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Bibliometric Analysis of Earthquake Technologies in Physics Education for Education for Sustainable Development

Hanan Zaki Alhusni[1], Binar Kurnia Prahani[1], Titin Sunarti[1], Madlazim[1], Salma Hasna Hamiyda[2]

[1]Universitas Negeri Surabaya, Surabaya, Indonesia
[2]Al-Azhar University, Cairo, Egypt

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ABSTRACT

Objective: *This study aims to explore the intersection of earthquake technologies, physics education, and Education for Sustainable Development (ESD) through bibliometric analysis. The objectives include mapping the existing literature, identifying key trends, gaps, and influential publications, and highlighting the contributions of top authors and geographical hotspots in this interdisciplinary field.* ***Method:*** *A comprehensive bibliometric analysis was conducted using publications from 2021 to 2025, sourced from databases like Scopus. Keywords related to earthquake technologies, physics education, and ESD were employed to gather articles. The study utilized tools like VOSviewer and Bibliometrix for citation analysis, co-authorship patterns, and thematic evolution, allowing for the identification of key research trends and collaborations.* ***Results:*** *The analysis reveals a growing body of research, particularly in Asia, with a focus on specific technologies like virtual reality simulations and mobile applications for disaster preparedness. However, the study also highlights a fragmentation in the field, with limited holistic approaches that bridge these technologies and educational frameworks. The most influential authors include Deng X and Xu D, with significant contributions from countries like China, Indonesia, and Japan.* ***Novelty:*** *This study provides a unique bibliometric overview of the intersection between earthquake technologies, physics education, and ESD, a topic not extensively covered in recent literature. It offers new insights into the state of research, identifies key gaps, and lays the foundation for future research in integrating technological innovations into disaster preparedness and education for sustainable development.*

INTRODUCTION

The integration of physics education and sustainable development has become an essential component in preparing future generations to respond effectively to natural disasters (UNESCO, 2017; Langa et al., 2019). The hope is that advancements in educational technologies can facilitate this integration, specifically in the context of earthquake preparedness (Wang et al., 2018; Müller et al., 2020; O'Neill et al., 2021; Lawrence & Smith, 2022). By leveraging technologies such as virtual reality (VR) simulations and mobile applications for earthquake response, students can not only grasp the fundamental physics behind seismic activities but also develop the skills necessary for sustainable disaster risk management (González & Lee, 2017; Zhang & Li, 2019; Tanaka et al., 2020; Liu et al., 2021; Rojas et al., 2021; Zulhilmi et al., 2025; Tan & Tan, 2025; Masocha & Ntim, 2025). This approach is seen as a pivotal tool for promoting Education for Sustainable Development (ESD), with the potential to reshape how both physics and disaster risk reduction are taught globally (Shaw & Oikawa, 2014; Cabello et al., 2021; Parajuli, 2020; Oikawa & Shaw, 2014; Kurths et al., 2025)..

Recent studies have shown that educational technologies are being increasingly incorporated into disaster risk reduction (DRR) education, yet a significant gap remains in their application specifically within physics education for earthquake preparedness

(Bucchi, 2019; González & Lee, 2017). For instance, various authors have examined the role of interactive simulations and VR in improving learning outcomes in science and physics education (Bucchi, 2019; Hamilton et al., 2020). In these studies, students' ability to understand complex phenomena like earthquakes and their physical implications has been found to improve significantly when such technologies are used. Furthermore, the role of ESD in promoting disaster resilience is well established, with numerous studies acknowledging its impact in areas such as climate change, disaster risk, and environmental education (Jiang et al., 2021; Smith & Adams, 2022). However, there is a lack of cohesive research that specifically addresses the intersection of earthquake technologies, physics education, and sustainable development.

Despite the evident potential of educational technologies in disaster preparedness and physics education, there remains a considerable gap in the literature regarding their integration within the context of ESD, particularly for earthquake education (Rodríguez et al., 2019; Paredes et al., 2020). While there is a body of research on disaster risk reduction and technology-enhanced learning, few studies specifically address how these innovations are applied within physics education for sustainable development (Moore, 2018; Harris et al., 2019; Young et al., 2020; Nixon & Lee, 2021). Moreover, the existing literature tends to focus on either technological tools in education or sustainability education but rarely combines them to address both physics learning and earthquake preparedness (Harris et al., 2019; O'Neill et al., 2021). This gap limits the understanding of how educational technologies can be optimized to teach not only the scientific principles of earthquakes but also their real-world implications for sustainable development.

The lack of a comprehensive bibliometric study focusing on earthquake technologies in physics education for sustainable development creates significant challenges for researchers and educators (Rojas et al., 2021; Liu & Chen, 2022; Morante-Carballo et al., 2023; Misbah et al., 2024; Fayda-Kinik, 2025). Without a systematic mapping of the existing research, it becomes difficult to identify key trends, gaps, and opportunities in this field. Additionally, the absence of such research hinders the development of curricula that can effectively integrate earthquake science, physics principles, and sustainability concepts (Chavez et al., 2020; Rodríguez et al., 2020). Furthermore, the absence of a consolidated view of relevant studies makes it difficult for educators to adopt best practices or for policymakers to create informed educational strategies.

Several studies have attempted to address aspects of this issue. For example, Tanaka et al. (2020) explored the use of VR simulations to teach earthquake preparedness, finding that immersive environments significantly improved students' understanding of seismic events and their ability to respond in emergencies. Similarly, the work by Müller et al. (2018) on mobile applications for disaster education demonstrated that such tools could effectively engage students in learning about natural disasters, including earthquakes. However, while these studies demonstrate the potential of technology in education, they often fail to bridge the gap between earthquake education, physics, and sustainability in a cohesive framework (Moore, 2018; Schwarz & Weber, 2020). The existing research is fragmented, and there is a notable absence of studies that integrate all three areas—earthquake science, physics education, and ESD—within a single, comprehensive analysis (Sato et al., 2019; Schwarz & Weber, 2020).

This article aims to address this gap by conducting a bibliometric analysis that maps the existing literature on earthquake technologies in physics education within the

framework of sustainable development. By examining the trends in publications, identifying the most productive authors and institutions, and highlighting key thematic areas, this research will provide valuable insights into the current state of research at the intersection of these fields. This study is the first to systematically analyze the global body of work in this area, offering a unique perspective on how technology is shaping earthquake education within the context of ESD.

The primary goal of this article is to conduct a thorough bibliometric analysis of the literature on earthquake technologies in physics education for sustainable development. Specifically, the study will: (a) identify key trends in publications over the last five years; (b) explore the thematic evolution of research at the intersection of earthquake science, physics education, and ESD; (c) pinpoint leading authors, institutions, and journals in the field; and (d) recommend future research directions for enhancing the integration of technology in physics education for disaster preparedness. This article will serve as a foundational reference for educators, researchers, and policymakers seeking to integrate sustainable development principles into physics education through the use of earthquake-related technologies.

The novelty of this study lies in its comprehensive bibliometric approach to an underexplored area in educational research. While previous studies have addressed the role of technology in education or in disaster preparedness, none have systematically analyzed the intersection of earthquake technologies, physics education, and ESD. By filling this gap, this article contributes a unique perspective on how technology can support the development of sustainable disaster preparedness skills in students. It also provides a roadmap for future research that could help shape the next generation of physics curricula with a focus on real-world applications and sustainability.

RESEARCH METHOD

This study employs a bibliometric analysis to explore the intersection of earthquake technologies, physics education, and Education for Sustainable Development (ESD), with the aim of mapping existing literature, identifying trends, gaps, and future research directions (Bucchi, 2019; Liu et al., 2021). The analysis is based on scholarly publications, including articles, books, and conference proceedings, with no human subjects involved. Data were collected primarily from the Scopus database using a comprehensive search strategy that combined keywords such as "earthquake technologies," "seismic simulation," "earthquake preparedness," "physics education," "science education," "education for sustainable development," "ESD," "disaster risk reduction," "disaster preparedness," "disaster education," "technology-enhanced learning," "digital learning," and "educational technology." The search was restricted to publications from 2021 to 2025, in English, and limited to peer-reviewed articles and conference papers to ensure a focused, up-to-date, and relevant dataset for analysis.

