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# A Bibliometric Analysis Examining the Current Advancements in Tsunami Disaster Risk Reduction Research

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**Abstract** Tsunamis are a threat that can come at any time, and their impacts can be mitigated effectively. This research undertakes a comprehensive literature review concerning tsunami disaster risk reduction (DRR) aspects between the years 1993 and 2025. The purpose is to identify existing research gaps and delineate the current state-of-the-art in tsunami DRR by analyzing scientific publications based on five DRR analytical component frames. Employing bibliometric methodologies, relevant scholarly articles were retrieved using keywords such as tsunami risk reduction and disaster risk reduction for tsunami hazard. Data collection was performed via the Google Scholar database, resulting in an assemblage of 1,000 bibliographic records spanning from 1975 to 2025. The dataset encompasses over 40,000 citations, an h-index of 100, and approximately 20,000 citations per author, all formatted in RIS. Subsequent analysis involved binary and clustering computational techniques to elicit pertinent research themes and temporal clusters associated with disaster risk reduction studies. The findings of the investigation revealed a significant research gap in tsunami DRR. This gap was identified based on the decreasing number of tsunami DRR studies since 2021. A Large number of tsunami early warning systems that have been implemented have not successfully minimized human and material losses. This study found that casualty-related research plays an important role in bridging the gap between evacuation research and tsunami scenario research within DRR programs. We also identified that the current state-of-the-art in this field lies in tsunami scenario studies, which serve as conceptual databases consisting of various potential tsunami modeling scenarios.

**Keywords:** bibliometric analysis, tsunami scenarios, tsunami risk reduction, evacuation, casualty

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# 1. INTRODUCTION

Natural disasters such as tsunamis have occurred periodically, resulting in significant loss of life and material damage. Scientists continue to seek the most effective methods for tsunami disaster risk reduction (DRR) in tsunami-prone areas (Jain et al., 2021). To advance the development of DRR strategies, it is essential to address the research gaps identified in previous studies. This study collects and analyses scientific articles related to tsunami disasters to determine the current state of DRR research. A bibliometric analysis is used to identify research gaps and assess the current state of resource management studies in disaster response, as discussed by Geng et al. (2024).

Building on this bibliometric analysis, several key indicators have been identified as central to research on tsunami disaster risk reduction. Five key indicators guide research on tsunami disaster risk reduction as part of broader efforts toward disaster risk reduction context. These encompass the identification of tsunami source (Setyonegoro et al., 2024a), the tsunami modeling scenarios utilized, the employed methodologies, the resolution of bathymetric and topographic data (Supendi et al., 2022), the delineation of tsunami-prone areas, the adopted disaster risk reduction strategies (Satake, 2014) and the application of emerging technologies (Wibowo et al., 2023). The initial focus of this research domain involves key indicators, notably the determination of tsunami source origins (Supendi et al., 2022; Widiyantoro et al., 2020). Consequently, recent studies have emphasized DRR analytical components pertinent to enhancing environmental robustness and socio-economic resilience of communities in the context of tsunami hazards. Given that earthquake magnitude estimation varies considerably with wave period (Ammon et al., 2006), precise identification of tsunami sources is critically linked to optimizing mitigation strategies aimed at reducing tsunami disaster risk. Sources characterization and earthquake magnitude assessments can be performed through diverse approaches including scaling laws relating fault area to earthquake energy (Li et al., 2020), tomography (Muttaqy et al., 2022; Nugraha et al., 2018), relocation (Supendi et al., 2022; Widiyantoro et al., 2020), landslide potential (Brune et al., 2010; Tarwidi et al., 2024; Barnhart et al., 2025), double-difference (DD) and earthquake decay seismicity (Sladen & Tervisan, 2018; Kato et al., 2007), teletomoDD, and geodynamics (Nugraha et al., 2018; Takemura, 1998; Wells & Coppersmith, 1994; Fauzi et al., 2020; Ramadhan et al., 2020; Rogozhin et al., 2019). The accuracy of identifying tsunami source causes will lead to the development of precise technologies and mitigation strategies in tsunami-affected environments.

The second indicator aspect pertains to the implementation of tsunami modeling scenarios used to identify tsunami damage levels, which directly influence environmental sustainability through various approaches. These include monitoring seismic frequency (Ammon et al., 2006; Wenyuan et al., 2017), field surveys (Lavigne et al., 2007), Vp/Vs velocity structure (Muttaqy et al., 2022), focal mechanism analysis (Supendi et al., 2020), subsurface bathymetric structure (Patria & Aulia, 2020; Polina, 2020) and numerical tsunami scenario modeling using COMCOT, TUNAMI F1, TUNAMI N2, and Delft3D (Setyonegoro et al., 2024a; Wibowo et al., 2023; Widiyantoro et al., 2020). Several reviews indicate that methods for assessing the intensity of tsunami-induced damage from earthquake sources can be correlated with the socio-economic recovery outcomes of affected populations. The third aspect concerns environmental DRR analytical components. Relevant studies address the development of tsunami disaster risk reduction (DRR) through disaster management strategies (Satake, 2014; Asbi et al., 2025) as well as mitigation and risk assessment (Ophiyandri et al., 2020; Alhamid et al., 2024; Nurhasanah, et al., 2025). Investigation and evaluation of tsunami hazard utilize impact analysis, vulnerability assessments (Sesar et al., 2025), risk zone mapping, and GIS modeling techniques (Jumadi et al., 2025; Rahmadani et al., 2025). Additionally, tsunami early warning systems incorporate tools such as DART buoys, tide gauges, and tsunami travel time analyses (Purnama et al., 2025; Wang et al., 2025). The concept of tsunami disaster resilience is also explored based on vegetation/mangrove and other relevant factors (Udarika & Tanaka, 2025; Harris et al., 2019).

