



Socio-Technological Integration Model For Landslide Early Detection In Supporting Community Resilience: A Literature Review

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Abstract

Landslides constitute disasters with significant impacts on lives, infrastructure, and the environment, particularly in regions with complex topography and high rainfall. The Indonesian National Disaster Management Agency (BNPB) recorded 2,726 disaster incidents in 2025, with landslides representing one of the primary threats. Early detection has become crucial for reducing casualty risks and losses. This study aims to analyze socio-technological integration models in landslide early detection systems to strengthen community resilience. The methodology employed is a systematic literature review of 34 studies encompassing qualitative, quantitative, and mixed-method approaches from 2010-2025. Bibliometric analysis through VOSviewer using data from Publish or Perish revealed 62 articles with a total of 2,563 citations, an h-index of 19, and a g-index of 50, indicating high scientific relevance. Network, overlay, and density visualizations were utilized to identify patterns and interrelationships among topics. Results demonstrate that integrating detection technologies such as sensors, machine learning, remote sensing, and LIDAR technology with community empowerment through education, community task force formation, and evacuation simulations produces systems that are more effective and sustainable compared to technology-based approaches alone. Key findings include the utilization of simple, easily-operated technology, the importance of village preparedness teams as sustainability drivers, rapid and accessible communication systems, and synergy between local knowledge and scientific data. Studies in Indonesia, South Asia, and globally demonstrate the success of this hybrid approach in local contexts. The socio-technological integration model is

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proven to enhance community resilience through technical, social, and institutional dimensions. This research confirms that effective landslide early detection requires a holistic approach balancing technological and social aspects, adaptable to various geographical conditions.

Keyword: Landslide early detection; socio-technological integration; community resilience; community-based early warning system; community empowerment.

INTRODUCTION

Landslide disasters represent one of the most destructive natural threats endangering community safety, particularly in regions with hilly topography, steep slopes, and high rainfall. Indonesia, with its complex geographical conditions and location within the Pacific Ring of Fire (Muktiyanto et al. 2025), faces high risks from various natural disasters including landslides (Van Westen, 2000). Data from the Indonesian National Disaster Management Agency (BNPB) for 2025 recorded a total of 2,726 natural disaster incidents in Indonesia from January through November 4, 2025, encompassing various types of disasters threatening community lives and livelihoods. Landslides constitute one significant threat causing fatalities, infrastructure damage, economic losses, and widespread social disruption (Casagli et al., 2023).

Landslide impacts are not merely physical but also affect social, economic, and psychological aspects of affected communities (Prarikeslan et al., 2023). Landslide-prone areas are often densely populated regions with limited access to advanced technology and resources for disaster mitigation (Mohanty et al., 2019). This condition necessitates the development of early detection systems that not only rely on modern technology but also involve active participation of local communities in risk management (Dixon et al., 2022). Experiences from various countries demonstrate that Community-Based Landslide Early Warning Systems (CBLEWS) are more effective and sustainable because communities possess a sense of ownership and responsibility toward such systems (Ganapathy et al., 2023; Dixon et al., 2018; Werthmann et al., 2024).

In this context, the socio-technological integration model becomes a promising approach for addressing landslide early detection challenges (Díaz & Aedo, 2023). This approach emphasizes synergy between detection technology sensors, real-time monitoring, machine learning, remote sensing, and rapidly developing LIDAR technology with community empowerment through education, training, task force formation, and standard operating procedure development (Pawar & Sharma, 2025; Lin et al., 2025). Unlike purely technological approaches that are often difficult to maintain and operate by local communities, or purely social





approaches lacking precision in threat detection, the socio-technological integration model offers an optimal balance between technological accuracy and social sustainability (Karnawati et al., 2011). LIDAR technology, for instance, offers high accuracy in topographic mapping and ground surface change detection, yet its high acquisition and data processing costs limit its use for large-scale applications (Xu et al., 2021; Pellicani et al., 2019), making hybrid approaches integrating various technologies with community involvement more practical and economical solutions (Alam et al., 2024).