A total of 3,186 articles were initially retrieved from the database search. After applying the publication year filter (2021–2025), 1,268 articles were excluded, leaving 1,918 articles. Further exclusion based on document type, by removing non-article (AR) and non-conference paper (CP) documents, eliminated 1,068 articles, resulting in 850 articles. Articles not published in English were then excluded, removing 101 articles, leaving a total of 749 articles. Finally, the dataset was limited to specific subject areas as follows: Earth and Planetary Sciences (344 articles), Social Sciences (305 articles), Environmental Science (258 articles), Computer Science (163 articles), Energy (83

articles), Decision Sciences (63 articles), Physics and Astronomy (50 articles), Multidisciplinary (24 articles), Materials Science (23 articles), and Arts and Humanities (23 articles).

Articles were included if they focused on integrating earthquake technologies or seismic simulations in physics education, addressed disaster preparedness in education, and were peer-reviewed. Articles without educational relevance, that were not peer-reviewed, or lacked sufficient data were excluded. The selected articles were categorized by themes, methodology, and findings, with data on titles, authors, keywords, journals, years, citations, and abstracts. The bibliometric analysis used VOSviewer to visualize relationships and Bibliometrix for citation, co-authorship, and thematic evolution analyses. These analyses included citation counts, collaboration patterns, and keyword co-occurrences to identify trends such as virtual reality simulations and mobile apps for disaster education.

Figure 1. Flowchart diagram

To further understand the evolution of the field, thematic evolution was analyzed, mapping how key topics and technologies have developed over time. This analysis helped clarify shifts in research focus and highlighted areas requiring further investigation. Network visualizations were created using VOSviewer to display the relationships between authors, institutions, and research topics. These visualizations provided an overview of the intellectual structure of the field, identifying influential works and key research clusters. Finally, the results from these analyses were interpreted to identify trends in research output, emerging technologies, and the integration of Education for Sustainable Development (ESD) in physics education. The strengths and weaknesses of the research landscape were also discussed, pointing out gaps in the current literature and suggesting directions for future research.

RESULTS AND DISCUSSION

Results

The main information about the dataset indicates that the bibliometric analysis covers the timespan from 2021 to 2025, including a total of 748 documents sourced from 289 journals, books, and other academic outlets. Among these, 42 documents were single-authored, while the total number of authors involved reached 2,706, with an average of 4.1 co-authors per document, reflecting a high level of collaboration. The dataset contains 4,598 author keywords and 3,107 Keywords Plus, with international co-

authorship accounting for 23.93% of the publications. Document types include 553 articles and 195 conference papers, with an average document age of 1.75 years and an average of 5.905 citations per document. The annual growth rate of publications in this field is 8.2%, highlighting a steady increase in scholarly output.

Figure 2. Main information

The annual scientific production of articles related to earthquake technologies, physics education, and Education for Sustainable Development (ESD) shows a fluctuating but generally increasing trend from 2021 to 2025. In 2021, 135 articles were published, followed by 108 articles in 2022. The number slightly increased to 122 in 2023, then rose more significantly to 198 in 2024, and slightly decreased to 185 in 2025, indicating growing scholarly interest in this interdisciplinary field over the five-year period.

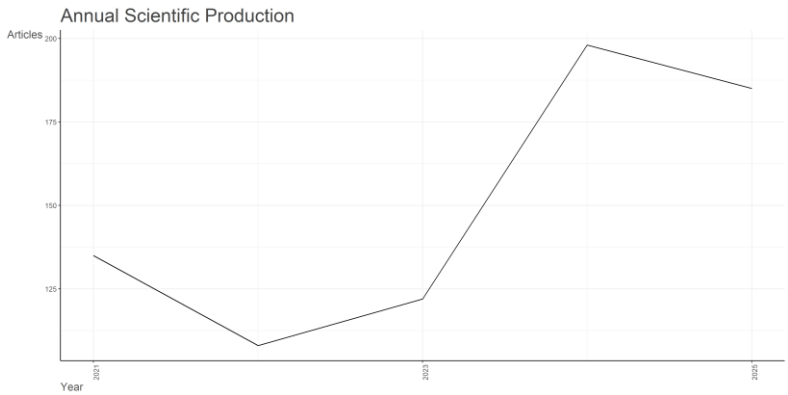

Figure 3. Annual scientific production

The analysis of average citations per year shows that publications from 2021 received the highest mean total citations per article (13.01) with an average of 2.60 citations per year over five citable years. Articles published in 2022 had a slightly lower mean total citation of 12.56, averaging 3.14 citations per year across four citable years. In 2023, the mean total citations per article dropped to 6.20, with 2.07 citations per year over three citable years. For 2024, the mean total citations further decreased to 2.30, corresponding to 1.15 citations per year over two citable years, while 2025 publications showed the lowest impact with a mean total citation of 0.50 and 0.50 citations per year for the single citable year. This trend highlights a gradual decline in citation accumulation for more recent publications.

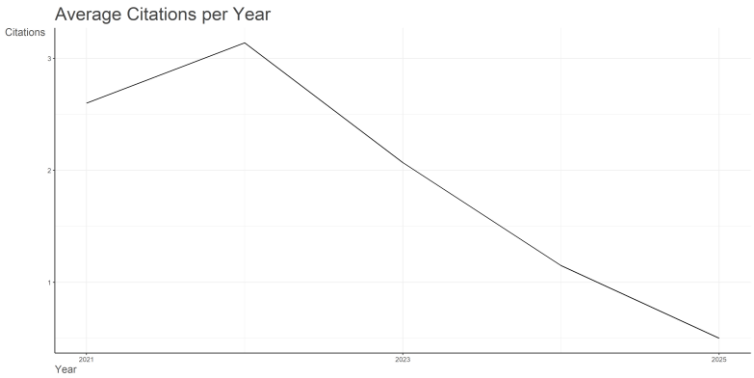

Figure 4. Average citations per year

The analysis of the most relevant sources indicates that the International Journal of Disaster Risk Reduction is the leading publication, contributing 90 articles to the dataset. This is followed by IOP Conference Series: Earth and Environmental Science with 46 articles, and Natural Hazards with 34 articles. Other notable sources include Sustainability (Switzerland) with 27 articles, E3S Web of Conferences with 22 articles, and AIP Conference Proceedings with 11 articles. Smaller contributions come from Progress in Disaster Science (9 articles), Journal of Physics: Conference Series (8 articles), International Journal of Disaster Risk Science (7 articles), and International Journal of Environmental Research and Public Health (7 articles), highlighting the journals and conferences most frequently publishing research at the intersection of earthquake technologies, physics education, and sustainable development.