The fourth indicator aspect pertains to DRR strategies, encompassing the adoption of research methodologies grounded in sustainability development indicators from social perspectives, such as the Sustainable Development Goals (SDGs) approach (Fuady et al., 2025; Ham et al., 2025). This includes training methods, public awareness initiatives, and evacuation simulations. The fifth indicator concerns sustainability development indicators from economic aspects, involving the estimation of economic loss impacts using the Synthetic Control Method (SCM) and Probabilistic Tsunami Hazard Analysis (PTHA) (Al Ghifari et al., 2025), alongside decision-making process in tsunami disaster risk management utilizing crowdsourcing methods (Harrison et al., 2024). Furthermore, satellite imagery and geological data are employed to map tsunami inundation hazard zones (Irawan et al., 2024). Additional disaster risk reduction approaches include the development of earthquake early warning systems (Wegsheider et al., 2011), real-time estimation of earthquake source parameters and tsunami potential, paleoseismology studies on past earthquakes and tsunamis, as well as studies on maximum potential magnitudes, recurrence variability, and long-term forecasting of major earthquakes within subduction zones (Satake, 2014). Moreover, other DRR methodologies have been explored by Wegscheider et al. (2011), focusing on identifying tsunami risk areas, bridging the gap between research and practical application, and applying these measures at the community level.

Through an analysis of five sustainability indicator aspects derived from a review of scientific literature related to tsunami scenario modeling research for tsunami DRR, it is evident that further scholarly contributions are necessary to identify research gaps and delineate the current state-of-the-art in tsunami disaster studies. Addressing the research question within the context of minimizing tsunami-related casualties, this study hypothesizes that tsunami simulation efforts will achieve optimal effectiveness when supported by enhanced investigations into tsunami scenario source identification. Such scenarios should integrate a combination of seismic events and geomorphic processes, such as submarine landslides. Notably, Anaya et al. (2025) documented geomorphic disaster phenomena triggered by earthquakes, such as landslides originating from steep coastal cliffs followed by tsunami waves. Similarly, Khashchevskaya et al. (2025) conducted studies focusing on geomorphic processes. The reliability of tsunami scenario modeling is inherently tied to the accuracy of source identification; therefore, precise determination of tsunami-generating sources is essential, although it should be noted that accurate tsunami scenarios also depend on additional factors such as wave generation, propagation dynamics, and coastal interactions and constitute a core component of emerging technologies aimed at enhancing tsunami DRR.

This study represents an initial stage in systematizing tsunami DRR research. Because tsunamis are infrequent yet high-impact events, systematic bibliometric evidence remains scarce. Accordingly, the general objective is to provide a preliminary mapping of the global research landscape on tsunami DRR. The specific objectives are: (1) to quantify temporal trends in publications and citations; (2) to identify dominant research clusters through keyword co-occurrence networks; (3) to relate these clusters to five DRR analytical component concepts; and (4) to highlight research gaps, particularly within the scenario, evacuation, and casualty nexus, that merit further investigation

## 2. MATERIALS AND METHODS

The present study undertakes an investigation aimed at identifying research gaps and reviewing the current advancements in tsunami simulation scenarios within the broader framework of disaster risk reduction for tsunamis. Bibliometric methods are employed to analyze scientific publications related to tsunamis conducted on the Google Scholar database (Putra et al., 2023). A study on crisis management in local communities was carried out using VOSviewer and Biblioshiny to perform bibliometric analysis and generate visualizations (Ivanova et al., 2025). Additionally, this study incorporates a systematic review alongside bibliometric analysis focused on tsunami vulnerability modeling using remote sensing and Geographic Information Systems (GIS), with the objective of evaluating research trends, methodologies, and challenges in disaster risk assessment (Nurhasanah et al., 2025). The bibliometric analysis was performed by collecting and reviewing scientific literature utilizing Harzing's Publish or Perish software, version 8.17. The data were retrieved from the Google Scholar database using the keyword *tsunami risk reduction*, resulting in 1,000 bibliographic records spanning from 1993 to 2025. The dataset comprises a total of 50,617 citations, an h-index of 110, and 22,215 citations per author. Concurrently, employing the keyword *disaster risk reduction for tsunami hazard* yielded 999 bibliographic records covering the period from 1975 to 2025. This dataset recorded a total of 47,146 citations, an h-index of 103 and 19,972 citations per author.

This study conducts a comprehensive review and analysis of scientific publication data pertaining to the keywords *tsunami risk reduction* and *disaster risk reduction for tsunami hazards*. Citation trends on an annual basis are systematically categorized (Figure 1) in accordance with the bibliometric methodology established by Ho and Hartley (2026). Concurrently, annual publication trends are examined utilizing the approach of Chatterjee and Sahasranamam (2014) to discern temporal shifts in disciplinary emphasis. A preceding bibliometric investigation by Chiu and Ho (2007), based on data from 1991 to 2004, demonstrated that the majority of tsunami-related publications appeared in the categories of pure and applied geophysics as well as multidisciplinary geoscience, thereby reflecting the historical focus on earthquake-induced tsunamis within a geophysical paradigm.

