing a scientific and technological gap to be explored (Wang; Rezaei; Hicks, 2025).

Recent studies indicate that the integration of *in situ* monitoring and remote sensing techniques provides a more comprehensive characterization of the spatiotemporal dynamics of slopes, significantly contributing to improved deformation analysis accuracy and reduced uncertainties and false alarms in Landslide Early Warning Systems (LEWS) (Ambika et al., 2025; Mirus et al., 2025; Parenti et al., 2023). However, challenges related to sensor calibration, system interoperability, energy consumption, and continuous data transmission still restrict the large-scale adoption of these solutions, particularly in contexts characterized by poor infrastructure (Liu et al., 2023b; Marino et al., 2023).

In this scenario, low-cost sensors emerge as a strategic alternative for democratizing landslide monitoring and mitigating technological inequalities, consolidating themselves as a rapidly expanding field of investigation within the state of the art.

Against this background, the present study provides a Systematic Literature Review (SLR) on low-cost systems and sensors applied to landslide monitoring and early warning, focusing on economically viable and technically robust solutions. The study aims to identify application contexts, technologies employed, and different interpretations of the low-cost concept, as well as gaps, challenges, and future research directions, considering both laboratory experimental approaches and field applications. It is emphasized that the adoption of these solutions requires a critical assessment of technical, logistical, and social aspects to enhance the effectiveness of LEWS.

2. Materials and Methods

The first step consisted of defining a systematic workflow to conduct, report, and record the results of this SLR. To this end, the research was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. This is a standardized methodological protocol, comprising specific criteria and a decision flow, designed to guide the bibliographic search with maximum scientific rigor. By requiring the detailed and justified recording of each step of article search, screening, and exclusion, the adoption of PRISMA minimizes selection bias and ensures the transparency and reproducibility of the document analysis process (Rethlefsen; Page, 2022). The overarching framework delineated for this review, structured according to these guidelines, is schematized in Figure 1.1

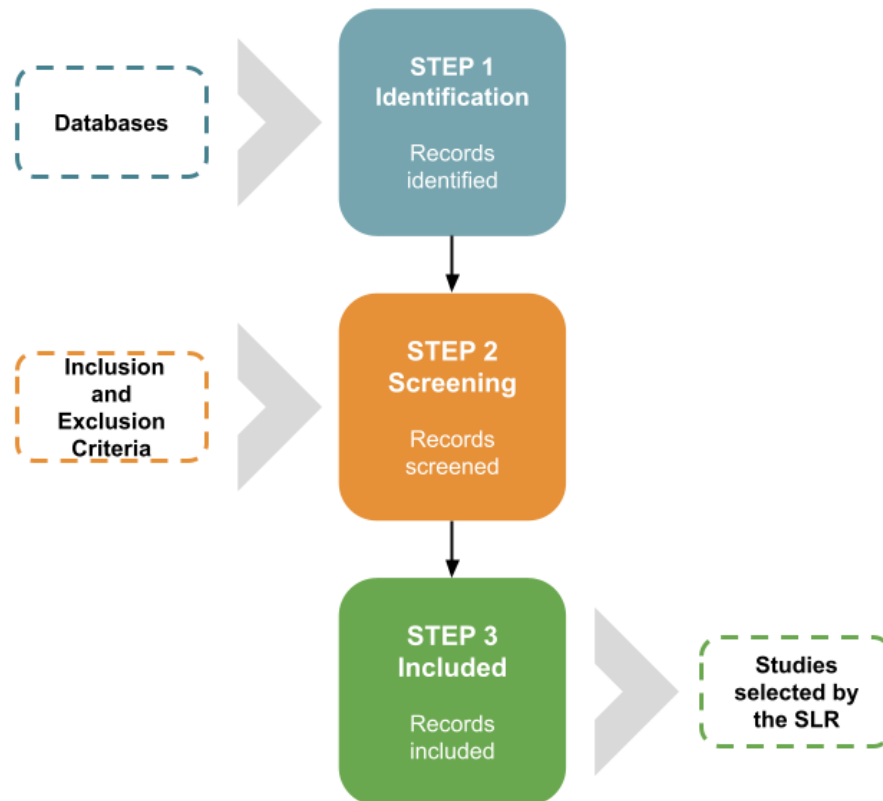


Figure 1. Schematic PRISMA flowchart of the SLR method. Source: Silva, Cuperschmid, and Vaz (2026).

2.1 Step 1 – Study Identification

Step 1 (Identification) consisted of searching for recent publications related to the topics of “landslides,” “sensors,” and “low cost,” according to the following criteria:

- Studies presenting combinations of terms distributed across five thematic groups: Group 1 – Phenomenon (landslide and slope failure); Group 2 – Technology (sensor, monitoring device, wireless device, and IoT device); Group 3 – Cost (low-cost and cost-effective); Group 4 – Application (monitoring, early warning, and prediction); and Group 5 – Key concept (digital twin).
- Articles published exclusively in peer-reviewed scientific journals.
- Works indexed in the Scopus and Web of Science (WoS) databases.
- Publications containing at least one of the terms in the title, keywords, or abstract.
- Articles published between 2020 and 2025.
- Publications written in English.
- Primary research articles, excluding literature reviews.

After preliminary tests with different term combinations, it was found that the inclusion of Group 5 (digital twin) excessively restricted the search, returning no results associated with the remaining criteria. For this reason, a strategy aligned with the central objective of the research was adopted, focusing exclusively on the first four thematic groups. The exact search string and the logical operators formulated based on this delimitation are

detailed in Figure 2. Applying this strategy to the databases yielded an initial set of 139 records (68 from Scopus and 71 from WoS), considered suitable for subsequent analyses in this SLR.2

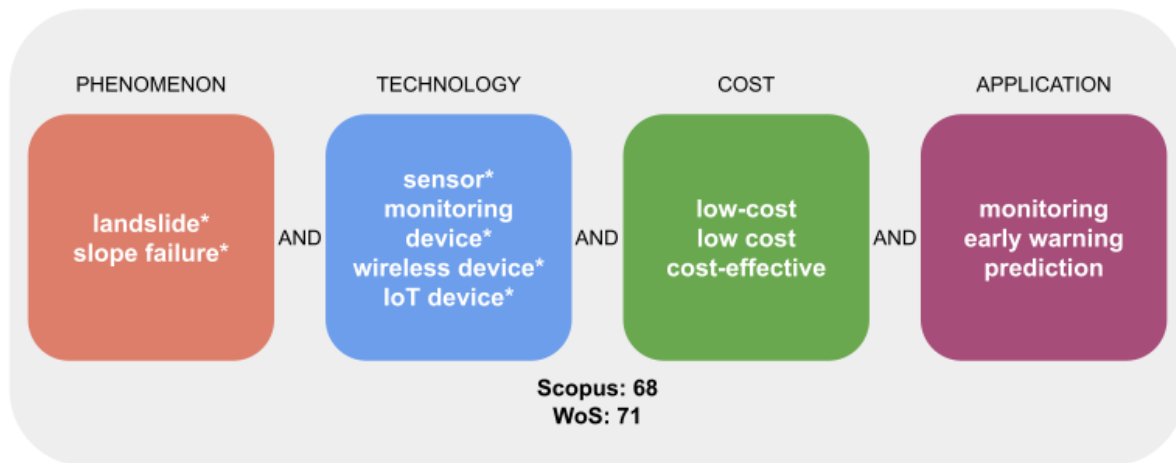


Figure 2. Search string: strategy focused on the first four thematic groups. Source: Silva, Cuperschmid, and Vaz (2026).