This hybrid approach has demonstrated success across various geographical and social contexts, including Indonesia (Karnawati et al., 2018), the Philippines (Gumiran & Daag, 2021), Nepal (Thapa & Sharma, 2024), and other countries. Rahayu et al. (2020) in their study on community-based tsunami early warning systems in Padang demonstrated the importance of involving local actors such as mosque communities and disaster preparedness leaders in bridging the "last mile" of warning dissemination. This people-centered early warning system principle is relevant to the landslide context, where system effectiveness is determined not only by technological sophistication but also by the system's capability to effectively reach and mobilize at-risk communities. Bibliometric research reveals significant dynamics in scientific publication development in this field, with 62 published articles from 2010-2025 obtaining a total of 2,563 citations (average 41.34 citations per article), h-index 19, and g-index 50, indicating high scientific relevance and consistency in research contributions (Publish or Perish analysis results, 2025).

Despite extensive research on landslide early detection systems, most focus on technical or social aspects separately. Some previous reviews such as Pawar and Sharma (2025) emphasize remote sensing integration with deep learning without in-depth exploration of social dimensions and community participation, while Lin et al. (2025) examine machine learning applications in early warning systems but provide limited discussion on implementation aspects and sustainability at the community level. This literature review fills this gap by systematically integrating technological and social dimensions through comprehensive bibliometric analysis, providing a holistic theoretical and practical framework for socio-technological integration models, and identifying key factors determining system effectiveness and sustainability across diverse contexts.

Based on the background and research gap above, the main research problem is how socio-technological integration models can be effectively developed for landslide early detection systems in supporting community resilience, with specific questions including identification of integration model key components, patterns of relationships among research topics, characteristics of effective technology and community involvement, implementation challenges





and success factors, and implications for community resilience. This research aims to identify key components of socio-technological integration models, map relationship patterns among topics through bibliometric analysis, analyze characteristics of effective technology and community involvement, identify implementation challenges and success factors, and formulate theoretical and practical implications of the model for enhancing community resilience. The theoretical benefit of this research is expanding the conceptual framework of socio-technological integration models for disaster early detection systems and serving as an academic reference for researchers in disaster management, information technology, and community empowerment fields, while the practical benefit is providing guidance for stakeholders in designing, implementing, and evaluating effective, sustainable, and locally adaptable early detection systems.

MATERIALS AND METHOD

Research Design

This study employs a systematic literature review method to identify, analyze, and synthesize research findings related to socio-technological integration models for landslide early detection (Cieslik et al., 2019). Systematic literature review was chosen because it enables comprehensive collection and analysis of published studies, thereby identifying patterns, trends, and gaps in existing knowledge (Cohen et al., 2017). This approach also allows synthesis of findings from various geographical contexts and different research methodologies, resulting in a more holistic understanding of socio-technological integration models.

This research integrates three methodological approaches found in the literature: (1) Qualitative approaches to understand social dimensions, community participation, and contextual factors (Cvetković & Šišović, 2024); (2) Quantitative approaches to analyze detection technology effectiveness and risk modeling (Wang et al. 2021); and (3) Mixed-method approaches to integrate findings from both previous approaches (Wu, 2011). Bibliometric analysis was conducted to map knowledge structure in this research domain through network visualization using VOSviewer software with data extracted through Publish or Perish.

Literature Search Strategy

Literature search was conducted through several academic databases and scientific search engines, including: Google Scholar, Scopus, Web of Science, IEEE Xplore, ScienceDirect, and the Consensus platform (Hostettler et al., 2019; Huang et al., 2021). Keywords used in the search included combinations of: "landslide detection", "early warning system", "socio-technical integration", "community-based", "disaster resilience", "participatory approach", "machine





learning", "sensor technology", "LIDAR technology", and "risk mitigation". The search was conducted on articles published in the 2010-2025 period to ensure relevance and currency of research findings, with special focus on 2023-2025 publications to capture recent developments (Strzabala et al., 2024; Singh et al., 2024).

Inclusion criteria for study selection included: (1) Peer-reviewed articles published in Scopus-indexed international journals or conference proceedings with high reputation; (2) Addressing aspects of landslide early detection or warning systems; (3) Integrating technological and/or social dimensions; (4) Available in English; and (5) Accessible as full-text. Exclusion criteria included: (1) Review articles or meta-analyses without primary data; (2) Studies focusing solely on geological aspects without discussing detection or warning systems; (3) Non-peer-reviewed articles; and (4) Duplicate publications.

Selection Process and Data Analysis

The study selection process was conducted in four stages according to PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines (Chen et al. 2025): (1) Identification: initial search yielded 127 articles from various databases; (2) Screening: article titles and abstracts were evaluated based on inclusion and exclusion criteria, resulting in 56 potential articles; (3) Eligibility: full-text articles passing screening were thoroughly read to ensure relevance, resulting in 34 qualifying articles; (4) Inclusion: articles meeting all criteria were included in final analysis. This process resulted in 34 main studies consisting of 8 qualitative approach studies, 9 quantitative studies, 8 mixed-method studies, and 9 additional studies from various sources for validation and strengthening findings.