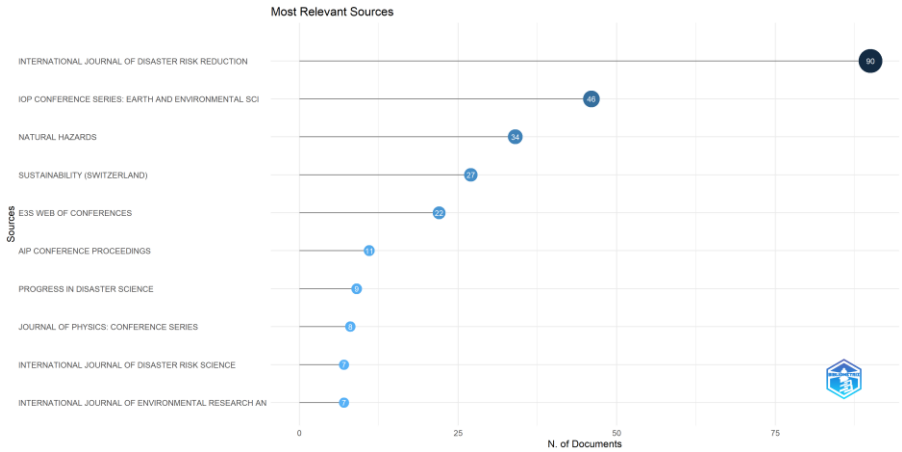

Figure 5. Most relevant sources

Based on Bradford's Law, the core sources of publications in the field of earthquake technologies, physics education, and Education for Sustainable Development (ESD) were identified by ranking journals according to the number of articles published. Zone 1, representing the most productive and influential journals, includes the International Journal of Disaster Risk Reduction (90 articles), IOP Conference Series: Earth and Environmental Science (46 articles), Natural Hazards (34 articles), Sustainability (Switzerland) (27 articles), E3S Web of Conferences (22 articles), and AIP Conference Proceedings (11 articles). Zone 2, consisting of less frequently publishing but still relevant journals, includes Progress in Disaster Science (9 articles), Journal of Physics:

Conference Series (8 articles), International Journal of Disaster Risk Science (7 articles), and International Journal of Environmental Research and Public Health (7 articles). This distribution highlights that a relatively small number of journals account for the majority of publications in the field, illustrating the concentration of scholarly output in core sources.

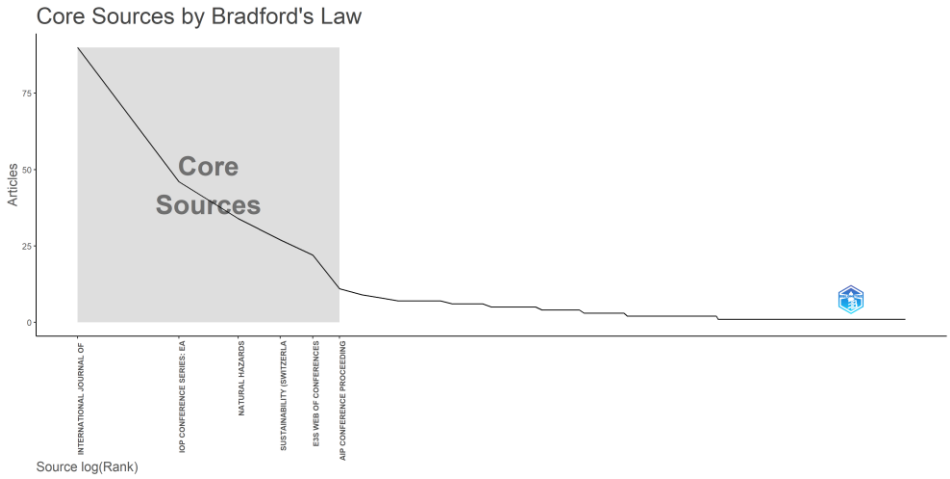

Figure 6. Core sources by Bradford's law

The analysis of sources' local impact shows that the International Journal of Disaster Risk Reduction leads with the highest h-index (18), g-index (31), and total citations (1,202) from 90 publications, indicating strong influence and productivity. Natural Hazards and Sustainability (Switzerland) follow with moderate impact, while journals like IOP Conference Series: Earth and Environmental Science and Bulletin of Earthquake Engineering have lower indices and citation counts, reflecting smaller contributions. Overall, a few core journals dominate both productivity and scholarly influence, whereas others play a more limited role in the field.

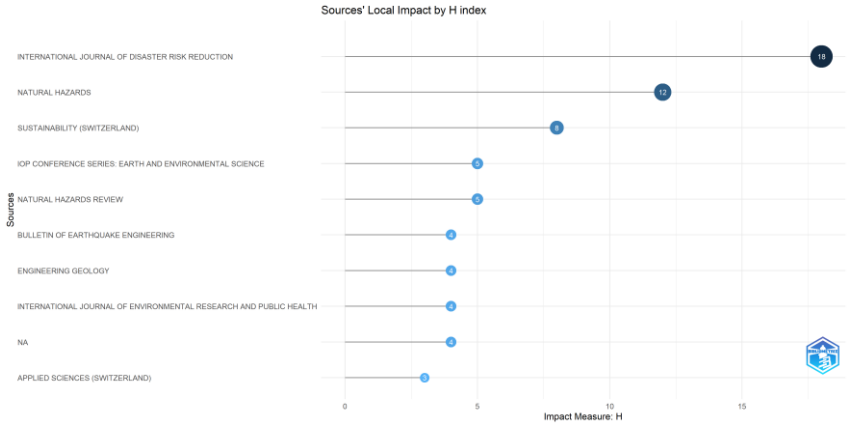

Figure 7. Sources' local impact

The analysis of sources' production over time shows a consistent growth in the number of publications across all core journals from 2021 to 2025. The International Journal of Disaster Risk Reduction demonstrates the most significant increase, rising from 28 articles in 2021 to 90 in 2025, indicating its growing dominance in the field. Other journals, including IOP Conference Series: Earth and Environmental Science, Natural Hazards, Sustainability (Switzerland), and E3S Web of Conferences, also show steady increases, reflecting an expanding research interest and a progressive

accumulation of scholarly output in earthquake technologies, physics education, and Education for Sustainable Development (ESD). This trend highlights both the increasing attention to the topic and the strengthening role of these core sources in disseminating research.

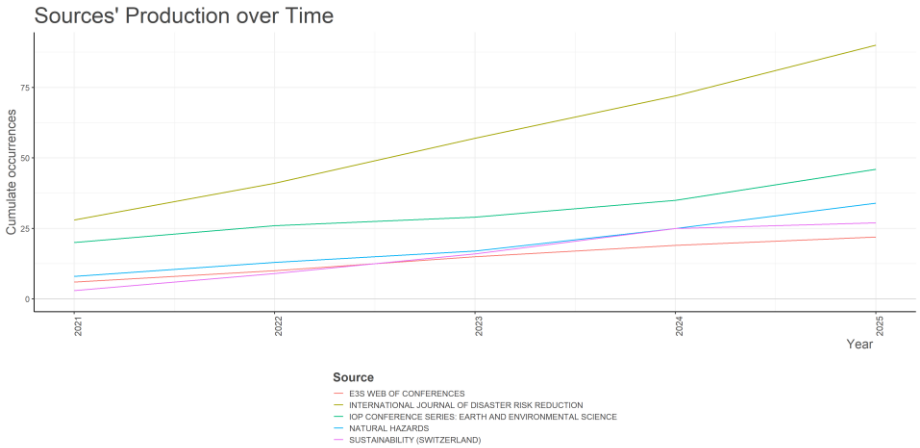

Figure 8. Sources' production over time

The analysis of the most relevant authors in the field indicates that Deng X and Xu D are the most productive, each contributing six publications with an average of 1.42 citations per document. Other notable contributors include Lee C (5 publications, 2.00 citations per document), Liu Y (5 publications, 1.23 citations per document), Oktari RS (5 publications, 1.26 citations per document), Quagliarini E (5 publications, 1.32 citations per document), Wang J (5 publications, 1.42 citations per document), and Windupranata W (5 publications, 1.04 citations per document). Authors with four publications, such as Alvarez PP (1.07 citations per document) and Bernardini G (1.12 citations per document), also show significant contributions. This distribution highlights a relatively small group of authors driving research output and influencing the development of knowledge in earthquake technologies, physics education, and Education for Sustainable Development (ESD).