In the subsequent information screening stage, Artificial Intelligence (AI) tools were used in an ethical and responsible manner (Sampaio; Sabbatini; Limongi, 2024), specifically the Rayyan platform (article selection and screening), NotebookLM, and AnswerThis (data extraction and organization). The use of these tools aimed to optimize the structured information analysis process, providing greater efficiency and accuracy in data organization.

It should be noted, however, that all data extracted through these tools were rigorously cross-checked against the original sources, ensuring the reliability and validity of the analyzed material. Furthermore, priority was given to articles published in peer-reviewed journals and studies conducted by recognized institutions and researchers in the field, to preserve the scientific rigor of the review.

2.2 Step 2 – Study Screening

Step 2 (Screening) consisted of removing duplicate records, systematically applying the exclusion and inclusion criteria, and verifying the availability of full-text access. This process was conducted with the support of Zotero and Rayyan software, widely used in systematic reviews for their efficiency in study organization and collaborative screening.

1. Exclusion Criteria:

- **(E-1):** Articles of an exclusively theoretical nature, without an experimental approach or practical application, as well as literature reviews.
- **(E-2):** Studies that did not address monitoring or early warning systems for landslides.

2. Inclusion Criteria:

- **(I-1):** Articles presenting experiments in small-scale physical slope models or case studies with full-scale implementation.
- **(I-2):** Studies addressing systems or sensors classified by the authors as low-cost.

2.3 Step 3 – Selected Studies

As a result of the identification and screening stages, 69 articles were included in the final study set of this SLR. Figure 3 summarizes the study exclusion and inclusion flow, detailing the three operational phases (Identification, Screening, and Included) prescribed by the PRISMA method guidelines, previously described in Section 2.

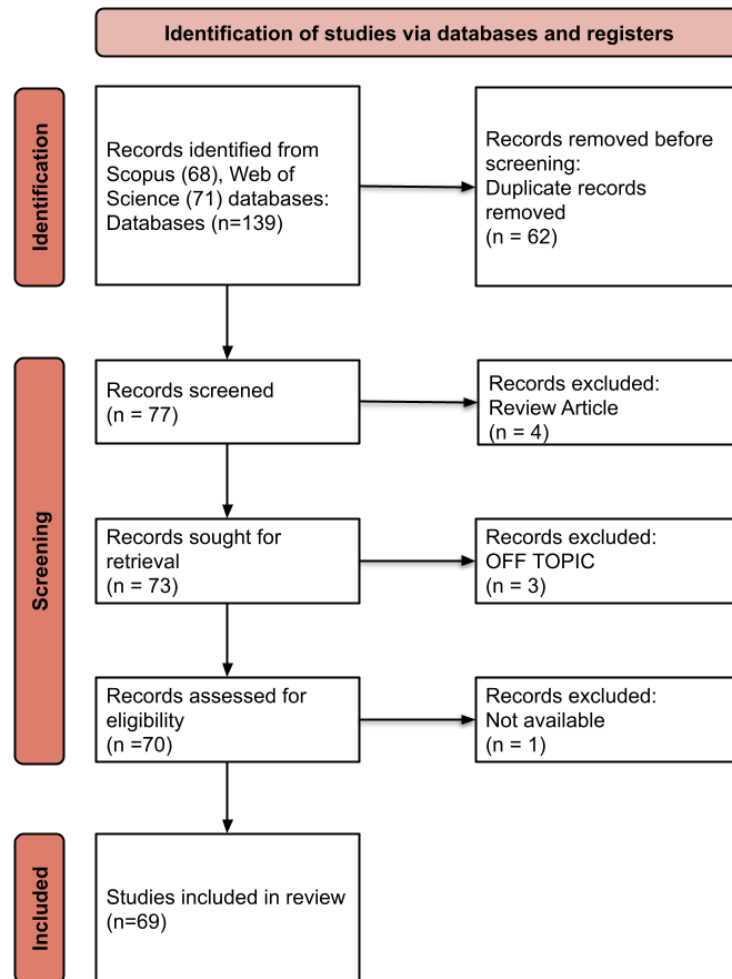


Figure 3. PRISMA flowchart of the SLR. Source: Silva, Cuperschmid, and Vaz (2026).

Following the selection process, a comprehensive analysis of all 69 articles was conducted to extract information capable of addressing the central research questions. To support the structured organization and synthesis of data, the AnswerThis and NotebookLM tools were used. Additionally, for the bibliometric analysis — specifically the construction and visualization of keyword co-occurrence networks — VOSviewer software was employed.

Prior to the analysis itself, the SLR research questions were formulated, organized around three complementary analytical axes: (1) bibliometric analysis; (2) thematic analysis; and (3) qualitative analysis.

1. Bibliometric Analysis:

- In which scientific journals were the studies published?
- In which countries were the studies conducted?
- What were the most recurrent keywords among the studies?

2. Thematic Analysis:

- What was the type of experimental implementation (laboratory physical model or field application)?
- What data acquisition methods were used (remote sensing, ground-based sensing, or hybrid approaches)?
- What was the application focus of the studies (informal settlements, roads, dams, mining, among others)?
- What were the main causes of landslides identified (rainfall, earthquakes, anthropogenic interventions, etc.)?
- What technologies were used for data transmission and communication?

3. Qualitative Analysis:

- What criteria did the authors use to classify sensors as low-cost? Are there comparative analyses?
- Do the studies relate low-cost sensors to climatic variables or to the impacts of climate change on landslide processes?
- What artificial intelligence or machine learning techniques were applied, and for what purposes?
- Did the studies explicitly address the digital twin concept or employ technologies aimed at real-time digitization?
- What were the main results and advances reported?
- What challenges and limitations were identified?
- What research gaps were identified?
- What opportunities or recommendations for future work were proposed?

The bibliometric analysis aimed to contextualize the scientific output, considering the publication journals, the geographical distribution of studies, and the main topics addressed. The thematic analysis sought to identify correlations among methodological approaches, technologies employed, and application contexts of monitoring and early warning systems. Finally, the qualitative analysis aimed to understand how the low-cost concept is treated, as well as the main results, challenges, gaps, and future directions identified in the literature.

Based on these analyses, it was possible to organize and categorize the findings, providing a comprehensive overview of the state of the art in research conducted between 2020 and 2025.

3. Results and Discussion

3.1 Results of the Bibliometric Analysis

The analyzed studies on low-cost systems for landslide monitoring and early warning were published between 2020 and 2025, in journals covering mainly the areas of engineering, geosciences, information technology, remote sensing, and environmental sciences.

3.1.1 Scientific Journals

The distribution of articles by journal (Table 1) reveals a significant concentration of publications in journals focused on instrumentation, sensing, and geotechnical monitoring, notably *Sensors* and *Remote Sensing*. Established geotechnical journals, such as *Engineering Geology* and *Landslides*, concentrate studies with greater physical and geotechnical depth, while multidisciplinary journals bring together integrated approaches, frequently associated with socio-environmental aspects.¹

Table 1. Main journals identified in the SLR.

Journals	Impact Factor (JCR-2024) ¹	No. of articles	%
<i>Sensors</i>	3.5	12	17.39
<i>Remote Sensing</i>	4.1	5	7.25
<i>Landslides</i>	7.0	3	4.34
<i>IEEE Transactions on Instrumentation and Measurement</i>	5.9	3	4.34
<i>Engineering Geology</i>	8.4	3	4.34
<i>Water</i>	3.0	2	2.90
<i>Measurement</i>	5.6	2	2.90
<i>Italian Journal of Engineering Geology and Environment</i>	0.7	2	2.90
<i>IEEE Sensors Journal</i>	4.5	2	2.90
<i>Geosciences</i>	2.1	2	2.90
<i>Bulletin of Engineering Geology and the Environment</i>	4.2	2	2.90
Other journals (1 article each)	-	31	44.94
Total	-	69	100.00

¹ Journal impact factors were retrieved from the Journal Citation Reports (Clarivate Analytics) via institutional access to the Web of Science platform, considering the most recent available edition (2024).