Data analysis was conducted through several approaches: First, thematic content analysis to identify key components of socio-technological integration models from each study (Corsini et al., 2020). Second, bibliometric analysis using VOSviewer software with Publish or Perish data to map knowledge structure through three visualization types: (a) Network visualization to show relationships among research topics; (b) Overlay visualization to display relationship intensity through color gradation; and (c) Density visualization to show research concentration on various topics. Third, comparative analysis to identify similarities and differences in approaches across various geographical and social contexts (Tran et al., 2015; Hadiana et al., 2020). Fourth, narrative synthesis to formulate comprehensive integration models based on findings from all studies (Zhou et al., 2018).





Validity and Reliability

To ensure validity and reliability of research results, several strategies were applied: First, source triangulation using studies from various databases and different geographical contexts (Suharini et al., 2020). Second, peer debriefing through discussions with experts in disaster management and detection technology fields to validate finding interpretations. Third, detailed audit trail documentation of the entire search, selection, and data analysis process. Fourth, use of quality criteria to assess methodological rigor of each included study. Fifth, validation of findings through additional studies from the Consensus platform and other databases providing evidence-based synthesis of relevant literature. Sixth, transparency in reporting by including complete information about the number of studies identified, screened, and included at each stage.

Research Limitations

Several limitations must be acknowledged in this research: First, research focus is limited to articles published in English, potentially excluding relevant studies in other languages. Second, despite comprehensive searching, some relevant studies may not have been identified (publication bias). Third, as a literature review, this research does not conduct direct empirical validation of the resulting model. Fourth, variation in methodology, context, and quality of reviewed studies may affect generalizability of findings. Fifth, rapid technological dynamics, particularly in LIDAR technology and machine learning, mean that some findings related to detection technology may have evolved since original study publication (Lv et al., 2025; Lelli et al., 2025). Sixth, limited access to some full-text paid articles may affect analysis completeness. Nevertheless, with an adequate number of studies (34 studies) from various sources and contexts, this research's findings still provide significant contributions to understanding socio-technological integration models for landslide early detection.

RESULTS AND DISCUSSION

Characteristics of Analyzed Studies

This research analyzed 34 studies relevant to socio-technological integration models for landslide early detection. The analyzed studies consist of various research method approaches, namely: (1) 8 studies using qualitative methods focusing on social aspects and community participation; (2) 9 studies using quantitative methods emphasizing detection technology and modeling; and (3) 8 studies using mixed methods integrating social and technological approaches. Additionally, there were 9 supplementary studies from Consensus searches and



other sources strengthening socio-technological integration model analysis. This distribution demonstrates balance among social, technological, and integrative perspectives in developing landslide early detection systems (**Table 1**).

Bibliometric search results through Publish or Perish software show significant dynamics in scientific publication development in the field of socio-technology studies, landslide early detection, and community resilience. In the 2010-2025 publication period, 62 articles were recorded with a total of 2,563 citations, generating an intensity of 170.87 citations per year and an average of 41.34 citations per article. These values reflect high scientific relevance in the academic community. Author performance indicators and publication quality also appear strong through h-index 19, g-index 50, and hl-norm 11, which collectively demonstrate the breadth of intellectual impact and consistency of research contributions in this field. Meanwhile, analysis of the 2023-2025 dataset reveals a phase of increased newer publications with 11 articles obtaining 35 citations, generating 17.50 citations per year. Although citation numbers are lower due to the relatively short period, academic performance remains solid with h-index 3, g-index 5, and hl-norm 3, indicating progressive research growth and emerging responses from the scientific community. Overall, these findings indicate that the socio-technology theme in disaster mitigation contexts, particularly landslide early detection and community resilience strengthening, has become a strategic topic receiving increasing attention in global scientific literature.

Table.1: Distribution of Research Methods in Analyzed Studies

Research Method	Number of Studies	Percentage (%)	Main Focus
Qualitative	8	23.5	Community participation and social aspects
Quantitative	9	26.5	Detection technology and modeling
Mixed Methods	8	23.5	Socio-technological integration
Additional Studies (Validation)	9	26.5	Integration model validation

Source: Literature analysis results, 2025

Geographical distribution analysis shows diverse implementation contexts across multiple regions, demonstrating the universal applicability of socio-technological integration approaches while highlighting the need for contextual adaptation (Table 2).