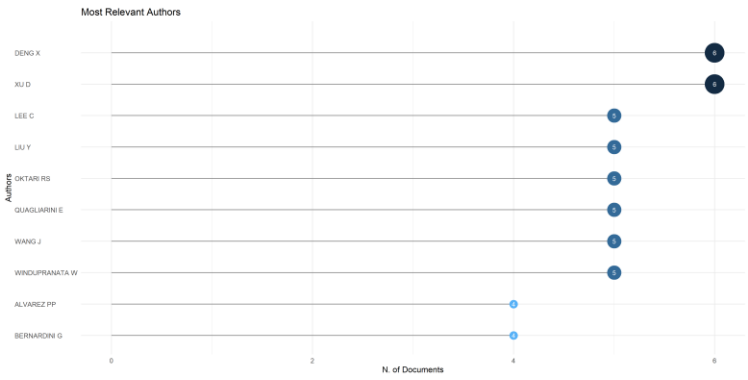

Figure 9. Most relevant authors

The analysis of authors' production over time shows varying publication patterns and citation impacts. Deng X demonstrates the highest productivity and influence, with three publications in 2021 accumulating 116 citations, followed by two publications in 2022 with 32 citations, and one publication in 2023 with 14 citations. Bernardini G

published three articles in 2021 with 34 citations and one in 2023 with 24 citations, indicating a consistent contribution. Lee C contributed one article each in 2021, 2023, and 2024, with citations ranging from 4 to 17 per year. Alvarez PP published two articles in both 2022 and 2024, with moderate citation counts of 5 and 3, respectively. Overall, this data highlights that a few key authors, particularly Deng X and Bernardini G, have maintained high research output and citation impact over the examined period, driving scholarly influence in earthquake technologies, physics education, and ESD.

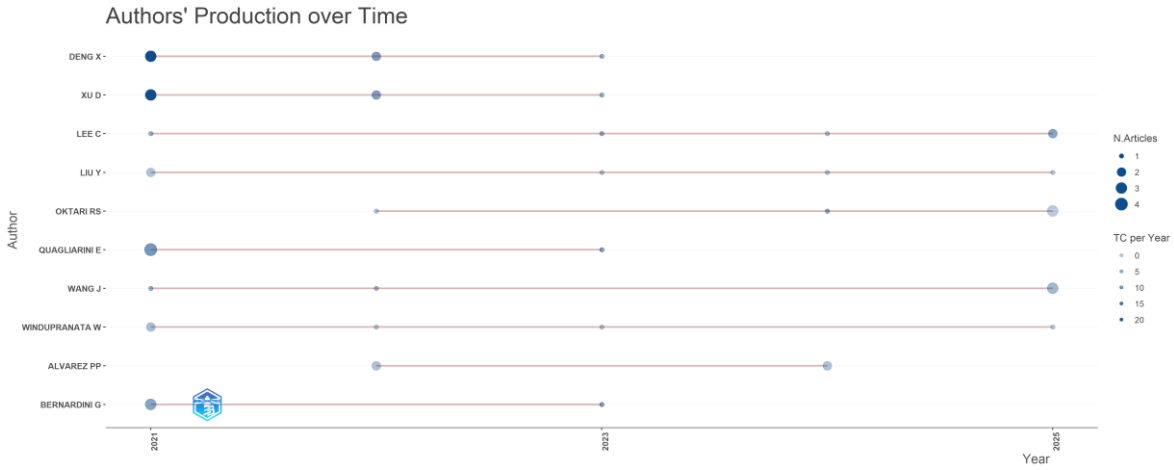

Figure 10. Authors' production over time

The author productivity analysis based on Lotka's Law shows that most authors in the field are single-contribution authors. Out of the total, 2,444 authors (90.3%) wrote only one document, which is higher than the theoretical proportion of 67.1%. Fewer authors produced multiple papers: 193 authors (7.1%) wrote two documents, 48 authors (1.8%) wrote three, and only a very small number contributed four to six papers. This indicates a typical Lotka's Law pattern, where a small core of authors is highly productive, while the majority of authors contribute minimally to the literature on earthquake technologies, physics education, and Education for Sustainable Development (ESD).

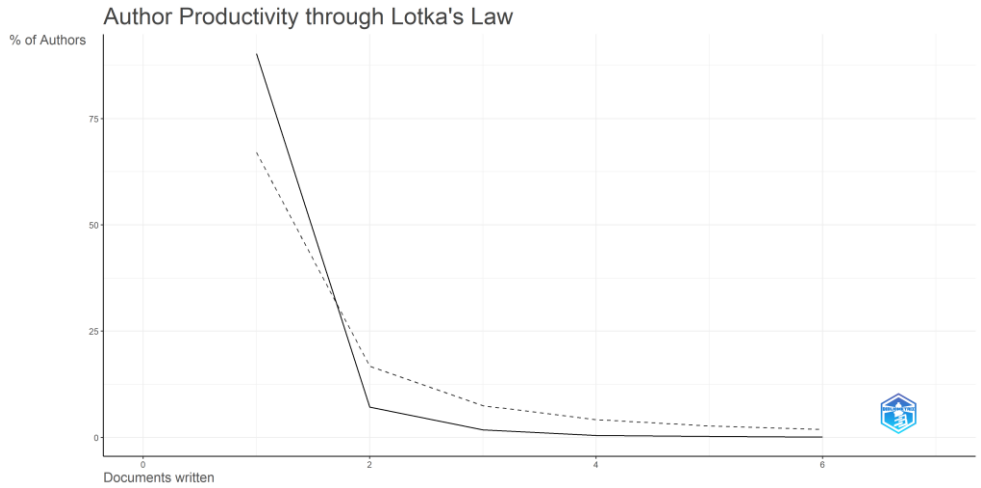

Figure 11. Author productivity through Lotka's law

The analysis of authors' local impact indicates that DENG X and XU D are the most influential authors in the field, each with an h-index of 6, g-index of 6, and a total of 162 citations from 6 publications since 2021. Other notable contributors include Lee C And Quagliarini E, both with an h-index of 4, g-index of 5, and total citations of 49 and 70, respectively. Authors such as Bernardini G, Bostrom A, Han Z, Li R, Liu Y, And Mcbride Sk have moderate impact, with h-indices of 3, g-indices ranging from 3 to 4, and total citations between 12 and 109. This distribution shows that while a few authors dominate the citation landscape, most authors contribute moderately to the development of research on earthquake technologies, physics education, and Education for Sustainable Development (ESD).