3.1.2 Countries with Study Areas

The identified articles are primarily concentrated in countries such as Italy, China, India, Japan, the United States, Colombia, Slovenia, and Taiwan (Figure 4), where institutions are strongly engaged in developing technologies for slope instability monitoring (Notti et al., 2020; Chu et al., 2021; Gamperl et al., 2023). Studies conducted in mountainous regions and informal settlements within specific socio-environmental contexts are also recurrent.³

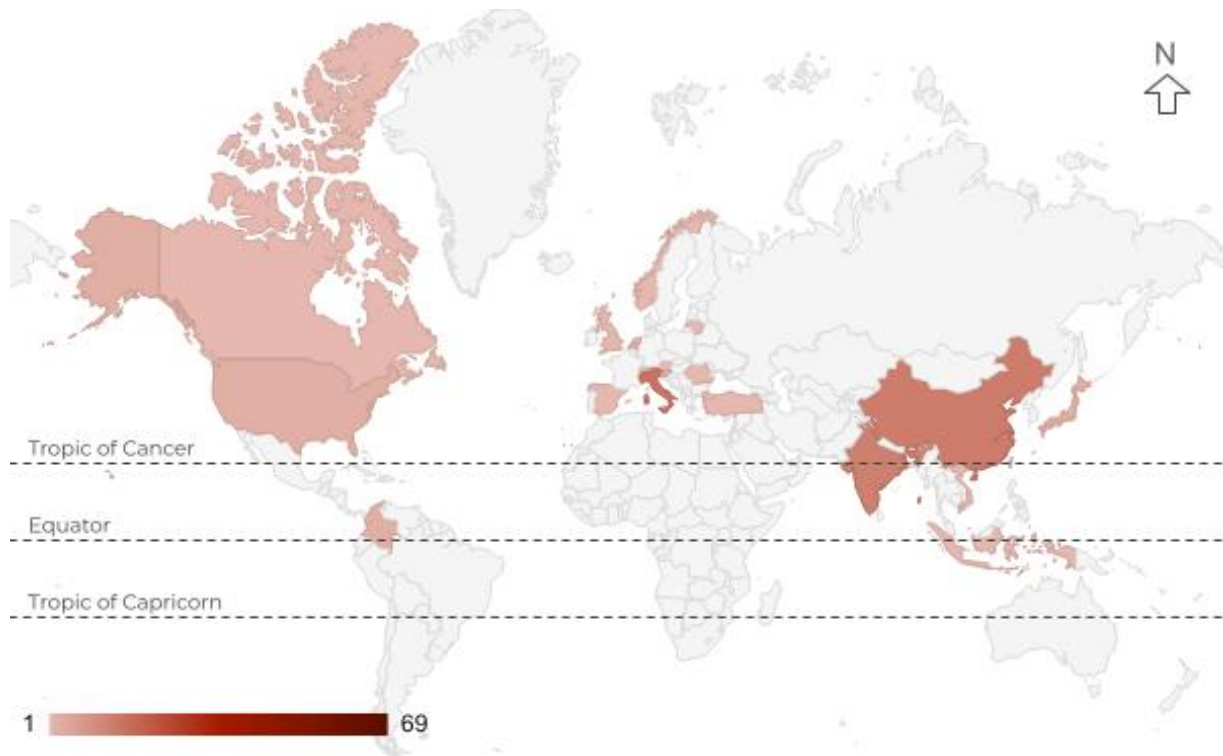


Figure 4. Geographical distribution of the study origins. Source: Silva, Cuperschmid, and Vaz (2026).

Considering the set of 69 analyzed articles, Italy, China, and India account for approximately 48% of the publications. No studies reporting experiments or applications of monitoring systems in countries in Oceania or Africa were identified. In the context of Latin America and the Caribbean, only Colombia presented relevant publications during the analyzed period.

It is important to note that the restriction of Latin American results to Colombia is a direct consequence of the methodological protocol adopted in this SLR (focused on the English language and the Scopus and WoS databases) and does not necessarily indicate the absence of research in the region. In Brazil, for example, there are relevant and historically consolidated initiatives conducted by institutions such as the University of São Paulo (USP), São Paulo State University (Unesp), Federal University of Pernambuco (UFPE), and the National Center for Monitoring and Alerting of Natural Disasters (Cemaden), involving the use of moisture, temperature, and suction sensors for slope monitoring (e.g., Coutinho et al., 2023; Mendes et al., 2018; Sousa et al., 2023). The fact that such studies were not captured by the present search highlights the publication bias inherent to the adopted methodology, reinforcing the importance and necessity of exploring regional databases and repositories for a more comprehensive mapping of the Global South.

This distribution reveals a significant geographical gap, indicating the need for greater research focus on Global South regions, which present high socio-environmental vulnerability and demand solutions adapted to their specific contexts. Expanding the geographical scope of studies is essential for developing more effective and inclusive global strategies for landslide monitoring and impact mitigation (Sapena et al., 2023).

3.1.3 Recurrent Keywords in the Studies

Among the most frequent terms, those directly related to landslide monitoring and alerting stand out, such as landslides, monitoring, early warning system, and low-cost, present in studies ranging from data collection to distributed autonomous systems (Bagwari et al., 2021; Chu et al., 2021; Liu et al., 2023a).

The use of IoT and wireless networks was also recurrent, reflected in keywords such as Internet of Things, Wireless Sensor Networks (WSN), and specific technologies such as GPS and InSAR. The keyword co-occurrence is presented in Figure 5.4

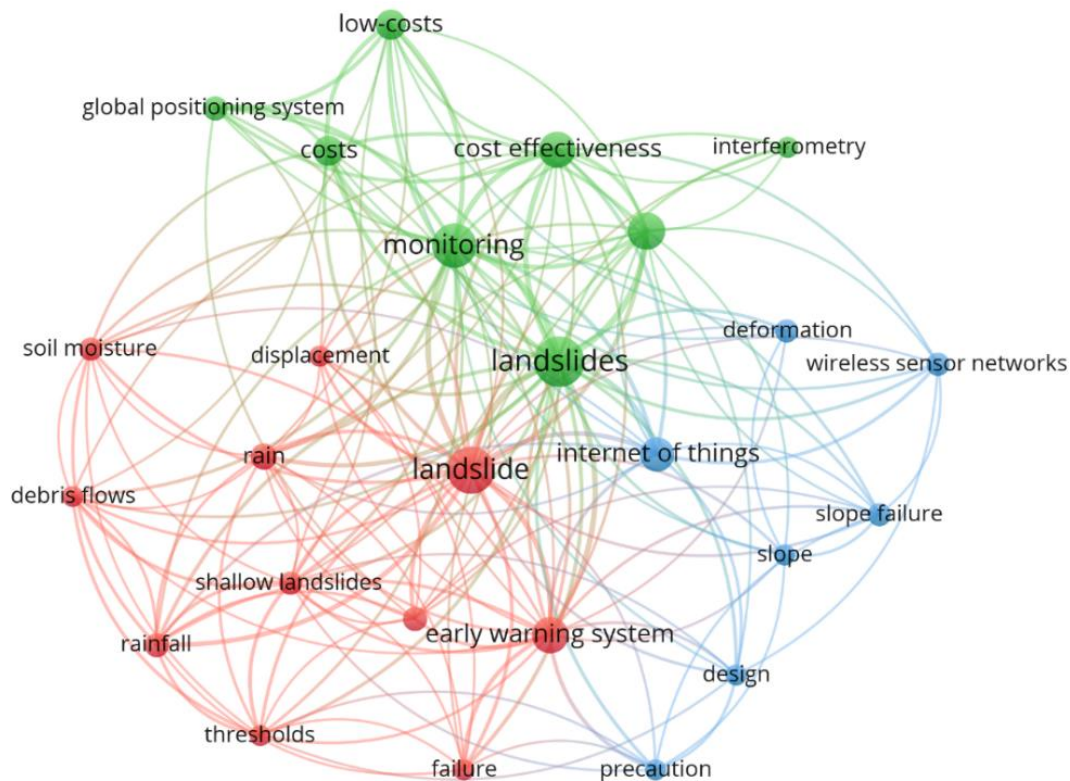


Figure 5. Co-occurrence of keywords in English, as defined in the database used. Source: Silva, Cuperschmid, and Vaz (2026).