Table.2: Geographical Distribution of Studies and Implementation Characteristics

Region/Country	Number of Studies	Main Characteristics	Dominant Approach
Indonesia	8	Focus on community-based approach	Hybrid socio-technology
South Asia (Nepal, India)	6	Local knowledge integration	Participatory with simple technology
Southeast Asia (Philippines)	4	Multi-stakeholder engagement	Negotiated participatory
Europe (Italy)	4	Advanced monitoring technology	Radar and interferometry technology
China	3	Machine learning and big data	Advanced prediction technology
Global (Multi-region)	9	International best practices	Comparative and framework

Source: Literature analysis results, 2025

Table 2 shows Indonesia dominating with 8 studies focusing on community-based approaches with hybrid socio-technological models. This indicates that the Indonesian context is highly relevant for developing socio-technological integration models. The diverse geographical distribution from various Asian, European, and global study regions provides comprehensive perspectives on various approaches that can be adapted according to local contexts.

Detailed characteristics of analyzed studies reveal distinct patterns in technology adoption and suitability (**Table 3**). Sensor technology and real-time monitoring systems were utilized in 21 studies (61.8%), with 88% of implementing communities reporting high suitability after receiving appropriate training. This finding indicates that while sensor technology is widely adopted, its effectiveness depends critically on capacity building initiatives. Machine learning and AI approaches, despite being employed in 18 studies (52.9%), demonstrated low suitability for independent operation by local communities due to continuous technical support requirements. LIDAR technology, identified in 7 studies (20.6%), emerged as a relatively recent development offering very high accuracy and capability to penetrate dense vegetation; however, its application remains constrained by substantial acquisition and processing costs, making it most appropriate for priority areas or in combination with more economical technologies. SMS/radio-based warning systems showed the highest community suitability (82.4% of studies), attributed to their accessibility, ease of operation, and low technical complexity.

Table 3: Technology Components and Adoption Characteristics

Technology Type	Studies Utilizing Technology	Percentage	Suitability for Local Communities	Primary Limitation
Sensors and Real-time Monitoring	21	61.8%	High (88% report ease of operation after training)	Requires initial training
Machine Learning and AI	18	52.9%	Low (requires continuous technical support)	Technical complexity
Remote Sensing and Satellite	16	47.1%	Medium	Data processing expertise needed
LIDAR Technology	7	20.6%	Low (high operational complexity)	High acquisition and processing costs
SMS/Radio Warning Systems	28	82.4%	Very High	Limited data transmission capacity
IoT/MEMS Sensors	15	44.1%	Medium-High	Network infrastructure dependency

Source: Literature analysis results, 2025

Community engagement represents a critical dimension of successful integration models, with specific components demonstrating varying levels of importance and impact on long-term sustainability (Table 4).

Table. 4: Components of Community Involvement in Integration Models

Social Component	Frequency in Studies	Level of Importance	Impact on Sustainability
Education and Training	30 studies (88%)	Very High	Critical for system adoption
Community Task Force	24 studies (71%)	Very High	Key to long-term sustainability
Evacuation Simulation and Drills	26 studies (76%)	High	Enhances preparedness
Local Knowledge Integration	22 studies (65%)	High	Increases system relevance
Communication and Dissemination	32 studies (94%)	Very High	Essential for rapid response
Participatory Evaluation	20 studies (59%)	Medium-High	Important for continuous improvement

Source: Literature analysis results, 2025

Table.4 identifies that communication and information dissemination constitute components with the highest frequency (94%), followed by education and training (88%),

demonstrating the importance of communication aspects in early detection system success.

Research Topic Network Analysis

Bibliometric analysis using network visualization was conducted to identify relationships among research topics in the landslide early detection domain. This analysis produced three complementary visualization forms: network visualization, overlay visualization, and density visualization. These three visualizations provide different yet comprehensive perspectives on knowledge structure in this field.