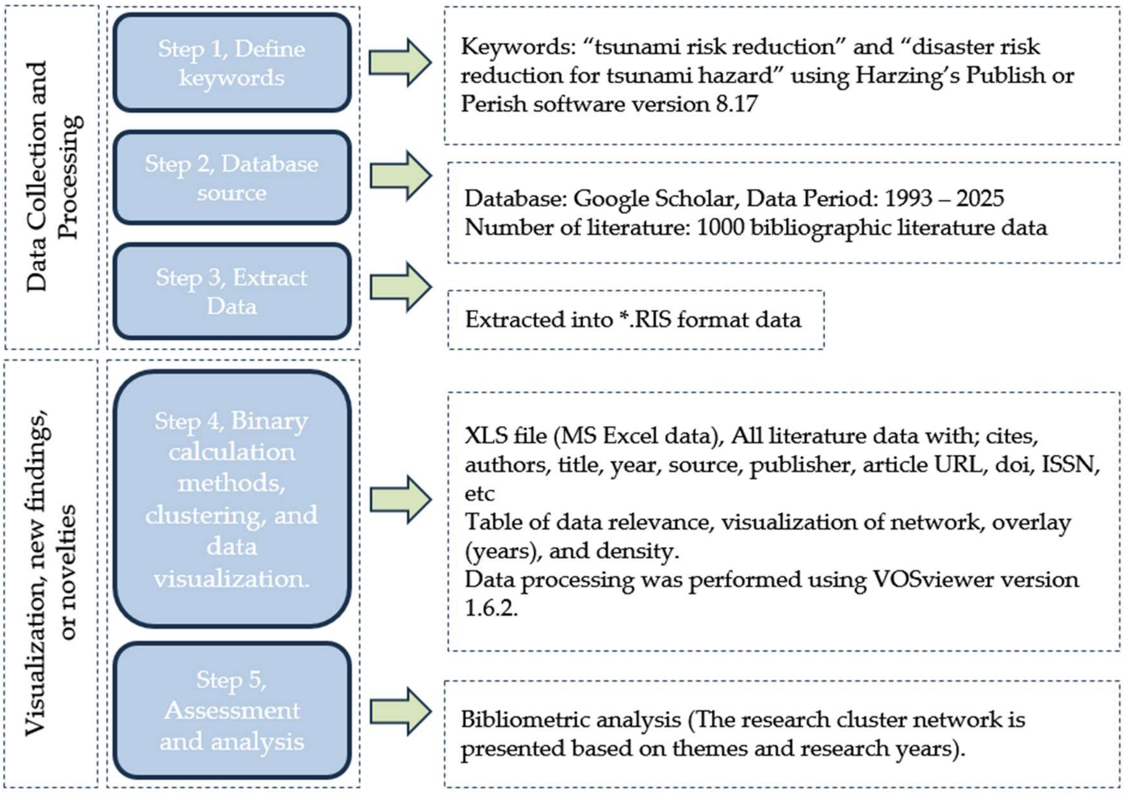


**Figure 1**. Steps to identify the state of the art in keywords tsunami risk reduction and disaster risk reduction for tsunami hazard based on a bibliometric study

Previous bibliometric studies have been conducted to examine research trends and growth patterns in disaster risk assessment, as well as to identify methodological nuances within this field (Vishnu et al., 2024). In recent years, however, research on tsunami has expanded to encompass more complex and localized tsunami sources, such as earthquake-triggered submarine landslides and other geomorphic processes (Setyonegoro et al., 2024a). These non-seismic sources pose considerable challenges for tsunami preparedness due to their localized nature and the difficulties associated with rapid detection (Usman et al., 2025). Consequently, contemporary tsunami research is confronted with the critical imperative of enhancing source identification capabilities to facilitate timely and effective disaster risk reduction.

To address this identified gap, it is essential to adopt advanced approaches that integrate innovations in data science and modeling techniques. This study hypothesizes that artificial intelligence (AI) can be leveraged to analyze large-scale data and develop a comprehensive database of tsunami scenarios, supported by previous studies (e.g., Wibowo et al., 2023) that demonstrate the integration of AI in tsunami databases and early warning systems. A precedent for this approach was established by Setyonegoro et al. (2024b), who developed tsunami modeling scenarios within the framework of risk reduction initiatives. Similarly, a bibliometric investigation conducted by Jain et al. (2021), encompassing fifteen years of tsunami-related research, underscored significant advancements in mitigation, response, and recovery strategies, with particular emphasis on early warning systems. Their study represents a pivotal contribution to the application of emerging technologies for tsunami risk reduction. Building upon this groundwork, the current research incorporates bibliometric, numerical, and spatial analyses, as previously demonstrated by Eck & Waltman (2010), to further enhance tsunami disaster preparedness and mitigation strategies.

Subsequently, the data underwent processing through binary analysis and clustering methods. The findings delineate a prioritized list of research areas deemed critical for future investigations, accompanied by a network of thematically and temporally categorized research clusters categorized by theme and year, related to disaster risk reduction.

The scientific article review data collected using Publish or Perish (PoP) software version 8.17 (Harzing, 2007) was extracted into *.ris format and subsequently processed using VOSviewer version 1.6.2, This study adopts the approach of Eck & Waltman (2010), who used VOSviewer for bibliometric mapping. The processed data was then used to perform a bibliometric analysis, reviewing all literature data including: citations, authors, titles, publication years, sources, publishers, article URLs, DOIs, ISSNs, relevance tables, and visualizations of the network, overlay (by year), and density (Donthu et al., 2021; Kumar et al., 2022). As a result, this data processing enables the identification of the state of the art of tsunami disaster risk reduction research in correlation with tsunami scenarios (Figure 1). The formula used in Publish or Perish (PoP) relates to citation metrics, particularly the h-index. The h-index is a metric that measures both the productivity and cumulative impact of a researcher's scientific work (Harzing, 2013). The basic formula is presented in equation 1:

$$N(c, tot) = ah^2 \tag{1}$$

Where N(c,tot) is the total number of citations, h is the h-index, and a is the proportionality constant. Publish or Perish also calculates other metrics such as the e-index which is the square root of the surplus of citations beyond the h-index. Other formulas used are as in equation 2 below:

$$h \sim mn \tag{2}$$

Where m is the ratio parameter, and n is the number of years since the first publication. The Publish or Perish software uses these formulas to calculate various citation metrics from data retrieved from online journal databases. This study adopts the bibliometric analysis approach using Publish or Perish as a citation data collection tool for sources such as Scopus and Google Scholar (Harzing, 2013). In other words, Publish or Perish applies these formulas to analyze and present citation data in an easy-to-understand format, helping researchers evaluate the impact and productivity of their scientific work. A number of scientific articles retrieved from Scopus and Google Scholar are further analyzed and visualized using Publish or Perish to examine citation distribution and perform keyword analysis (Harzing, 2013). This study also follows the approach of Harzing (Harzing, 2007; Harzing, 2013), who conducted a scientific analysis of a preliminary test of Google Scholar as a source of citation data using Publish or Perish.

## 3. RESULTS AND DISCUSSION

An analysis was conducted on the annual number of studies and their corresponding citation trends over time, based on review of scientific literature using the keywords *disaster risk reduction for tsunami hazard* and *tsunami risk reduction*. As illustrated in Figure 2, both keywords demonstrate an increasing number of publications beginning in 2005. A notable pattern is observed in Figure 2(a), where a significant spike in citations in 2005 is likely attributable to the impact of the 26 December 2004 Aceh tsunami event. Following this peak, research activity declined before experiencing a renewed increase around 2012, likely stimulated by the 2011 Tōhoku tsunami in Japan.