Furthermore, terms related to the physical and environmental conditions associated with landslides, such as soil moisture, rainfall, and slope failure, were widely used, reflecting a focus on identifying triggering factors and monitoring terrain heterogeneity (Kumar and Ramesh, 2022; Liu et al., 2023a; Pavanello et al., 2024).

3.2 Results of the Thematic Analysis

3.2.1 Type of Experimental Implementation

The analyzed studies (Figure 6) are distributed among laboratory physical model experiments (Paswan; Shrivastava, 2023, 2024), field applications (Notti et al., 2020; Gamperl et al., 2023), and hybrid approaches (Qiao et al., 2020; Kumar et al., 2024), the latter frequently employed to strengthen system validation. Only two studies were based exclusively on computational simulations (Menon et al., 2021; Bai et al., 2022).⁵

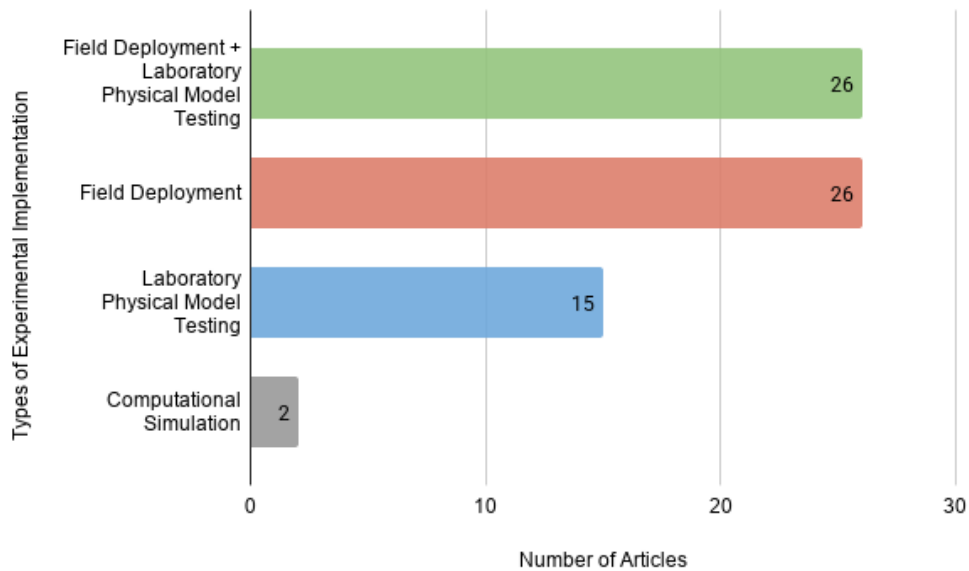


Figure 6. Types of experimental implementation. Source: Silva, Cuperschmid, and Vaz (2026).

3.2.2 Application Focus in Urban and Other Contexts

The studies addressed multiple application contexts, demonstrating the diversity of scenarios in which LEWS can contribute to risk mitigation (Figure 7). In informal settlements and vulnerable urban areas, particularly in developing countries, systems were applied to monitor slopes with high social exposure and precarious infrastructure, as demonstrated by projects in Medellín, Colombia (Gamperl, Singer, Thuro, 2021; Gamperl et al., 2023).

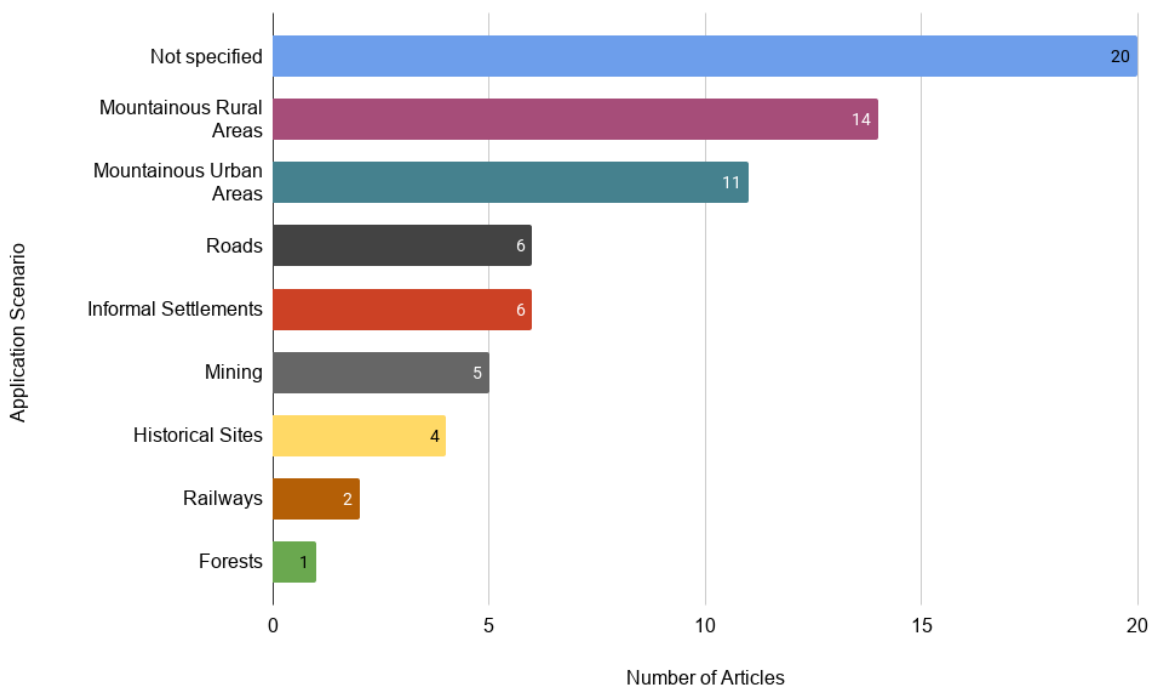


Figure 7. Application scenario: urban, rural, and others. Source: Silva, Cuperschmid, and Vaz (2026).

Another relevant application domain refers to linear infrastructure (roads, railways, and pipelines), where continuous terrain monitoring is essential to ensure the safety of people and assets (Yadav et al., 2021; Mazza et al., 2023). Mining activity was also the subject of several studies, given the impact of operations on slope stability and the need for specialized, real-time monitoring (Dorthi, Bayyapu, Karra, 2020; Yadav et al., 2021; Dorthi and Karra, 2023).

Also noteworthy is the considerable number of studies conducted in mountainous rural areas, particularly in Italian inland villages (Bovolenta et al., 2020; Dei Cas et al., 2022; Zuliani et al., 2022a; Marino et al., 2023; Cifaldi et al., 2024; Famiglietti et al., 2024; Pavanello et al., 2024).