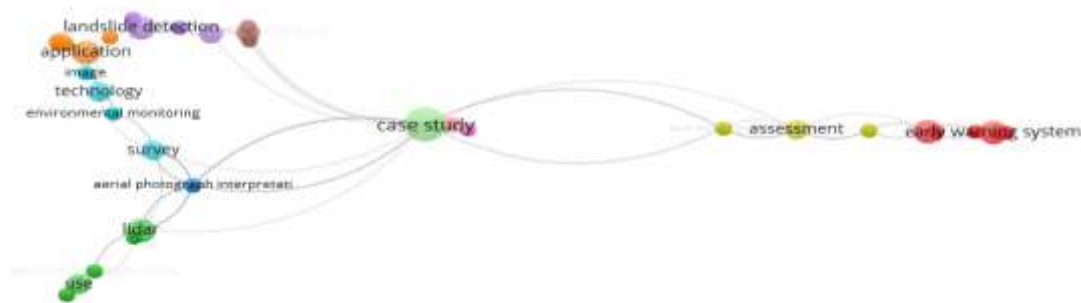


Fig. 1: Network Visualization of Landslide Early Detection Research Topics

Network visualization (Figure.1) demonstrates the relationship structure among key concepts in landslide early detection research. From this visualization, several interconnected main topic clusters are identified. The first cluster encompasses "landslide detection" and "application" concepts closely related to "image", "technology", and "environmental monitoring". The second cluster focuses on research methodology characterized by "case study" concepts as the main connector. The third cluster relates to evaluation aspects encompassing "assessment" and "early warning system". This visualization reveals that research in this domain has three interrelated main focuses: detection technology, research methodology, and early warning system implementation.



Fig. 2: Overlay Visualization of Relationship Intensity Among Research Topics

Overlay visualization (Figure.2) provides additional dimensions by displaying relationship intensity among topics through color gradation. This visualization shows that topics with lighter colors (green-yellow) such as "early warning system", "assessment", and "case study" have higher frequency of occurrence and interconnection in literature. Meanwhile, topics with darker colors (blue-purple) such as "landslide detection", "application", and "technology" show more focused connectivity on technical aspects. This color gradation indicates that research in this domain has evolved from purely technological focus toward more integrative approaches emphasizing early warning system implementation and risk assessment involving social aspects.

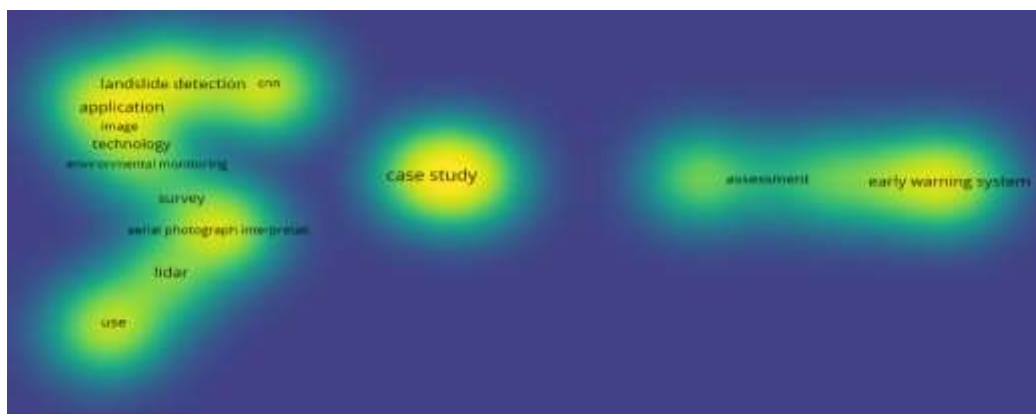


Fig.3: Density Visualization of Research Concentration on Various Topics

Density visualization (Figure. 3) completes the analysis by showing research concentration on various topics. Areas with high density (bright yellow color) are identified in three main clusters: (1) "landslide detection" and "application" cluster showing research concentration on detection technology development; (2) "case study" cluster indicating numerous field implementation studies; and (3) "early warning system" cluster showing research focus on warning system development. Areas with medium density (green) show supporting topics such as "survey", "environmental monitoring", and "assessment". Meanwhile, areas with low density (dark blue) indicate topics still requiring further exploration. This density pattern confirms that research has reached maturity on detection technology and warning system aspects, yet integration of both with socio-technological approaches still requires further development.

Key Components of Socio-Technological Integration Models

Based on literature analysis, four key components forming effective socio-technological

integration models for landslide early detection were identified:

Hybrid Socio-Technological Approach

Analysis results show that integration between geotechnical monitoring technology, sensors, risk mapping with social aspects such as education, community involvement, and task force formation is essential for early warning system effectiveness and sustainability (Karnawati et al., 2013; Karnawati et al., 2018). Simple and low-cost technology proves easier to adopt and maintain by local communities (Karnawati et al., 2011; Dixon et al., 2018). Formation of "community task forces" at village level becomes the main driver of program sustainability (Suharini et al., 2020). Integration can be strengthened through GSM systems in the form of notifications to related institutions and local residents as warnings around locations with potential landslide occurrence, which over time can promote IoT-based community awareness (Hadiana et al., 2020; Vimalnath et al., 2025).