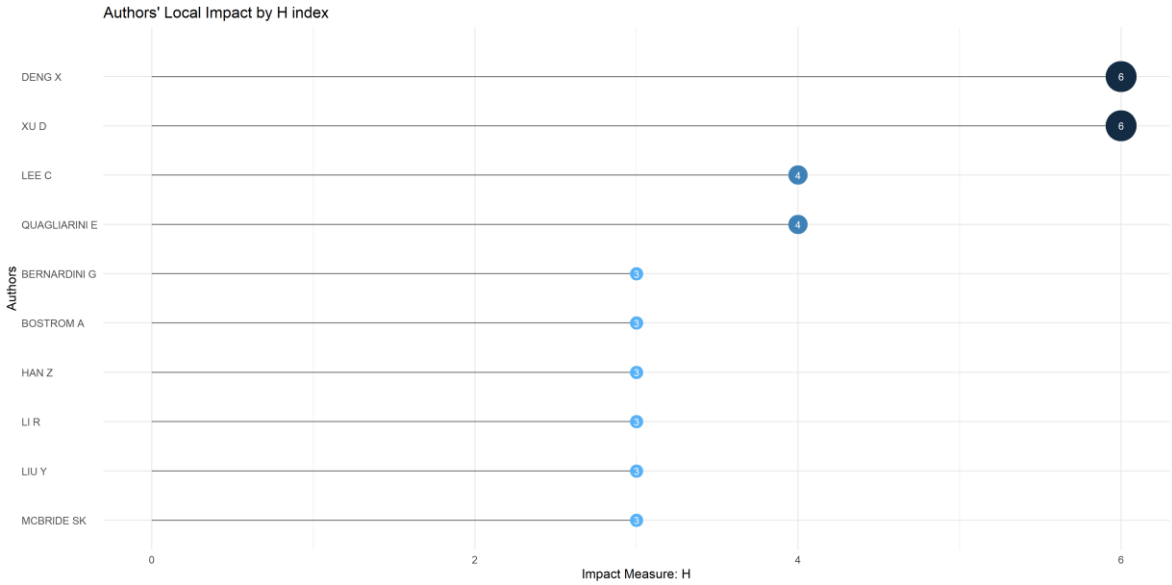

Figure 12. Authors' local impact

The analysis of the most relevant affiliations reveals that Universitas Syiah Kuala leads in contributions with 50 publications, followed by Institut Teknologi Bandung with 21 and Sichuan Agricultural University with 19. Other significant institutions include Universitas Gadjah Mada (17), Tohoku University (15), Universidad Nacional Autónoma de México (15), and Universitas Andalas (15). Additional contributors are listed as Not Reported (13), Universitas Negeri Yogyakarta (11), and Universitas Pendidikan Indonesia (11). This distribution highlights that a mix of Indonesian and international universities are actively contributing to research on earthquake technologies, physics education, and Education for Sustainable Development (ESD).

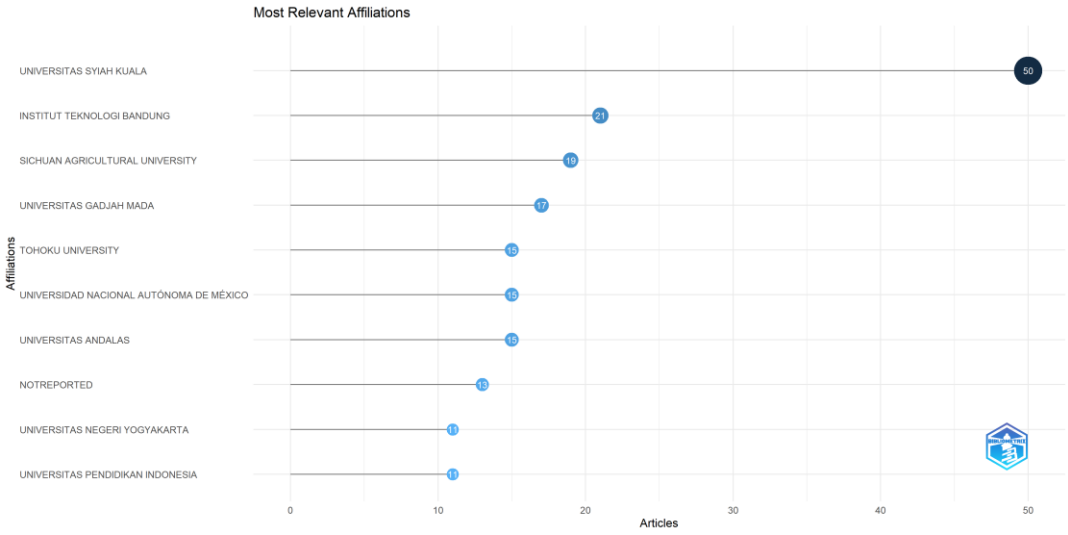

Figure 13. Most relevant affiliations

The analysis of affiliations' production over time shows a steady increase in publications from leading institutions. Institut Teknologi Bandung grew from 5 articles in 2021 to 21 articles in 2025, demonstrating consistent annual growth. Similarly, Sichuan Agricultural University increased its output from 9 articles in 2021 to 19 articles in 2025, reflecting sustained research activity over the five-year period. This trend indicates both institutions' expanding contributions to the fields of earthquake technologies, physics education, and Education for Sustainable Development (ESD).

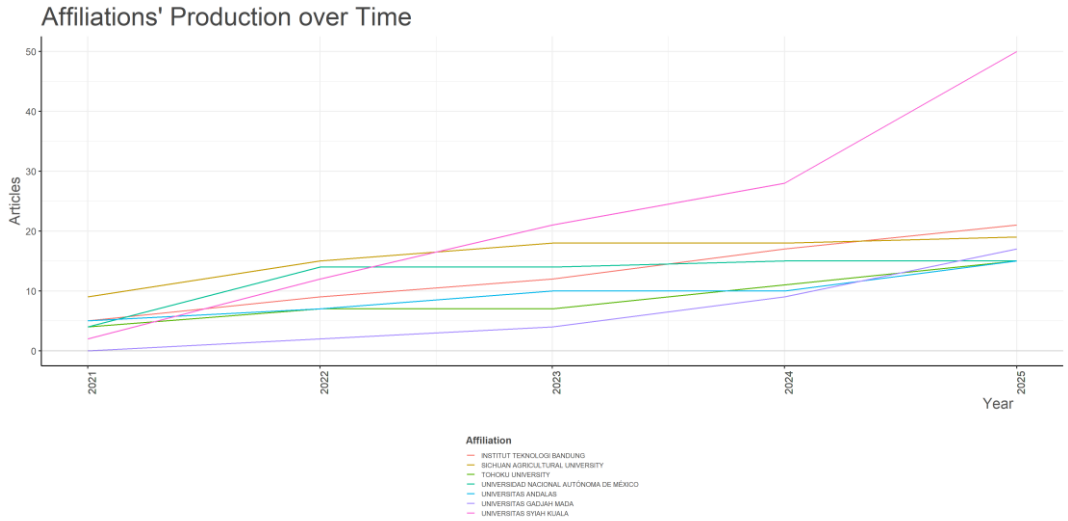

Figure 14. Affiliations' production over time

The analysis of corresponding authors' countries shows that Indonesia leads with 157 articles (21.0%), followed by China with 94 articles (12.6%) and India with 73 articles (9.8%). Japan contributed 54 articles (7.2%), while Turkey, Italy, and the USA each produced between 4.5% and 5.6% of the total output. Notably, Australia and Canada show high proportions of international collaborations, with 88.2% and 60.0% of their publications co-authored internationally, respectively, highlighting their strong global research partnerships despite a smaller overall output.

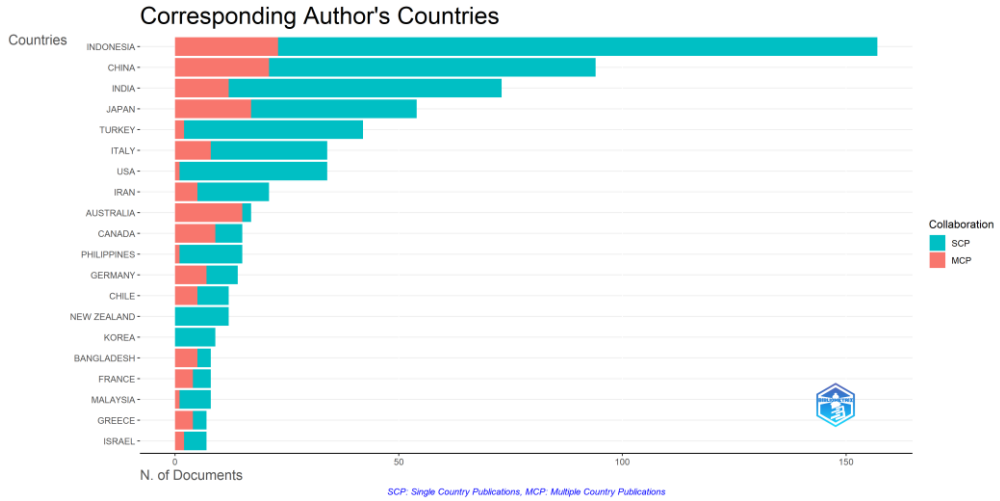

Figure 15. Corresponding author's countries

The analysis of countries' scientific production indicates that Indonesia is the most productive with 328 publications, followed by China with 267 and India with 172. Japan produced 161 articles, while the USA contributed 155. Turkey, Italy, and Iran have moderate outputs with 124, 70, and 57 publications respectively, and the UK and Germany contributed 53 and 46 publications. This distribution highlights the leading role of Asian countries, particularly Indonesia, China, and India, in research on earthquake technologies, physics education, and sustainable development.