3.2.3 Main Causes of Landslides Identified

Intense and/or prolonged rainfall is the predominant factor associated with most of the analyzed landslides, frequently linked to climate change, which intensifies extreme events and increases the frequency and magnitude of mass movements (Kumar et al., 2024; Hofmann, Berger, Wimmer, 2025; Hu et al., 2025). Many studies also point to the combination of multiple factors as triggers for instability processes (Figure 8).6

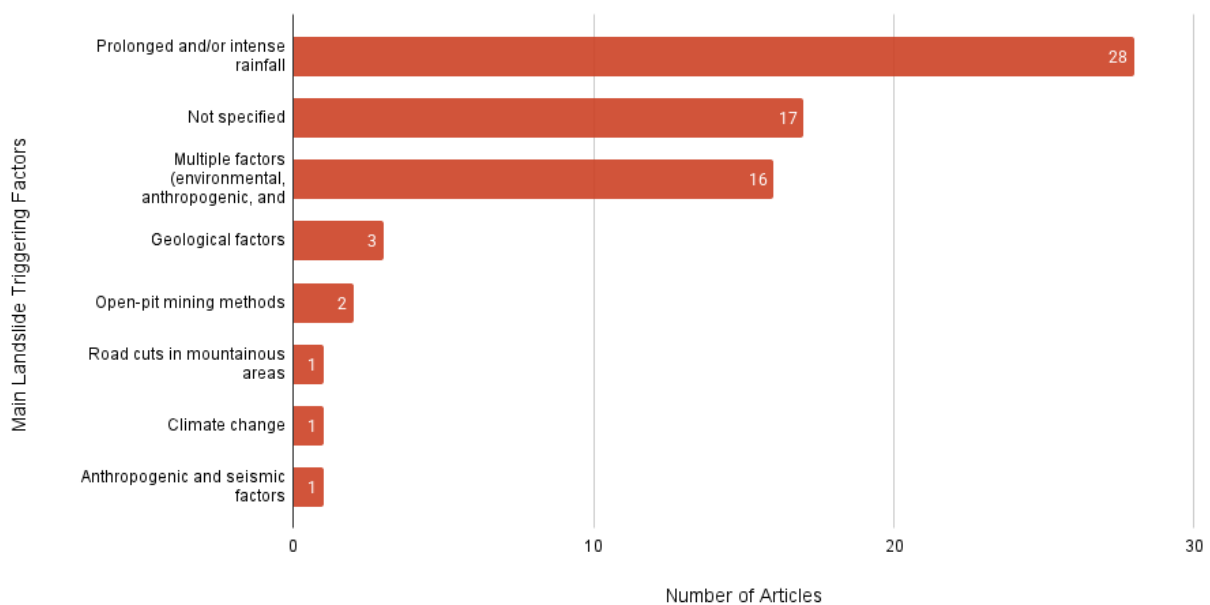


Figure 8. Main causes of landslides identified. Source: Silva, Cuperschmid, and Vaz (2026).

Seismic events appear as a relevant cause in regions of higher tectonic activity, where tremors can trigger or accelerate latent instabilities (Hu et al., 2025). Anthropogenic activities, such as irregular construction on slopes, unequal urbanization, deforestation, and inadequate mining practices, are frequently highlighted as factors that aggravate terrain vulnerability and increase landslide risk, particularly in informal settlements (Guilhot et al., 2021; Gamperl et al., 2023).

3.2.4 Sensing and Data Acquisition Methods, Techniques, and Technologies

The data acquisition methods employed in slope monitoring systems can be organized into three main categories: (i) remote sensing; (ii) ground-based sensing; and (iii) hybrid approach (Ragnoli et al., 2023; Xu et al., 2023; Lau et al., 2024).

Ground-based sensing focuses on the use of sensors or sensor networks installed directly in the soil or on the slope surface, including extensometers, inclinometers, piezometers, and soil moisture sensors. These technologies provide high temporal resolution point data, enabling the direct measurement of physical and hydrological processes occurring within the soil mass, albeit with limited spatial coverage (Cifaldi et al., 2024).

In turn, remote sensing relies on technologies such as LiDAR, UAVs, and InSAR, being particularly suitable for monitoring extensive or difficult-to-access areas. These methods enable integrated and multitemporal analyses

of terrain dynamics, although spatial and temporal resolutions depend on the technique adopted and environmental conditions (Famiglietti et al., 2024; Sestras et al., 2025).

The choice of the most suitable sensing solution for monitoring hazard-prone areas depends on multiple factors, such as resource availability, implementation costs, geomorphological characteristics, and access conditions. Nevertheless, several authors emphasize that, for a more comprehensive assessment of destabilization processes and for cross-validation purposes, the coordinated combination of multiple acquisition technologies is recommended (Xu et al., 2023).

In this context, a growing adoption of hybrid approaches is observed, which seek to integrate *in situ* sensors with remote sensing techniques, exploring different spatial and temporal scales of observation. This strategy has been successfully employed to produce more robust and reliable analyses of slope behavior (Guilhot et al., 2021; Bruland et al., 2025). Figure 9 illustrates the distribution of data acquisition methods adopted by the studies analyzed in this SLR.7

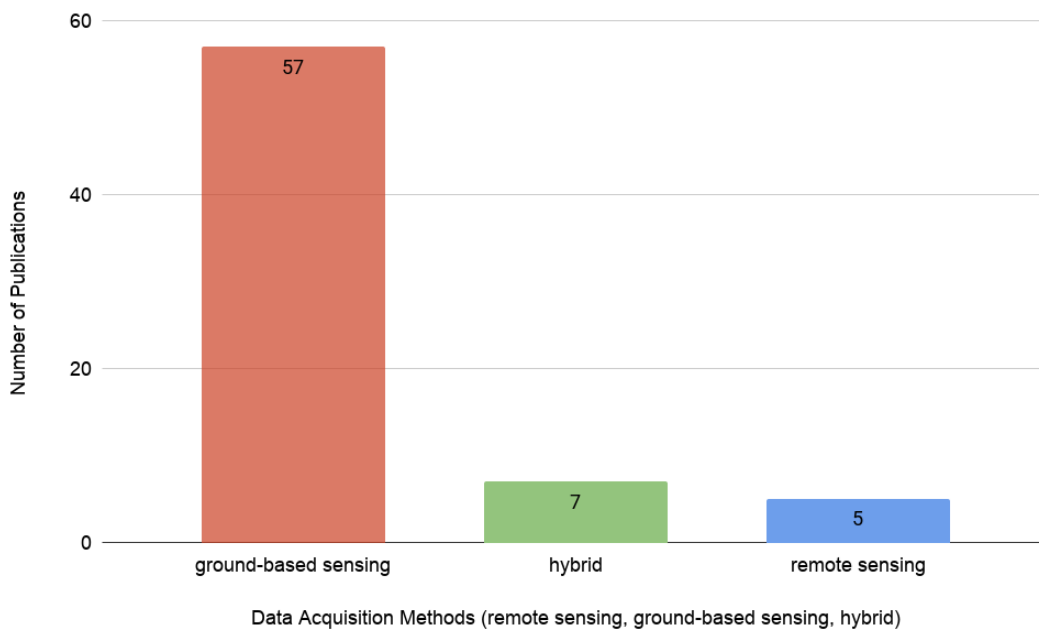


Figure 9. Data acquisition methods of the studies. Source: Silva, Cuperschmid, and Vaz (2026).

Considering the diversity of acquisition methods, each approach involves specific types of sensors and technologies associated with landslide monitoring. In this regard, Table 2 establishes a correlation between sensing techniques and technologies, and the respective acquisition methods employed in the studies composing this SLR.2

Table 2. Sensor techniques, technologies, and data acquisition methods.