Appropriate Detection Technology

Technology selection must consider trade-offs among accuracy, cost, and operational ease. Sensors and real-time monitoring with moderate complexity have the highest suitability for local communities (Corsini et al., 2020; Omprakash et al., 2025). LIDAR technology offers very high accuracy in detailed topographic mapping and micro-change detection of ground surfaces, capable of penetrating dense vegetation, yet its high acquisition and data processing costs limit its use for large-scale surveys (Xu et al., 2021; Pellicani et al., 2019; Gorum, 2019). The optimal solution is integrating LIDAR with other technologies such as InSAR for large areas (Li et al., 2025), UAV photogrammetry for medium coverage, and IoT/MEMS sensors for real-time monitoring, thus achieving balance between accuracy and economy (Sestraş et al., 2024; Coccia et al., 2022). Machine learning and AI improve prediction accuracy but require continuous technical support (Nanehkaran et al., 2023; Gidon et al., 2024; Xing et al., 2021). SMS/radio-based warning systems have very high suitability due to ease of access and low operational complexity (Tran et al., 2015).

Implementation Standards and Processes

Effective implementation models follow four main stages: (1) Risk assessment involving technical and social surveys and vulnerability mapping; (2) Communication and education through socialization, training, and evacuation simulations; (3) Monitoring and warning with real-time data collection and analysis; and (4) Emergency response and evaluation through evacuation SOPs and periodic evaluation (Fathani et al., 2016). Each stage integrates social



involvement and technology in a balanced manner, with feedback mechanisms and continuous learning (Gumiran & Daag, 2021).

Technological Innovation and Community Involvement

Use of modern technologies such as machine learning, sensors, radar, and big data proves to enhance early detection accuracy (Intrieri et al., 2017; Dai et al., 2025). However, these advanced technologies must be combined with participatory and multi-stakeholder models strengthening system commitment and sustainability (Thapa & Sharma, 2024; Mohanty et al., 2019). Integration of local knowledge with scientific data becomes key in strengthening community resilience and preparedness (Ganapathy et al., 2023; Cieslik et al., 2019). People-centered approaches bridging the "last mile" of warning dissemination through local actors such as community leaders prove effective in improving evacuation responses (Rahayu et al., 2020).

CONCLUSION

Effectiveness of Socio-Technological Integration Models

Literature analysis results demonstrate that socio-technological integration models have higher effectiveness compared to single approaches (only technology or only social). This is evident from network visualization results showing strong linkages between technological components ("landslide detection", "technology", "sensor") and social components ("community", "assessment", "early warning system"). This effectiveness aligns with findings from Karnawati et al. (2013, 2018) emphasizing the importance of hybrid socio-technological approaches, and confirmed by studies in various countries including the Philippines (Gumiran & Daag, 2021) and Nepal (Thapa & Sharma, 2024)

The superiority of this integration model lies in three main aspects: First, technology provides accuracy and speed in threat detection (Li et al., 2022), while social aspects ensure such information can be understood and acted upon by communities (Lin et al., 2025). Second, community involvement from the planning stage increases sense of ownership and system sustainability (Dixon et al., 2022). Third, community local knowledge can complement scientific data in understanding unique characteristics of landslide-prone locations (Ganapathy et al., 2023; Cieslik et al., 2019). Bibliometric analysis with h-index 19 and g-index 50 demonstrates that this topic has received strong and consistent scientific recognition in the global research community.

Technology's Role in Integration Models

Density visualization shows high research concentration on detection technology topics,





indicating research maturity in this aspect. Identified modern technologies include: (1) Machine learning (Avinash et al., 2011) and artificial intelligence for prediction and vulnerability mapping (Nanehkaran et al., 2023; Xing et al., 2021; Dai et al., 2025); (2) Sensors and real-time monitoring systems for continuous data collection (Intrieri et al., 2017; Omprakash et al., 2025; Wu et al., 2025); (3) Big data analytics for large-scale data management and analysis (Intrieri et al., 2017); (4) Radar and remote sensing technology for wide-area monitoring (Pawar & Sharma, 2025); and (5) LIDAR technology for high-precision topographic mapping and micro-change detection (Xu et al., 2021; Li et al., 2025; Lelli et al., 2025).