In contrast, Figure 2(b) indicates that the number of publications related to "tsunami risk reduction" reached its maximum in 2014. Both Figures 2(a) and 2(b) show a decline in research output starting in 2022; however, a notable divergence emerges. While citation counts in Figure 2(a) increase sharply during this period, those in Figure 2(b) decrease substantially. This contrasting pattern suggests the presence of a research gap, potentially reflecting a shift in research priorities or technological paradigms within tsunami-related studies. Moreover, the bibliometric patterns highlight differing conceptual emphases: Figure 2(a) underscores the prominence of the keyword "disaster risk," indicating a broader, multi-hazard perspective, whereas Figure 2(b) emphasizes "tsunami risk," reflecting a more hazard-specific focus. Further examination of Figure 2 reveals that articles associated with "disaster risk reduction" for tsunami hazards continued to receive substantial citation attention in 2023, despite a reduction in publication numbers. This trend indicates sustained scientific interest in tsunami-related disaster risks. Conversely, studies categorized under "tsunami risk reduction" experienced a pronounced decline in both publication volume and citation frequency as early as 2021 (Figure 2(b)). This reduction in scholarly output and visibility signals a critical research gap and raises concerns regarding the declining scientific emphasis on tsunami mitigation strategies. A key issue emerging from this trend is whether the observed decline reflects perceptions of limited effectiveness or incomplete implementation of tsunami early warning systems, potentially contributing to stagnation in research advancement. Despite decades of intensive scientific investigation, tsunami events continue to result in severe human losses worldwide. For instance, the 2018 Palu tsunami in Indonesia caused 4,340 fatalities and more than 10,000 injuries (Setyonegoro et al., 2024b), while the Anak Krakatau tsunami resulted in 426 deaths and thousands of injuries (Dogan et al., 2021; Borrero et al., 2020). More recently, the January 2022 tsunami triggered by the massive eruption of the Hunga Tonga–Hunga Ha'apai volcano (Gusman et al., 2022), an event potentially comparable in magnitude to the 1883 Krakatoa eruption (Terry et al., 2022), further underscores the persistent global vulnerability to tsunami hazards. These recurring disasters reveal unresolved deficiencies in disaster risk reduction frameworks and indicate that the stochastic and complex mechanisms

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governing tsunami generation remain insufficiently understood or inadequately integrated into current technological and policy-oriented approaches.

In light of these findings, this study emphasizes the importance of strengthening tsunami disaster risk reduction strategies. Specifically, it aims to contribute scientific evidence that can inform policy and decision-making processes, particularly with respect to zoning regulations and infrastructure development in tsunami-prone coastal regions. Consequently, further research is required to establish robust spatial classifications of tsunami hazard levels to support more effective and proactive tsunami disaster management.

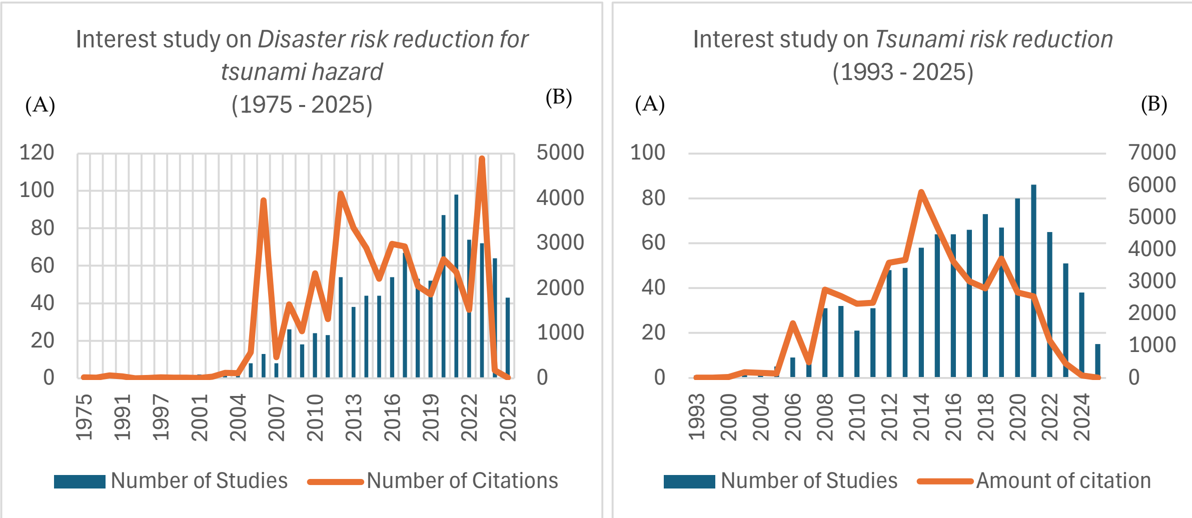


**Figure 2.** Graph of the number of interest studies (A) and the number of annual citations (B) using the keywords: (a) *Disaster risk reduction for tsunami hazard* for the period 1975-2024 (left), (b) *Tsunami risk reduction* for the period 1993-2025 (right)

In identifying the state of the art in tsunami disaster risk reduction research, the research gap identified in 2022 through the data analysis presented in Figures 2(a) and 2(b) emerges as a pivotal finding in formulating this research gap through bibliometric analysis illustrated in Figure 3. A systematic literature review employing the keyword *disaster risk reduction for tsunami hazard* (Figure 3) demonstrates that a considerable proportion of studies have concentrated on tsunami modeling within the context of tsunami risk reduction. Nevertheless, the majority of these modeling studies do not incorporate the concept of scenarios into their models. It is therefore critical to distinguish between tsunami models and tsunami scenarios. Tsunami models represent individual simulations of tsunami events, whereas tsunami modeling scenarios are composed of multiple tsunami models combined to represent a range of possible future events. To quantify temporal trends in tsunami DRR publications and citations was accomplished through the longitudinal analysis presented in Figure 2, which depicts variations between 1975 and 2025 and identifies post-event surges and a subsequent decline after 2021.