Sensor Technique / Technology	Acquisition Method	References
TLS (<i>Terrestrial Laser Scanning</i>)	<i>Ground-based sensing</i>	(Bainbridge et al., 2022; Kyriou; Nikolakopoulos; Koukouvelas, 2022)
GNSS	<i>Ground-based sensing</i>	(Notti et al., 2020; Khai et al., 2021; Lăpădat; Tiberius; Teunissen, 2021; Kyriou; Nikolakopoulos; Koukouvelas, 2022; Zuliani et al., 2022b; Aichinger-Rosenberger et al., 2023; Hamza, 2023; Hamza et al., 2023; Lau et al., 2023; Mazza et al., 2023; Sumathi; Anitha, 2023; Sestras et al., 2025)
Piezometers	<i>Ground-based sensing</i>	(Chu et al., 2021; Gamperl; Singer; Thuro, 2021; Zuliani et al., 2022a)

Sensor Technique / Technology	Acquisition Method	References
Accelerometers	Ground-based sensing	(Bagwari et al., 2021; Menon et al., 2021; Wielandt et al., 2022; Lau et al., 2023; Sanlı, 2023; Sharma et al., 2023; Lu et al., 2024; Najafabadi et al., 2024; Zhang et al., 2024)
Gyroscopes	Ground-based sensing	(Lu et al., 2024)
Inclinometers or Tiltmeters	Ground-based sensing	(Chen; Lin; Su, 2020; Qiao et al., 2020; Ruzza et al., 2020; Xie et al., 2020; Guilhot et al., 2021; Lăpădat; Tiberius; Teunissen, 2021; Fiolleau et al., 2023; Gamperl et al., 2023; Liu et al., 2023a; Paswan; Shrivastava, 2023, 2024)
Extensometers	Ground-based sensing	(Dorthi; Bayyapu; Karra, 2020; Gamperl; Singer; Thuro, 2021; Kumar M.; Ramesh, 2022; Gamperl et al., 2023; Setiono et al., 2023; Cifaldi et al., 2024)
Rain Gauges	Ground-based sensing	(Chu et al., 2021; Bainbridge et al., 2022; Zuliani et al., 2022a; Sapena et al., 2023; Liu et al., 2024; Pavanello et al., 2024)
Soil Moisture Sensors	Ground-based sensing	(Bovolenta et al., 2020; Chu et al., 2021; Kumar; Duttagupta; Rangan, 2021; Menon et al., 2021; Liu et al., 2023a; Marino et al., 2023; Sharma et al., 2023; Zhu et al., 2023; Hidayat; Hazarika; Kanaya, 2024; Paswan; Shrivastava, 2024; Hofmann; Berger; Wimmer, 2025)
Temperature Sensors	Ground-based sensing	(Wielandt et al., 2022; Marino et al., 2023)
Seismometers or Seismic Sensors	Ground-based sensing	(Bainbridge et al., 2022; Fiolleau et al., 2023; Khan; Martin; Lim, 2024; Bruland et al., 2025)
Atmospheric Sensors (humidity, temperature, barometric pressure)	Ground-based sensing	(Chu et al., 2021)
UWB (Ultra-wide band)	Ground-based sensing	(Si et al., 2025)
Optical Fiber	Ground-based sensing	(Ivanov et al., 2021a, 2021b; Di Gennaro et al., 2022; Leone et al., 2022)
Pore Water Pressure Sensors or Tensiometers	Ground-based sensing	(Kumar; Duttagupta; Rangan, 2021; Menon et al., 2021; Liu et al., 2023a)
ERT (Electrical Resistivity Tomography)	Ground-based sensing	(Bai et al., 2022; Zuliani et al., 2022a; Fiolleau et al., 2023b; Kumar et al., 2024)
FDR Sensors (Frequency Domain Reflectometer sensors)	Ground-based sensing	(Pavanello et al., 2024)
TDR Sensors (Time-Domain Reflectometer)	Ground-based sensing	(Ivanov et al., 2021b; Yadav et al., 2021; Pavanello et al., 2024)
CSM (Continuous Shear Monitor)	Ground-based sensing	(Gamperl; Singer; Thuro, 2021b)
Video Camera	Ground-based sensing	(Ivanov et al., 2021b; Bainbridge et al., 2022)
Ultrasonic Sensor	Ground-based sensing	(Sharma et al., 2023)
Total Station	Ground-based sensing	(Kumar et al., 2024; Lu et al., 2024)
RTS (Robotic Total Station)	Ground-based sensing	(Guilhot et al., 2021; Sumathi; Anitha, 2023)
SPGC (Sensor-enabled piezoelectric geocable)	Ground-based sensing	(Liu et al., 2023b; Hu et al., 2025)

Sensor Technique / Technology	Acquisition Method	References
LVDT (<i>Linear Variable Differential Transformer</i>)	Ground-based sensing	(Dorthi; Bayyapu; Karra, 2020; Dorthi; Karra, 2023)
EMI (<i>Electromechanical impedance</i>)	Ground-based sensing	(Wu et al., 2022)
UAV <i>Photogrammetry / LiDAR</i>	Remote sensing	(Khan; Gupta; Gupta, 2022; Kyriou; Nikolakopoulos; Koukouvelas, 2022; Mazza et al., 2023; Calò et al., 2024; Du et al., 2025; Sestras et al., 2025)
Satellite SAR (<i>Synthetic Aperture Radar</i>)	Remote sensing	(Sapena et al., 2023)
InSAR	Remote sensing	(Yang, 2020; Guillhot et al., 2021; Dei Cas et al., 2022; Calò et al., 2024; Famiglietti et al., 2024; Luzi; Gao; Espín-López, 2025)

In general, the sensors used can be grouped into three main categories: (i) soil parameter sensors; (ii) movement and deformation sensors; and (iii) geophysical and remote sensing sensors. These groups are frequently employed in a complementary manner, aiming to enhance the robustness and reliability of analyses.

3.2.5 Data Communication and Transmission Technologies

The analysis of the selected studies reveals a wide diversity of wireless communication technologies employed in slope landslide monitoring systems, reflecting both the heterogeneity of application contexts and the operational constraints associated with these systems. Figure 10 summarizes the frequency of use of communication technologies explicitly mentioned in the analyzed articles.

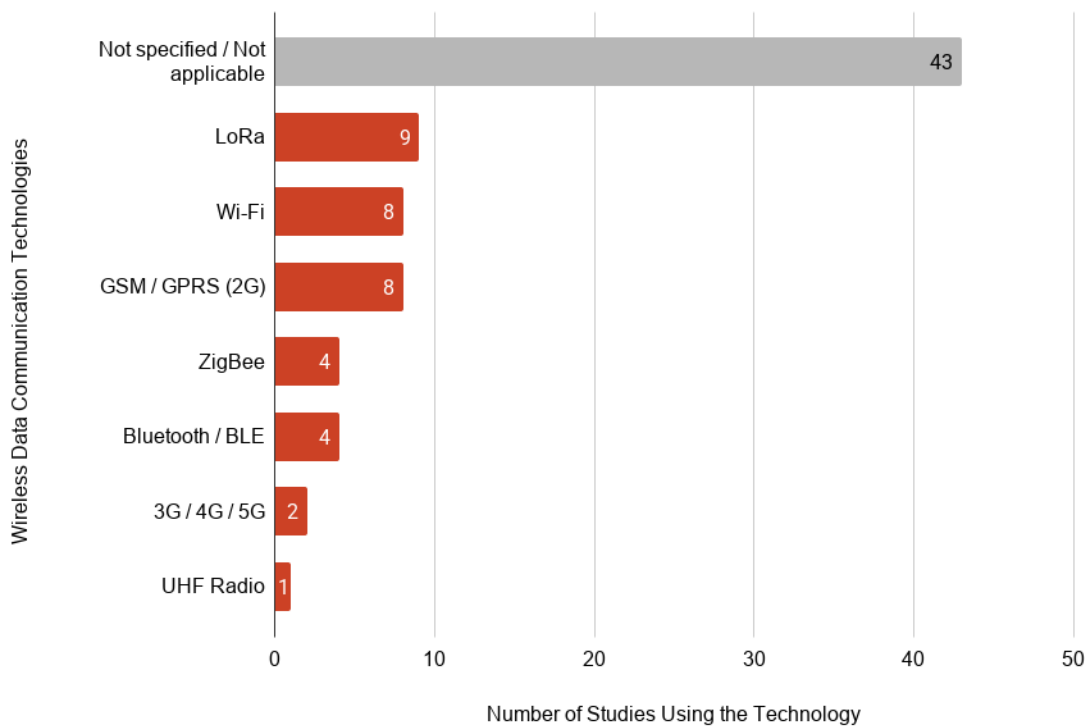


Figure 10. Wireless communication technologies used in the studies. Source: Silva, Cuperschmid, and Vaz (2026).