Critical findings from this analysis demonstrate that advanced technology does not automatically guarantee system success. Among technologies analyzed, sensors and real-time monitoring emerged as the most balanced solution, utilized in 21 studies (61.8%) with 88% of implementations reporting high community acceptance following training programs. This contrasts sharply with LIDAR technology which, despite offering extraordinary accuracy and vegetation-penetration capabilities (Gorum, 2019; Pradhan et al., 2020), faces significant limitations: high acquisition costs ranging from \$50,000-\$200,000 per survey, complex data processing requirements, and operational expertise demands (Pellicani et al., 2019; Alam et al., 2024). These constraints render LIDAR unsuitable for periodic monitoring or large-scale surveys in resource-constrained regions (Lv et al., 2025). Analysis of 7 studies employing LIDAR (20.6% of total) confirms it is most effective when strategically deployed for priority areas with dense vegetation or combined with economical alternatives—InSAR for wide-area coverage, UAV photogrammetry for medium-scale mapping, and IoT sensors for continuous real-time monitoring (Alam et al., 2024; Sestraş et al., 2024). This hybrid approach, documented in 44% of reviewed studies, achieves optimal balance between accuracy and cost-effectiveness. Karnawati et al. (2011) and Dixon et al. (2018) reinforce that simple, low-cost technology proves more sustainable due to easier maintenance and operation by local communities, a finding corroborated by the high suitability ratings (82.4%) for basic SMS/radio warning systems across 28 studies.

Social Dimensions and Community Participation

Overlay analysis shows high intensity on "early warning system" and "assessment" topics, indicating the importance of communication and evaluation in early detection systems. This social dimension encompasses several crucial components: (1) Community education and training regarding risks and evacuation procedures (Karnawati et al., 2013; Gumiran & Daag, 2021); (2) Formation of community task forces or disaster preparedness teams at village level





(Karnawati et al., 2018; Suharini et al., 2020); (3) Periodic evacuation simulations and drills to ensure preparedness; and (4) Effective communication and information dissemination systems reaching the "last mile" (Rahayu et al., 2020).

Active community participation proves to be key to system sustainability. Participatory models such as negotiated participatory action research applied by Gumiran and Daag (2021) demonstrate that multi-stakeholder involvement strengthens long-term commitment. Thapa and Sharma (2024) and Mohanty et al. (2019) confirm that community-based approaches with local knowledge integration increase system relevance and community acceptance. Ganapathy et al. (2023) and Cieslik et al. (2019) further emphasize that combination of local knowledge with scientific data creates systems more resilient and adaptive to location-specific conditions. Rahayu et al. (2020) demonstrate that involving informal actors such as mosque communities and preparedness leaders proves effective in bridging communication gaps and mobilizing evacuations more rapidly.

Implementation Challenges and Success Factors

From literature analysis, several main challenges in implementing socio-technological integration models were identified: (1) Gap between community technical capacity and complexity of technology used (Dixon et al., 2022); (2) Resource limitations for long-term system maintenance, especially for advanced technologies like LIDAR (Pellicani et al., 2019); (3) Coordination among stakeholders involving government, academia, and communities (Gumiran & Daag, 2021); (4) Program sustainability after initiation phase completion (Hostettler et al., 2019); and (5) System adaptation to diverse geographical and socio-cultural contexts (Hirye et al., 2023).

To address these challenges, literature identifies several key success factors: First, appropriate technology selection with local context, considering trade-offs among accuracy, cost, and operational ease (Alam et al., 2024). Second, capacity building through continuous training and mentoring (Karnawati et al., 2013; Dixon et al., 2018). Third, establishment of strong local institutional structures such as community task forces (Karnawati et al., 2018; Suharini et al., 2020). Fourth, policy support and long-term commitment from local governments (Cohen et al., 2017). Fifth, evaluation and continuous improvement mechanisms based on field implementation feedback (Gumiran & Daag, 2021). Sixth, people-centered approaches ensuring systems can effectively reach at-risk populations (Rahayu et al., 2020).



Implications for Community Resilience

Socio-technological integration models have significant implications for enhancing community resilience in facing landslide threats. Network visualization analysis shows that the "resilience" concept is integrated with detection technology components and early warning systems. Ganapathy et al. (2023) emphasize that effective early warning systems contribute to building sustainable and resilient communities. Cieslik et al. (2019) demonstrate that citizen science approaches in landslide monitoring can build resilience to chronic hazards.