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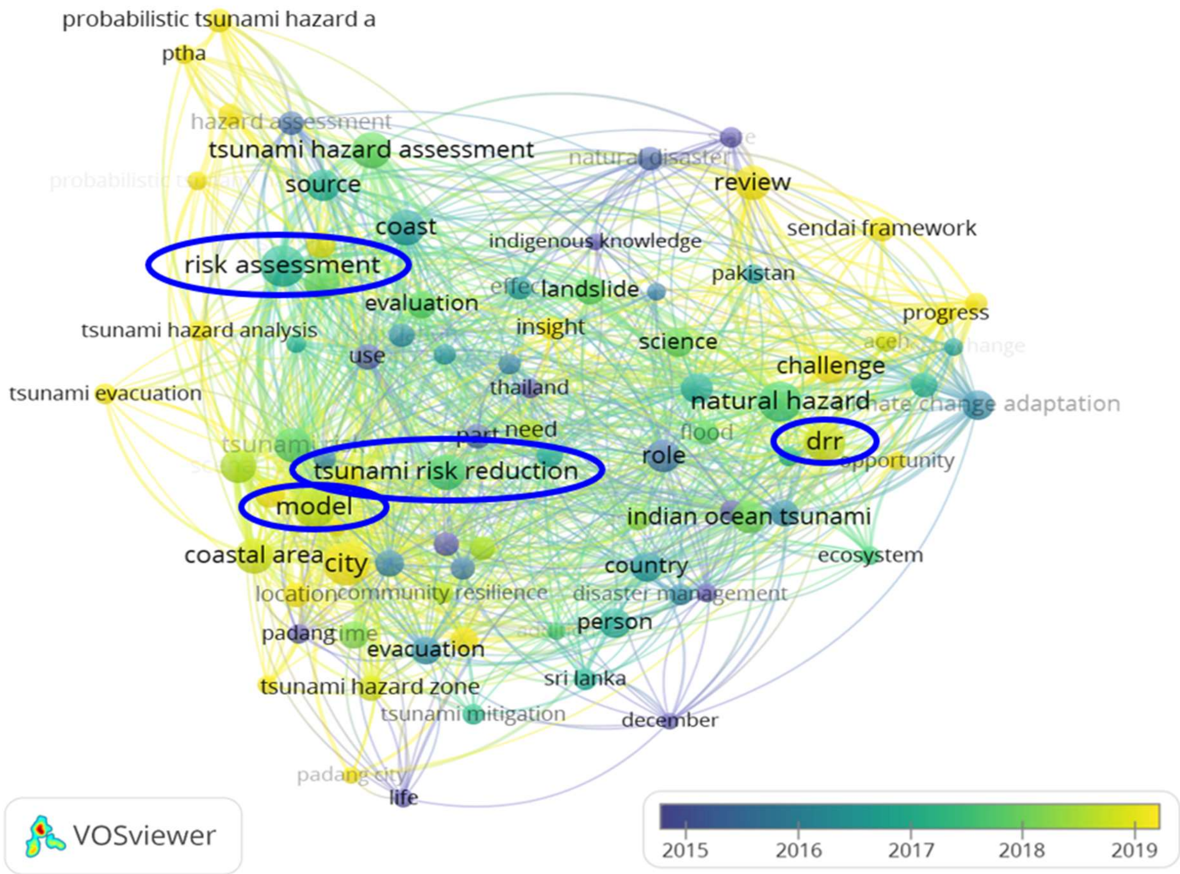


**Figure 3.** Literature review data processing using the keyword *disaster risk reduction for tsunami hazard* across the entire research period

When searching scientific articles using the keyword *tsunami risk reduction* without applying a time filter (Figure 4), only a limited number of studies focusing on tsunami scenarios were identified (denoted by thick blue highlights). These studies are relatively scarce and generally do not have a direct connection to disaster risk reduction strategies. The development of tsunami scenarios, derived from collections of tsunami models, is essential for hazard mapping, evacuation route planning, and tsunami event estimation, as also stated by Riancho et al. (2013). Moreover, such scenarios can provide a foundational basis for Decision Support Systems (DSS) employed in issuing tsunami warnings. Consequently, the development and application of tsunami scenarios represent an underexplored research domain within the broader context of tsunami disaster risk reduction.

It is important to emphasize that tsunami models and tsunami scenarios are fundamentally distinct; specifically, tsunami scenarios are constructed through the integration of multiple tsunami models. According to the bibliometric analysis presented in Figure 3, tsunami modeling scenarios are predominantly linked to research areas including risk assessment, tsunami risk reduction, and DRR, as evidenced by the prominent thick blue circles in the figure. Tsunami modeling scenarios serve as a valuable instrument for identifying zones susceptible to tsunami inundation and regions most vulnerable to tsunami wave impacts. Nonetheless, these studies typically rely on outputs from single-model simulations to depict potential tsunami hazards. In contrast, studies concentrated on tsunami scenarios incorporate multiple

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tsunami models to simulate a broader range of potential future events. In this study, a bibliometric analysis was performed utilizing the keyword *disaster risk reduction for tsunami hazard* (Figure 3). Although the selection of this keyword assists in delineating the scope of the investigation, it may produce less specific results and constrain the identification of precise research gaps in the field.