From a methodological standpoint, the high incidence of the "Not specified/Not applicable" category is noteworthy, present in 43 publications. This result highlights a recurrent gap in the description of the adopted communication infrastructure, which compromises study reproducibility, hinders comparison between solutions, and limits the critical evaluation of technological adequacy across different hazard scenarios.

Among the explicitly declared technologies, Long Range (LoRa) predominates, present in nine studies, consolidating itself as the main long-range, low-power communication solution. Its adoption is strongly associated with applications in remote areas or with limited telecommunications infrastructure, indicating a clear trend toward the use of Low Power Wide Area Network (LPWAN) architectures in low-cost sensor-based early warning systems (Chu et al., 2021; Gamperl, Singer, Thuro, 2021; Guilhot et al., 2021; Yadav et al., 2021; Wielandt et al., 2022; Gamperl et al., 2023; Sapena et al., 2023; Hofmann, Berger, Wimmer, 2025; Si et al., 2025).

Wi-Fi and GSM/GPRS technologies present similar frequencies but are associated with distinct contexts. Wi-Fi is predominantly used in controlled environments, such as laboratories, prototypes, and urban areas with consolidated infrastructure (Bagwari et al., 2021; Zuliani et al., 2022b; Lau et al., 2023; Marino et al., 2023; Sharma et al., 2023). GSM/GPRS (2G), in turn, remains relevant in field applications due to its wide coverage and operational robustness, despite being a legacy technology (Zuliani et al., 2022a; Setiono et al., 2023; Cifaldi et al., 2024).

Short-range, low-power protocols such as ZigBee and Bluetooth/BLE are primarily used in local sensor networks integrated into hierarchical architectures, where data are aggregated and retransmitted through longer-range gateways, such as LoRa or cellular networks (Qiao et al., 2020; Bagwari et al., 2021; Gamperl, Singer, Thuro, 2021; Yadav et al., 2021).

More recent cellular technologies (3G/4G/5G) are underrepresented in the analyzed literature, possibly due to higher energy consumption, operational costs, and dependence on more sophisticated telecommunications infrastructure — factors that limit their application in remote areas (Lau et al., 2023).

Narrowband Internet of Things (NB-IoT), despite its theoretical potential for environmental applications, is underexplored in the reviewed studies, mentioned only in a comparative or conceptual manner. The literature indicates that its dependence on licensed spectrum and telecommunications operators reduces system flexibility and autonomy, favoring the adoption of unlicensed LPWAN solutions such as LoRa (Gamperl, Singer, Thuro, 2021; Zhang et al., 2024).

Overall, the results indicate that no single dominant universal communication technology exists for landslide monitoring. The choice of solutions is strongly conditioned by factors such as range, energy consumption, cost, infrastructure availability, and the characteristics of the monitored territory. Nevertheless, a consistent trend toward the use of low-power, long-range technologies is observed, aligned with the advancement of distributed, modular, and low-cost systems, particularly aimed at socially vulnerable communities.

3.3 Results of the Qualitative Analysis

The qualitative analysis of the literature reveals a paradigm shift in landslide risk management, driven by the incorporation of IoT technologies and the pursuit of technically effective and economically viable solutions, particularly in contexts of high socio-environmental vulnerability.

3.3.1 Characterization and Criteria for the Low-Cost Concept

The low-cost concept is predominantly defined by comparative economic criteria, associated with ease of maintenance, replicability, and the use of open hardware. Systems classified in this category present costs significantly lower than conventional geotechnical solutions while maintaining functional performance adequate for continuous monitoring (Chu et al., 2021).

Platforms based on open-architecture microcontrollers (Arduino, ESP32) and commercial sensors allow cost reductions of one order of magnitude relative to professional equipment, enabling their adoption in distributed networks and low-income communities (Zuliani et al., 2022b; Gamperl et al., 2023; Cifaldi et al., 2024; Khan; Martin; Lim, 2024; Bruland et al., 2025). Paradigmatic examples include the replacement of PZT transducers with commercially available piezoelectric buzzers, which exhibit comparable sensitivities at a fraction of the cost, expanding the feasibility of scalable systems (Wu et al., 2022).

In this regard, the development of LEWS with a focus on cost reduction constitutes a strategic line of investigation, as it broadens the accessibility of these technologies in vulnerable regions, enabling large-scale preventive interventions, particularly in contexts with economic constraints and limited infrastructure.

3.3.2 Relationship between Sensors, Climatic Variables, and Extreme Events

Intense precipitation remains the primary landslide trigger, with its impact amplified by global climate change, which alters hydrological and thermal regimes (Bovolenta et al., 2020; Bainbridge et al., 2022; Hofmann, Berger, Wimmer, 2025; Si et al., 2025). In this context, low-cost sensors are employed to monitor critical variables, such as Soil Water Content (SWC), Pore Water Pressure (PWP), and matric suction, which are directly related to shear strength (Zhu et al., 2023; Pavanello et al., 2024).

The incorporation of hydrological variables into warning systems, in place of models based exclusively on rainfall thresholds, has been shown to reduce false alarms and increase the operational reliability of LEWS (Pavanello et al., 2024).

Recent innovations include bio-ionotronic sensors, which in practice operate as small self-sustaining batteries made of silk fibroin, bacterial cellulose, and calcium ions (Zhu et al., 2023). The electrical energy flow in these devices depends directly on water. Under normal conditions, soil moisture keeps the sensor's energy output stable. However, upon sudden infiltration — typical of events preceding landslides — excess water floods the device and causes an abrupt and immediate drop in voltage. This sudden energy drop acts precisely like a switch, triggering alerts within fractions of a second. In this way, the sensor uses the water from extreme infiltration itself as the physical alarm trigger, thereby avoiding false alerts caused by ordinary terrain moisture (Zhu et al., 2023).

3.3.3 Application of Artificial Intelligence and Machine Learning

Artificial Intelligence and Machine Learning (ML) techniques are widely employed to handle the large volumes of data generated by IoT networks and to expand the predictive capacity of the systems. Ensemble learning methods — such as Random Forest, XGBoost, and AdaBoost — have demonstrated significant accuracy gains over traditional threshold-based approaches, particularly in identifying deformation stages (Sharma et al., 2023; Liu et al., 2024).

Beyond prediction, algorithms such as the Dynamic Salp Swarm are employed for energy optimization and topological organization of sensor networks, extending system lifespan in remote environments (Menon et al., 2021). Neural network-based approaches such as the UWBformer, with spatial attention mechanisms, also demonstrate high potential for estimating millimeter-scale displacements under adverse conditions (Si et al., 2025).

3.3.4 Real-Time Digitization and the Digital Twin Concept

Although the digital twin concept was not explicitly adopted in the studies, several works incorporated monitoring architectures based on continuous real-time data integration. Big Data infrastructures and high-precision temporal synchronization enable coherent analysis of vibration and displacement in large-scale systems (Lau et al., 2023).