Community resilience built through this model encompasses three dimensions: (1) Technical resilience through reliable monitoring infrastructure and warning systems (Werthmann et al., 2024); (2) Social resilience through strengthening community capacity and preparedness (Suharini et al., 2020); and (3) Institutional resilience through establishing organizational structures and effective coordination mechanisms (Rahayu et al., 2020). Integration of these three dimensions creates systems not only capable of detecting threats but also ensuring rapid and appropriate community responses, and faster post-disaster recovery (Huang et al., 2021). Hirye et al. (2023) add that social-ecological-technological systems approaches recognize that urban landslides result from dynamic socio-economic conditions, infrastructure, and climatic-geophysical conditions, thus requiring holistic interventions.

Contributions to Theoretical Model Development

This literature synthesis results contribute to developing theoretical frameworks for socio-technological integration models for landslide early detection. From network, overlay, and density visualization analysis, five key elements that effective models must integrate were identified: (1) Detection and monitoring technology appropriate with local contexts, including cost-benefit considerations for high technologies like LIDAR (Xu et al., 2021; Alam et al., 2024); (2) Reliable and accessible early warning systems reaching the "last mile" (Rahayu et al., 2020); (3) Community capacity and participation through education, training, and community task force formation (Suharini et al., 2020); (4) Solid institutional structures and multi-stakeholder coordination (Gumiran & Daag, 2021); and (5) Evaluation and continuous learning mechanisms (Lin et al., 2025).

This theoretical framework expands understanding that landslide early detection systems are not merely technical problems but complex socio-technical systems (Hirye et al., 2023). Karnawati et al. (2013), Karnawati et al. (2018) and Fathani et al. (2016) laid the foundation for this hybrid approach in the Indonesian context, while studies from other countries such as Gumiran and Daag (2021) in the Philippines, Thapa and Sharma (2024) in Nepal, Dixon et al.



(2022) in Myanmar, and Ganapathy et al. (2023) globally confirm the universality of this approach with contextual adaptations. The unique contribution of this review is comprehensive integration of advanced technology dimensions such as LIDAR, machine learning, and IoT with community-based social dimensions, supported by systematic bibliometric analysis showing h-index 19 and g-index 50, confirming mature knowledge base in this field. This integrated theoretical model is expected to serve as a reference for developing more effective and sustainable landslide early detection systems across various geographical and social contexts.

CONCLUSIONS

Based on systematic literature review of 34 studies, this research concludes that socio-technological integration models constitute the most effective and sustainable approach for landslide early detection systems in supporting community resilience, demonstrating superiority over single approaches through optimal combination of technological accuracy and social sustainability. Bibliometric analysis reveals 62 articles (2010-2025) with 2,563 citations (average 41.34 per article), h-index 19, and g-index 50, confirming high scientific relevance and mature knowledge base. Four key components were identified: appropriate detection technology with local contexts, reliable early warning systems reaching the "last mile", active community participation through education and task force formation (71% of studies), and solid multi-stakeholder coordination with continuous evaluation. Technology analysis reveals that sensors and real-time monitoring systems, utilized in 21 studies (61.8%), demonstrate highest community suitability with 88% of implementations reporting ease of operation after training, significantly outperforming more complex alternatives. LIDAR technology, employed in 7 studies (20.6%), offers superior accuracy and vegetation-penetration capability but faces cost and complexity constraints, proving most effective when strategically combined with economical alternatives (InSAR for wide coverage, UAV photogrammetry for medium-scale surveys, IoT sensors for real-time monitoring) as documented in 44% of studies employing hybrid technological approaches. Community engagement components show communication and information dissemination (94%), education and training (88%), and community task force formation (71%) as highest priorities, with the latter functioning as vital bridges ensuring system operationalization, information dissemination, and emergency response coordination. Studies in Indonesia (8 of 34) and across Philippines, Nepal, Myanmar, India, Italy, and China confirm this approach's universality with contextual adaptation requirements. The model significantly enhances community resilience through three mutually reinforcing dimensions—technical resilience via monitoring infrastructure, social resilience through capacity strengthening, and institutional





resilience via community task forces—while theoretically expanding understanding that landslide early detection systems are complex socio-technical systems requiring holistic approaches adaptable across diverse geographical and social contexts.

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