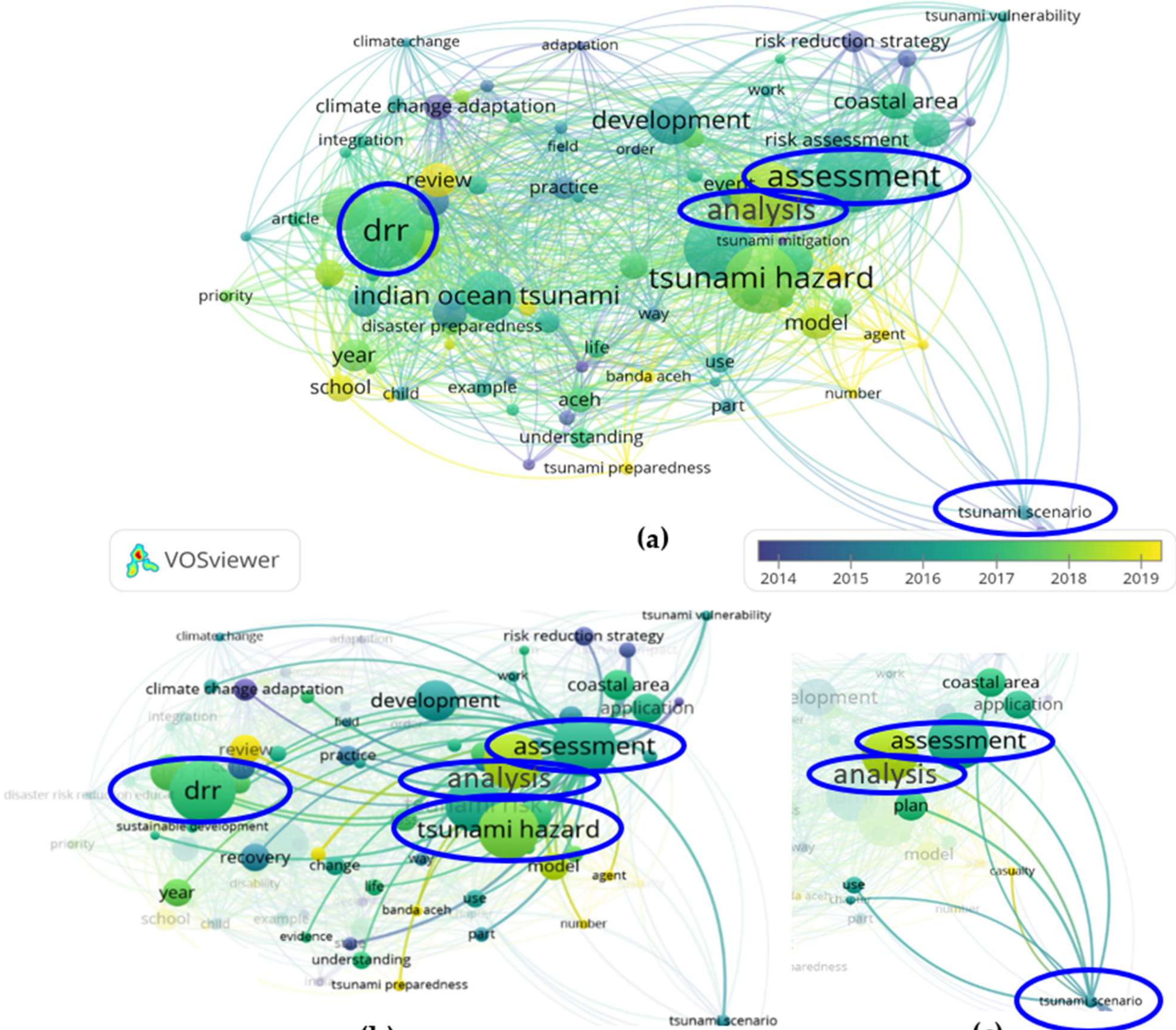


**Figure 4.** (a) Literature review data processing using the keyword *tsunami risk reduction* for the entire research period; (b) Disaster risk reduction research is connected to tsunami hazard, assessment, and tsunami scenario; (c) Tsunami scenario research is linked to assessment, coastal area, and analysis studies

Subsequently, the analysis focused on a more targeted search employing the keyword tsunami risk reduction, which uncovered studies pertinent to tsunami scenarios (Figure 4). The bibliometric literature review indicates that research on tsunami scenarios is relatively limited, as evidenced by the small-sized nodes and categorized as older studies (more than 8 years old, depicted in green), with connections predominantly associated with assessment and analysis topics (Figure 4(a)). Research on tsunami risk assessment and analysis serves as a bridge

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between tsunami scenario studies and disaster risk reduction initiatives (Figure 4(b)). Investigations into tsunami scenarios are essential for providing information and recommendations to support DRR. Furthermore, Tsunami scenario research demonstrates a close association with assessment and analysis, as illustrated in Figure 4c. To further focus the search for scientific articles using the keyword tsunami risk reduction, the temporal scope within Harzing's Publish or Perish software version 8.17 was confined to the years 2017–2025 (see Figure 5).