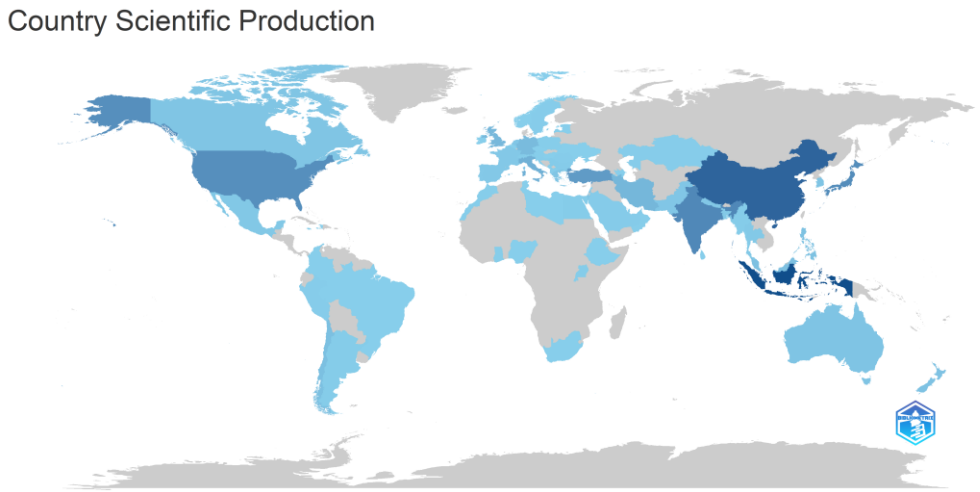

Figure 16. Countries' scientific production

The production of scientific articles over time shows a steady increase for both China and India in the field of earthquake technologies, physics education, and sustainable development. China's output grew from 60 articles in 2021 to 267 articles in 2025, demonstrating consistent annual growth. Similarly, India's publications increased from 24 in 2021 to 172 in 2025, indicating a significant rise in research activity over the five-year period. This trend highlights the expanding contribution of these countries to the global scientific literature in this domain.

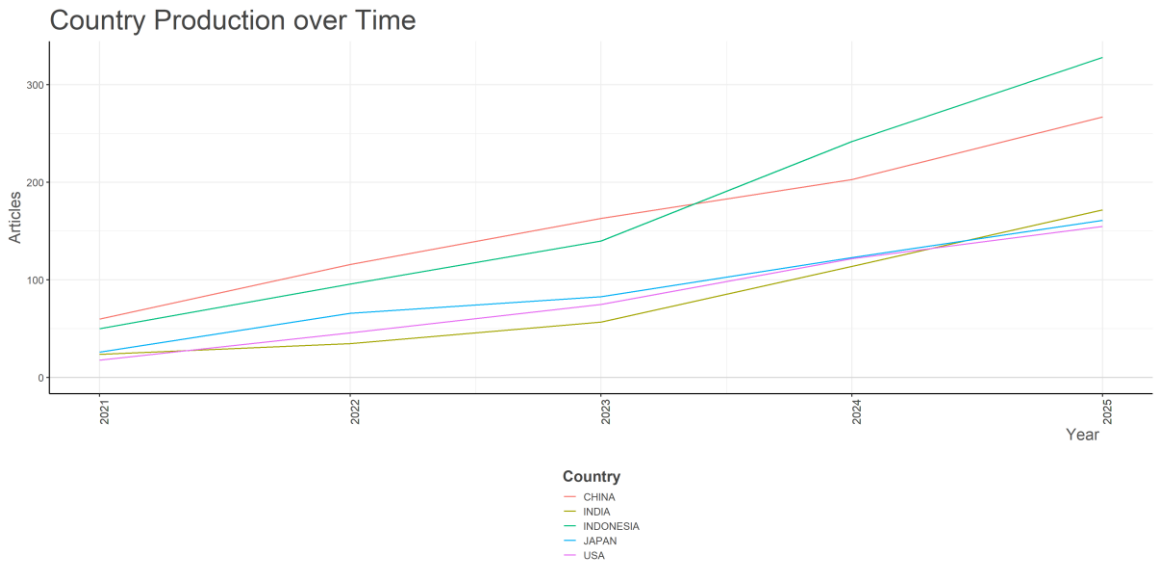

Figure 17. Countries' production over time

The analysis of most cited countries shows that China leads with 962 citations (10.2% of total), followed by India with 438 citations (6.0%) and Indonesia with 429 citations (2.7%). Other highly cited countries include Italy (390; 11.5%), Japan (251; 4.6%), Iran (248; 11.8%), and the USA (216; 6.4%). Turkey, Australia, and Canada also contributed significantly, with 169 (4.0%), 153 (9.0%), and 152 (10.1%) citations, respectively. This indicates that China, India, and Indonesia are major contributors in terms of publication volume, while Italy, Iran, Australia, and Canada have higher citation impact relative to their output.

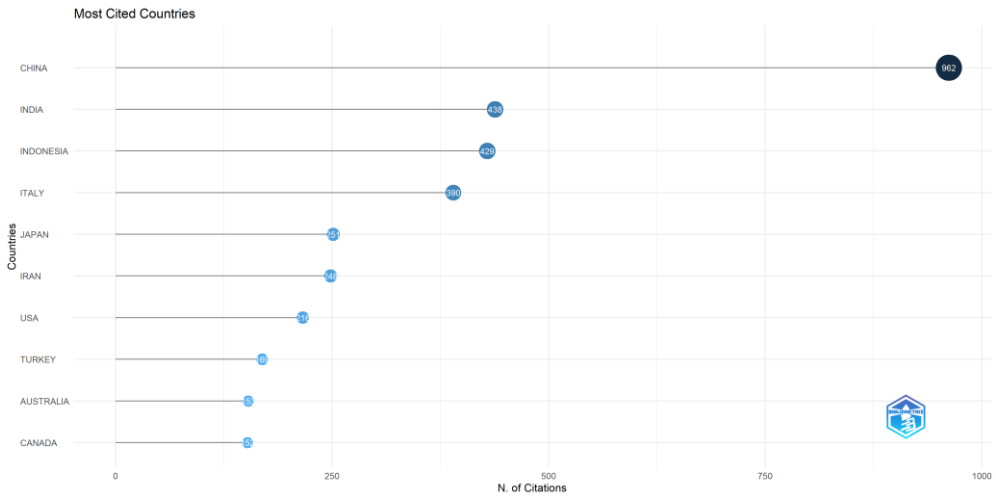

Figure 18. Most cited countries

The most globally cited documents in the field highlight influential research on earthquake technologies, physics education, and disaster risk reduction. The top-cited paper is by Cui P (2022, Engineering Geology) with 201 total citations and 50.25 citations per year, followed by Khan A (2022, Journal of Field Robotics) with 152 citations and 38.0 per year. Other highly cited works include Freddi F (2021, International Journal of Disaster Risk Reduction, 148 citations), Ong AKS (2021, 91 citations), and Behl S (2021, 84 citations). These documents demonstrate strong global

recognition, with normalized citation values indicating consistent impact across publication years, emphasizing key contributions to both technological integration and disaster risk education.