The adoption of Edge Computing (EC) and Fog Computing (FC) reduces latency and enables immediate alerts (Yadav et al., 2021; Kumar M. and Ramesh, 2022), while IoT platforms such as ThingSpeak facilitate remote data visualization and integrated slope management (Marino et al., 2023; Sharma et al., 2023).

3.3.5 Main Scientific and Technological Advances Reported

Recent advances include optical fiber sensors capable of identifying instability precursors minutes before surface manifestations (Ivanov et al., 2021b); hybrid digital models such as the Digital Feature Model (DFM) with high altimetric accuracy (Sestras et al., 2025); and low-cost subsurface inertial systems with centimetric precision (Fiber Optic Gyroscope, FOG), significantly expanding failure anticipation capability (Lu et al., 2024).

3.3.6 Challenges, Limitations, and Research Gaps

Challenges persist regarding the durability of low-cost components in harsh environments (Notti et al., 2020; Gamperl et al., 2023; Cifaldi et al., 2024); the need for calibration of sensors sensitive to environmental variables,

such as capacitive moisture sensors (Bovolenta et al., 2020; Hidayat; Hazarika; Kanaya, 2024; Pavanello et al., 2024); and the limitations of conventional technologies for monitoring non-rotational landslides (Qiao et al., 2020).

Furthermore, large-scale implementation encounters infrastructure and logistical feasibility constraints. A critical limitation is the frequent occurrence of hazard-prone areas in "shadow zones," devoid of cellular or internet signal coverage, which renders real-time alert transmission unfeasible. Another limiting factor is the scalability paradox: while individual devices are classified as low-cost for localized monitoring, their application in countries with vast susceptible areas and large populations in risk zones (such as Brazil) demands the installation of a massive number of sensors. This exponentially increases the total costs of infrastructure, installation, and continuous maintenance.

Social aspects, such as community engagement, remain underexplored despite their relevance to the effectiveness of LEWS (Gamperl et al., 2023; Sapena et al., 2023). In this context, it is important to highlight that the installation of equipment in public areas frequently faces the risk of vandalism and theft. Consequently, the practical and sustainable application of these technologies often becomes restricted to areas monitored and controlled by private stakeholders (such as mining companies and highway concessionaires), posing an additional challenge to their expansion as public policy in vulnerable communities. Furthermore, none of the analyzed studies implemented digital twins integrated with low-cost sensors, which reveals a relevant conceptual and technological gap.

3.3.7 Future Directions and Research Opportunities

The future directions identified by the authors converge toward the progressive automation of workflows and the implementation of machine learning algorithms directly on sensor devices (Edge Computing/Edge AI), aiming to reduce energy consumption, minimize latency, and enable real-time responses (Bagwari et al., 2021; Kumar and Ramesh, 2022; Fiolleau et al., 2023).

The development of modular, open-source systems is also recommended, capable of facilitating the installation, maintenance, and replication of solutions by local communities and public managers (Gamperl et al., 2023; Sapena et al., 2023), as well as the exploration of energy harvesting technologies as a strategy to extend the operational autonomy of monitoring networks (Bagwari et al., 2021; Liu et al., 2023a).

Another relevant opportunity lies in the fusion of heterogeneous data, aimed at cross-validation between surface deformation models and deep-seated movements, through the integration of low-cost sensors with InSAR monitoring and UAV surveys. This approach favors the development of hybrid warning systems that are more robust and resilient in the face of the complexity of slope destabilization processes (Guilhot et al., 2021; Famiglietti et al., 2024; Du et al., 2025).

3.3.8 Multiscale Synthesis of Slope Monitoring and Implications for Digital Twins

Beyond the results directly associated with the research questions formulated for the qualitative analysis, the systematic review enabled the identification of a cross-cutting pattern, not explicitly stated in the analyzed studies, but recurrent in the conception and operationalization of landslide monitoring solutions. This emergent finding refers to the implicit organization of monitoring strategies across different spatial and operational scales, which operate in a complementary manner.

The qualitative analysis indicates that slope monitoring for landslide risk mitigation can be understood at three main scales: orbital, aerial, and ground level. At the orbital scale, technologies based on InSAR and GNSS systems enable the detection of millimeter-scale deformations over extensive areas, being particularly relevant for tracking long-term trends in urban and regional contexts, although subject to limitations related to temporal resolution and interference from dense vegetation cover (Guilhot et al., 2021; Famiglietti et al., 2024; Sestras et al., 2025).

The aerial scale, based on the use of UAVs equipped with LiDAR sensors and photogrammetric systems, occupies an intermediate position between regional coverage and local detail, offering high operational flexibility and centimeter-level resolution. While photogrammetry excels in the detailed representation of surfaces and three-dimensional reconstruction of geomorphological features, LiDAR has the advantage of penetrating vegetation cover, enabling a more faithful characterization of the digital terrain model (Du et al., 2025; Sestras et al., 2025).

Finally, the ground scale involves *in situ* instrumentation with sensors such as inclinometers, extensometers, accelerometers, and environmental devices, providing direct, high-frequency data on the internal dynamics of slopes and associated hydrological processes, which are essential for the operation of early warning systems and for the calibration of physical and digital models (Lu et al., 2024).

The complementary articulation of these three scales underpins the transition from fragmented monitoring to the paradigm of Slope Digital Twins (SDTs). Although the present SLR has revealed that the explicit and systematic implementation of the Digital Twin concept, integrated with low-cost sensors, remains incipient – constituting a relevant technological gap – the identified architectures that combine orbital, aerial, and *in situ* data provide the heterogeneous data foundation necessary to feed such models. In this regard, SDTs can act as integrating infrastructures capable of consolidating heterogeneous data, physical models, and predictive analyses into a unified representation of slope behavior. This convergence can contribute not only to real-time visualization but also to the execution of more robust predictive analyses, enhancing the operational reliability of early warning systems.

4. Conclusions

The transition from conventional geotechnical monitoring to IoT-based Landslide Early Warning Systems (LEWS) has consolidated itself as an essential paradigm shift in disaster risk management. The main synthesis of this systematic review demonstrates that low-cost technologies have moved beyond the initial validation phase of isolated components and now present themselves as viable, modular infrastructures with high scalability potential for civil protection.

However, the effective democratization of these technologies is hindered by a severe geographical and socio-environmental paradox. Cutting-edge technological advances are concentrated in developed nations and major Asian hubs, while Global South regions – which concentrate the greatest socioeconomic vulnerabilities and precarious settlements – remain at the margins of high-impact international literature. This asymmetry demonstrates that future research agendas should focus not only on the laboratory development of these systems but also on the adaptation and validation of these technologies in real-world scenarios of infrastructure scarcity, addressing barriers such as communication shadow zones and high large-scale costs. Furthermore, the inherent limitations of searches restricted to the English language in global databases suggest that relevant community innovations may be underrepresented, making it advisable to explore regional repositories in future research for a truly global perspective.

From a technical and operational standpoint, it is concluded that the scientific challenge has shifted from mere hardware cost reduction to ensuring resilience and interoperability. The viability of large-scale systems drives the adoption of long-range, low-power networks, but faces the urgent need for architectural standardization. Additionally, to mitigate dependence on centralized processing and reduce alert latency, the transition toward Edge AI strategies emerges as a strong trend for making sensor networks more responsive and autonomous.

Finally, the recognition that effective monitoring can greatly benefit from multiscale approaches (integrating orbital, aerial, and *in situ* data) culminates in the urgency of adopting the Slope Digital Twin (SDT) paradigm. The SDT represents the potential integrating infrastructure, capable of fusing heterogeneous data and predictive models in real time. The development of these unified dynamic representations constitutes the most promising frontier for advancing disaster prevention in landslide-vulnerable areas.

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