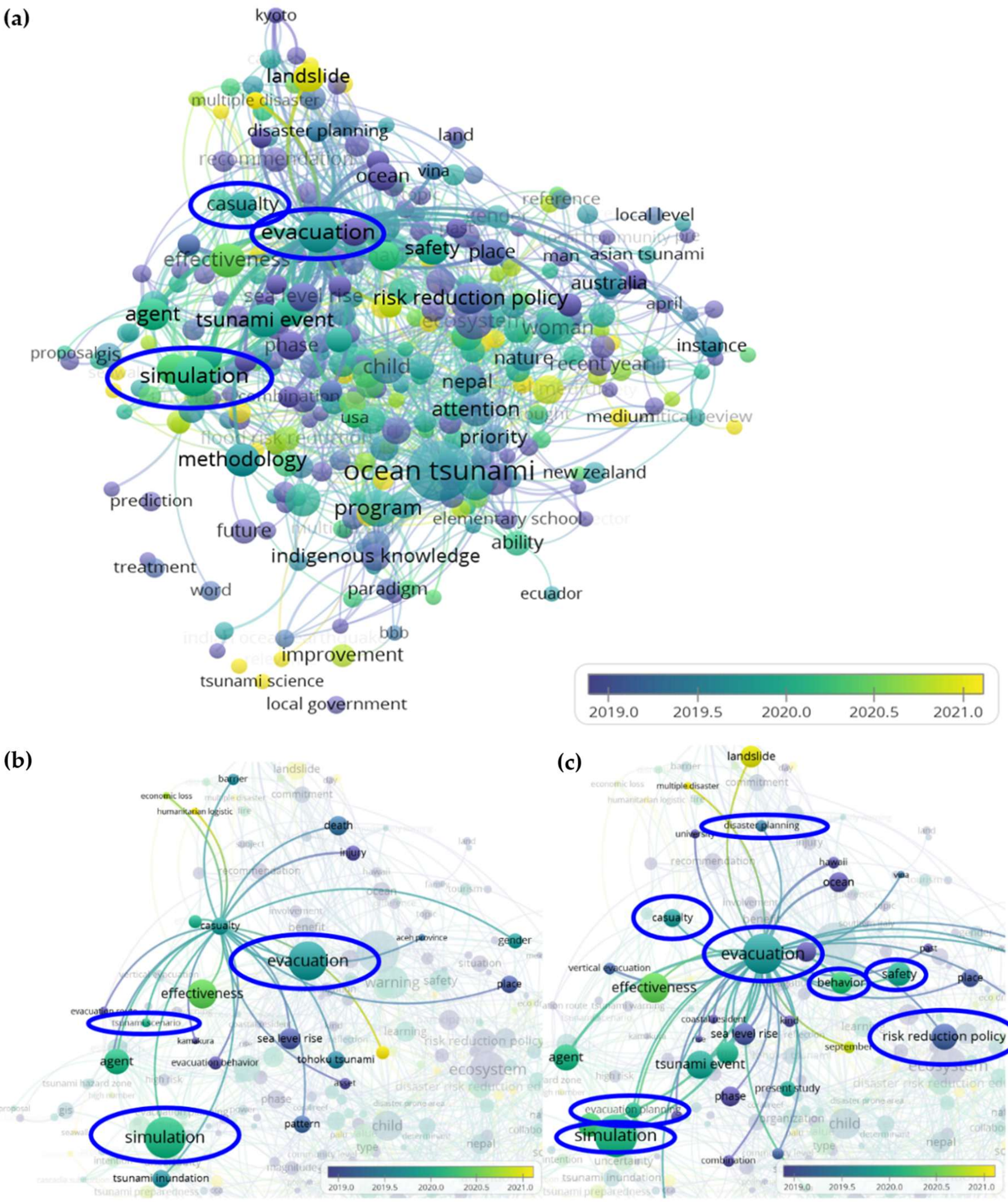


**Figure 5.** Literature review data processing using the keyword *tsunami risk reduction* limited to the period 2017–2025

This review endeavors to identify the most recent investigations concerning tsunami risk reduction up to early 2025. Nevertheless, the search outcomes reveal that the most current study pertaining to tsunami simulation identified in this dataset was conducted in 2021, although other studies published after 2021 exist but were not captured due to keyword and database limitations (Figure 5(a)). The bibliometric analysis presented in Figure 4(a) demonstrates that research on tsunami scenario is exclusively associated with casualties studies, which in turn are connected to evacuation-related research (Figure 5(b)). Consequently, evacuation studies serve as a bridge connecting tsunami simulation with risk reduction policy, disaster planning, evacuation planning, behavior, safety, coastal residents, landslides, and effectiveness. This clearly signifies that evacuation research constitutes a critical research gap capable of bridging tsunami simulation and risk reduction policy. To complement tsunami evacuation studies, further investigation into casualties is necessary. Moreover, Figure 5(c) illustrates that casualties studies maintain a direct connection solely with tsunami scenario research. The second objective to identify dominant research clusters and their interconnections was addressed through Figures 3–5, which reveal five major clusters and emphasize the simulation–evacuation–casualty nexus.

Based on the bibliometric analysis presented in Figure 5, the classification of study fields and the identification of research gaps in previous studies were derived. These gaps are further illustrated in a flowchart in Figure 6, underscoring the contemporary state of the art in tsunami disaster risk reduction research. Figure 6 demonstrates five fundamental concepts of DRR analytical components in tsunami mitigation research, which serve to assess the current state of tsunami disaster research: sources, simulation models, implementation, communication, and recovery.

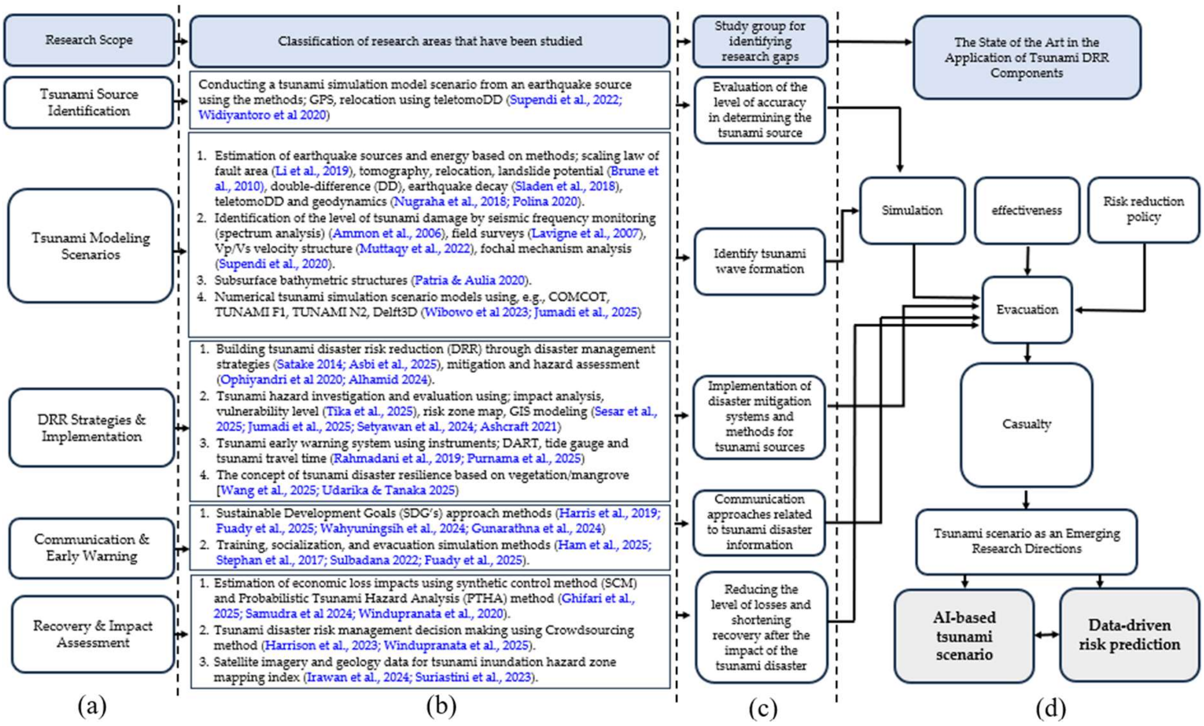


**Figure 6.** Conceptual framework of tsunami disaster risk reduction based on five core components

These five core elements ultimately converge within studies focused on simulation and evacuation. Both simulation and evacuation research share the overarching objective of mitigating casualties resulting from tsunami disasters. Consequently, to effectively diminish tsunami-related fatalities, it is imperative to explore evacuation studies from multiple perspectives, including scenario simulation models, risk reduction policies, disaster planning, evacuation planning, human behavior, safety, coastal communities, landslides, and overall effectiveness (as depicted in Figure 6). The bibliometric analysis process presented in Figure 6 further indicates that the development of efficacious evacuation strategies necessitates the integration of tsunami scenarios as an emerging technological approach aimed at disaster risk reduction.