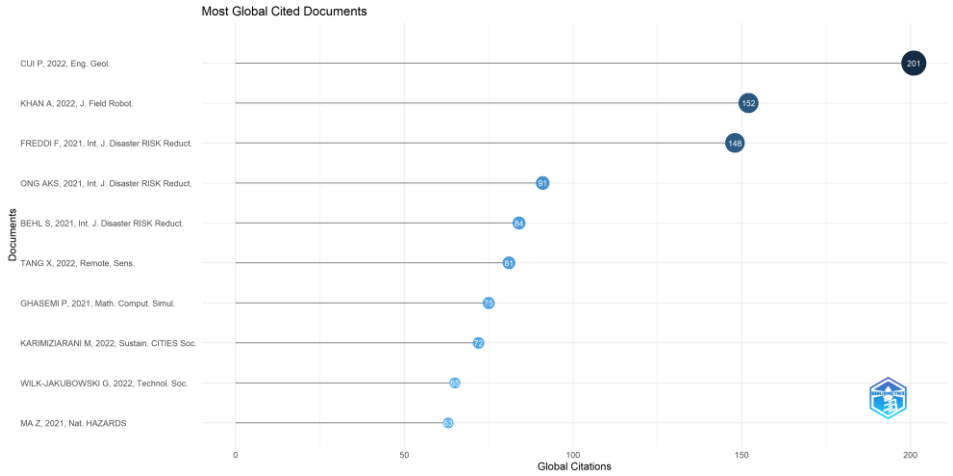

Figure 19. Most global cited documents

The most frequent words in the analyzed literature reflect the core focus areas of the field. Terms such as disaster management (197 occurrences), earthquakes (153), earthquake (151), disasters (134), disaster prevention (124), and disaster preparedness (109) dominate, alongside risk assessment (99) and earthquake event (62). This indicates a strong emphasis on understanding, preventing, and preparing for earthquake-related disasters within educational and technological contexts.

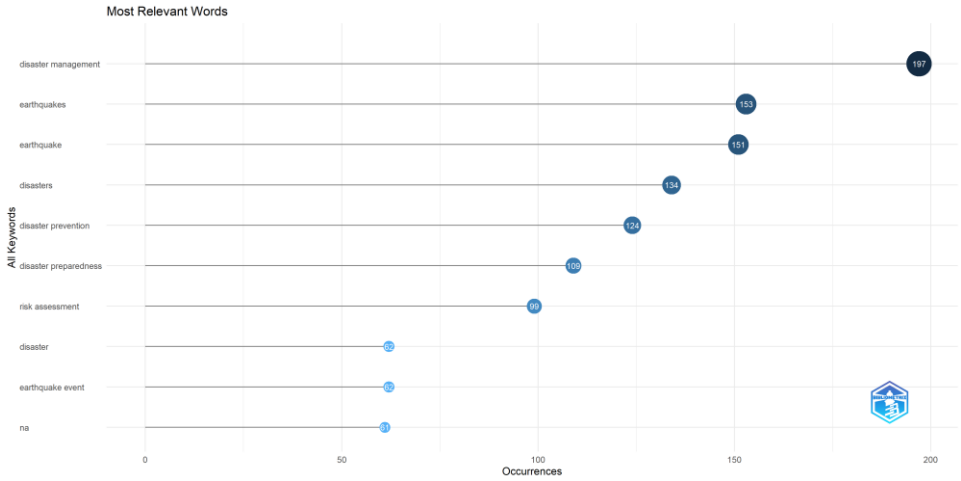

Figure 20. Most frequent words

The WordCloud visualization highlights the most frequently occurring terms in the literature, emphasizing key themes such as disaster management (197), earthquakes (153), earthquake (151), disasters (134), disaster prevention (124), and disaster preparedness (109). Other notable terms include risk assessment (99) and earthquake event (62), reflecting the central focus on earthquake-related disaster education, preparedness, and mitigation strategies.

Figure 21. Wordcloud

The TreeMap visualization organizes the most frequent terms by their relative importance, showing that disaster management (197) dominates the field, followed by earthquakes (153), earthquake (151), and disasters (134). Other significant terms include disaster prevention (124), disaster preparedness (109), risk assessment (99), and earthquake event (62), highlighting the central focus on disaster risk reduction, preparedness, and earthquake-related education in the analyzed literature.

Figure 22. Treemap

The analysis of words' frequency over time shows a consistent growth in the use of key terms related to disaster and earthquake research from 2021 to 2025. Disaster management increased from 30 occurrences in 2021 to 197 in 2025, while earthquakes and earthquake rose from 28 and 33 to 153 and 151, respectively. Similarly, terms like disasters, disaster prevention, and disaster preparedness also grew steadily, reflecting an increasing scholarly focus on disaster risk reduction, preparedness, and earthquake-

related education throughout the period. This trend indicates a growing research emphasis on practical and educational aspects of disaster management.

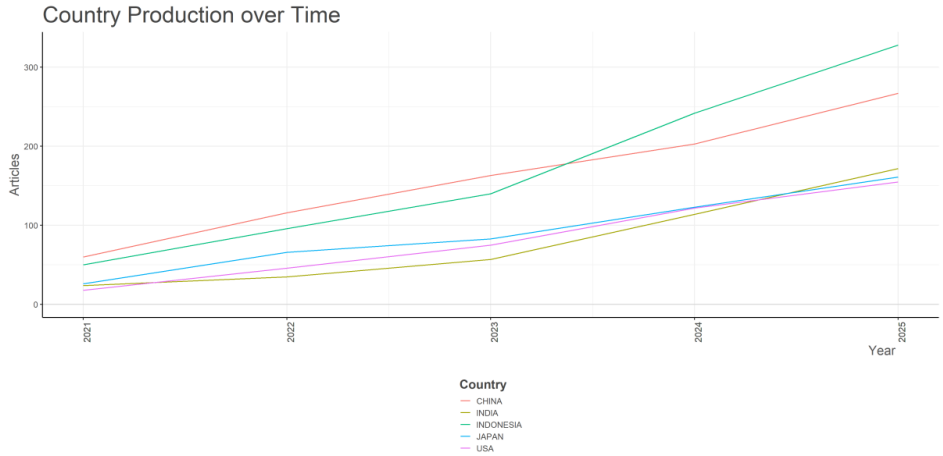

Figure 23. Words' frequency over time

The trend topics analysis highlights the evolving focus of research from 2021 to 2025. Early studies (2021–2022) emphasized regional events and surveys, such as Italy, Great East Japan Earthquakes, and general surveys. Over time, the focus shifted to broader disaster-related themes, with terms like China, disaster response, and students emerging between 2021 and 2024. By 2022–2025, research increasingly concentrated on core topics such as earthquakes, earthquake, disasters, and disaster management, reflecting a growing emphasis on practical disaster preparedness, management strategies, and education in earthquake-related contexts.

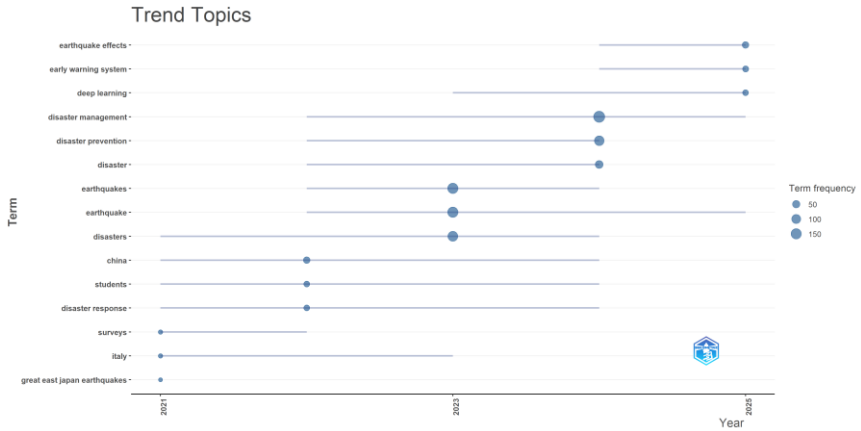

Figure 24. Trend topics

The co-occurrence network analysis of disaster-related literature reveals three main thematic clusters. The first cluster focuses on earthquake events, risk assessment, and disaster management, with central terms such as disaster management, earthquakes, earthquake, and disasters serving as key connectors to related concepts like risk perception, vulnerability, resilience, and tsunami. The second cluster emphasizes prevention, prediction, and technological approaches, highlighting terms like disaster prevention, seismic response, risk management, and earthquake prediction, which reflect research on forecasting, early warning systems, and the use of machine and deep learning for disaster mitigation. The third cluster centers on human and educational

aspects, including disaster, human, education, female, and male, indicating studies on preparedness, planning, and the social dimensions of disaster risk management. Overall, the network illustrates that while earthquake hazards and management dominate the field, prevention strategies, technological innovation, and human-centered approaches are closely interconnected, providing a comprehensive view of disaster research.