The emerging technological paradigm involves enhancing tsunami scenarios by leveraging AI capabilities to learn from potential future simulations based on predictive tsunami models. Acquiring knowledge from historical tsunami source data and previous research is vital for understanding the magnitudes of tsunami disasters and their consequent impacts on affected areas. Therefore, this emerging technology framework is intrinsically connected to the identification of tsunami sources.

The scope of the literature review on tsunami disaster risk reduction, as illustrated in Figure 6(a), is delineated into five distinct categories: tsunami modeling scenarios, studies of tsunami sources, and indicators of environmental, social, and economic sustainability. A comprehensive review of relevant articles is conducted to explore current research within this scope (Figure 6(b)), followed by a classification of study groups aimed at identifying research gaps (Figure 6(c)). Several gaps are identified, thereby underscoring the contemporray advancement that highlight the current state of the art in tsunami disaster risk reduction studies (Figure 6(d)). The third objective to relate the clusters to the five DRR analytical components concepts was fulfilled conceptually in Figure 6, which integrates the bibliometric results into an applied framework linking technological, social, environmental, economic, and institutional aspects. The fourth objective to identify research gaps and future directions was partially achieved, as the study delineated the above nexus as a promising frontier but deferred quantitative validation and cross-database comparison to future work. Collectively, these analyses demonstrate that the present bibliometric mapping provides an organized empirical foundation for more comprehensive tsunami DRR investigations.

## 4. CONCLUSION

We identified a research gap based on the declining number of disaster risk reduction (DRR) studies in recent years. This decline, observed from 2021 to the present, may be attributed to the absence of a tsunami warning system that has proven fully effective in preventing casualties and minimizing material losses during tsunami events. Our research contributes to the advancement of tsunami DRR technologies through a literature review grounded in the five DRR analytical components concepts. The analysis of the literature reveals that studies on tsunami scenarios are limited and lack a clear connection to tsunami disaster risk reduction studies. We found that research on casualties and evacuation plays a crucial role in bridging the gap between tsunami scenario studies and DRR efforts. Therefore, research focused on casualties and evacuation should be recognized as the state-of-the-art in tsunami scenario studies for advancing tsunami disaster risk reduction. As an initial-stage bibliometric mapping, the present study entails inherent limitations that justify the partial attainment of its objectives. The analysis relied exclusively on Google Scholar data, which, while extensive, may include duplicate or non-peer-reviewed items and may omit regionally indexed sources. The VOSviewer parameters were standardized rather than optimized across databases, possibly influencing cluster sensitivity. Furthermore, the interpretation of the post-2021 decline in publications remains tentative pending validation against Scopus or Web of Science data. These constraints are characteristic of exploratory research intended to establish a first empirical baseline rather than definitive statistical conclusions. Future work should integrate multi-database searches, refine parameter settings, and complement quantitative mapping with qualitative content analysis and implementation case studies. Through these steps, the current exploratory findings can evolve into a comprehensive, practice-oriented tsunami DRR research framework.

## 5. RECOMMENDATIONS FOR IMPLEMENTING TSUNAMI SCENARIOS IN DRR STUDIES

Research on tsunami scenarios is increasingly recognized as a critical component of disaster risk reduction (DRR). These scenarios can be systematically developed through rigorous research and implemented using automated systems. The integration of advanced technologies in tsunami scenario research enables the creation of dynamic, continuously updated systems informed by new scientific findings. Tsunami scenario studies explore a range of possibilities, such as different source types, field evidence, survey data, and evolving tsunami modeling scenarios through the adoption of advanced simulation tools and methodologies. The outcomes of such research contribute directly to the enhancement of automated tsunami warning systems. Consequently, tsunami scenarios serve as essential intelligence databases within decision support systems (DSS), playing a key role in guiding evacuation decisions when potential tsunami threats are detected. The ultimate goal is to minimize casualties.

In this context, studies focusing on evacuation and casualty estimation are considered priorities and represent the state-of-the-art in tsunami scenario development for DRR. The implementation of tsunami scenarios within warning systems typically follows five core concepts that reflect current technological advancements in tsunami risk reduction research: source, tsunami modeling scenarios, implementation, communication, and recovery. These interconnected components converge in evacuation planning, all with the shared objective of reducing human loss. Research aimed at minimizing casualties is most effective when supported by robust tsunami scenario studies, particularly those enhanced by AI that can learn from simulations of potential future tsunamis. Tsunami modeling scenarios depend fundamentally on precise source identification. Therefore, reliable source identification is critical to the effectiveness of tsunami scenarios as a foundational element of emerging technologies in tsunami DRR. In applying emerging technology for tsunami DRR purposes, several countries vulnerable to tsunami impacts have implemented tsunami scenarios in their warning systems.

According to Evangelio et al. (2024), a persistent gap remains between knowledge of potential risks, understanding of the nature and value of early warning systems (EWS), environmental education, and community participation, particularly in relation to their effective implementation. Therefore, the focus is on how DRR can be implemented and made known to residents in tsunami-prone areas. For example, Indonesia has initiated the Indonesia Tsunami Early Warning System (InaTEWS), which uses stochastic tsunami scenarios and numerical models for hazard forecasting (Purnama et al., 2025). Second, Japan operates the Japan Meteorological Agency (JMA), which uses real-time tsunami modeling based on precomputed scenarios and seismic data (Suppasri et al., 2016). Third, Chile's National Seismological Center utilizes COMCOT and MOST models for tsunami forecasting based on earthquake scenarios (Titov et al., 2005). Fourth, Turkey has the KOERI Tsunami Warning System, which applies scenario-based modeling for tsunamis in the Eastern Mediterranean (Necmioğlu et al., 2021). Lastly, Australia's Joint Australian Tsunami Warning Center uses scenario and event-based modeling for alert generation (Allen & Greenslade, 2008).

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