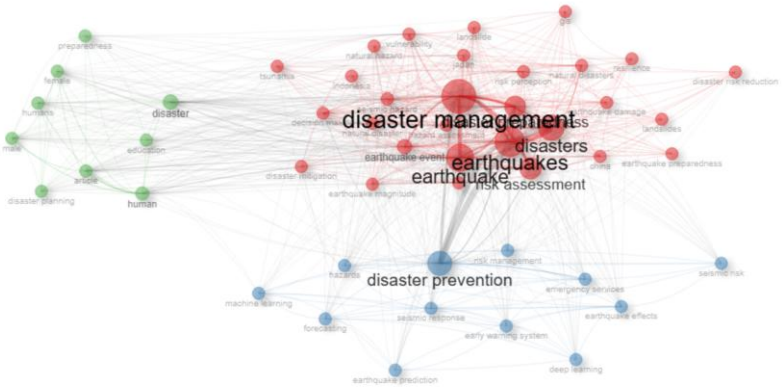

Figure 25. Co-occurrence network

The thematic cluster analysis identifies three main research clusters in the field. The largest and most central cluster, disaster management, has the highest frequency (2,373 occurrences) and a strong Callon centrality (12.703), indicating it is both a dominant and highly connected theme. The disaster prevention cluster, with 1,276 occurrences, shows the highest Callon density (32.951), reflecting a well-developed and internally cohesive topic. The human cluster, although smaller with 302 occurrences, has the highest density (36.396) relative to its centrality, suggesting a specialized but tightly focused area of research within the broader field. Overall, disaster management dominates the landscape, while disaster prevention and human-related studies represent more developed and niche thematic areas.

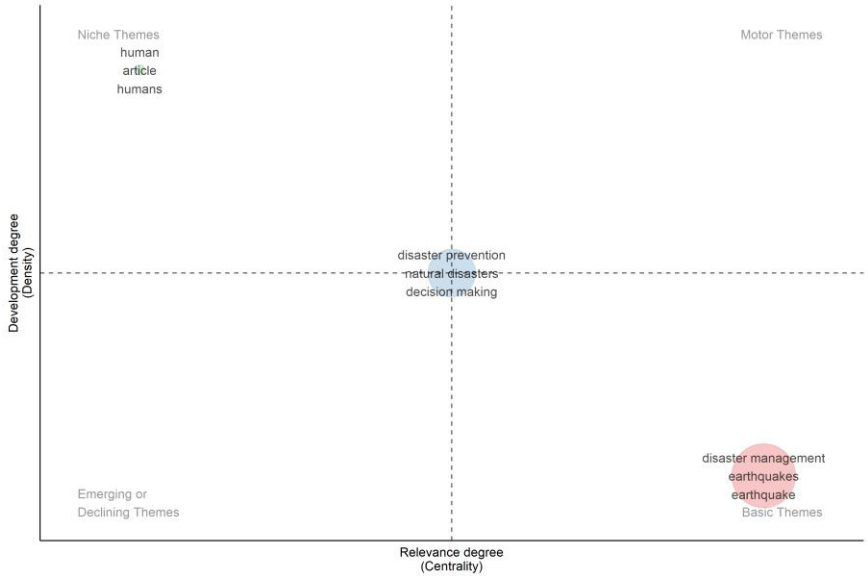

Figure 26. Thematic map

The thematic map analysis highlights that the central focus of the field is on disaster management, with key terms including disaster management, earthquakes, earthquake, disasters, disaster preparedness, risk assessment, and earthquake event. These terms form a tightly connected cluster, reflecting the dominance of research on hazard mitigation, preparedness, and risk evaluation. High betweenness centrality values, particularly for disaster preparedness and earthquake event, indicate their role as crucial bridging concepts linking other topics within the cluster. Overall, the thematic map confirms that disaster management and earthquake-related studies are the core themes driving scholarly attention in this research area.

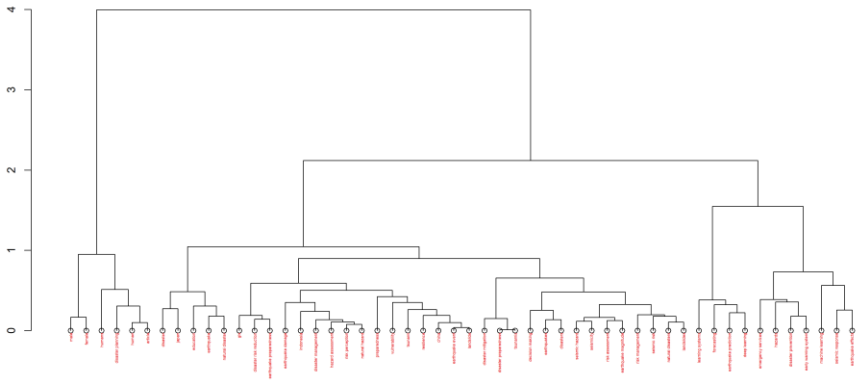

Figure 27. Topic dendrogram factorial analysis

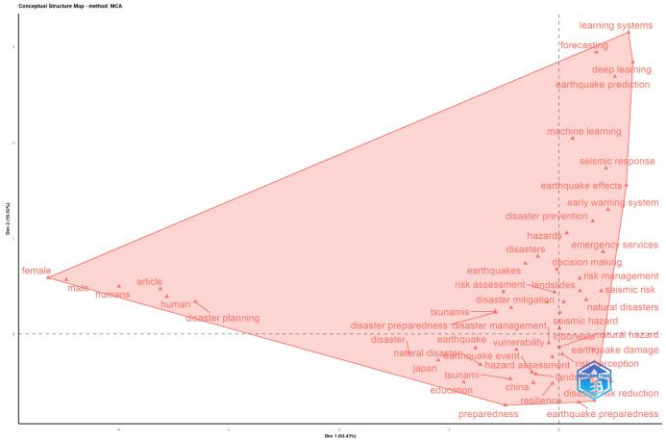

Figure 28. Word map factorial analysis

The factorial analysis of keywords related to disaster management shows that all terms belong to a single cluster, with two main dimensions explaining the patterns of association among them. The first dimension differentiates words based on social versus technical focus; terms with large negative values, such as male, female, humans, and disaster planning, are related to human or social aspects of disasters, whereas words near zero or positive, such as risk management, machine learning, and forecasting, are associated with technology, mitigation, and risk analysis. The second dimension highlights the distinction between technical/scientific activities and disaster impacts or planning; words with high positive values, such as learning systems, deep learning, and earthquake prediction, relate to prediction and technology, while words

with lower values, such as preparedness, disaster risk reduction, and earthquake preparedness, pertain to readiness and risk reduction. Overall, this analysis illustrates a spectrum of research spanning human and planning aspects of disasters to data- and technology-driven approaches, with all terms interconnected under the broader theme of disaster management.

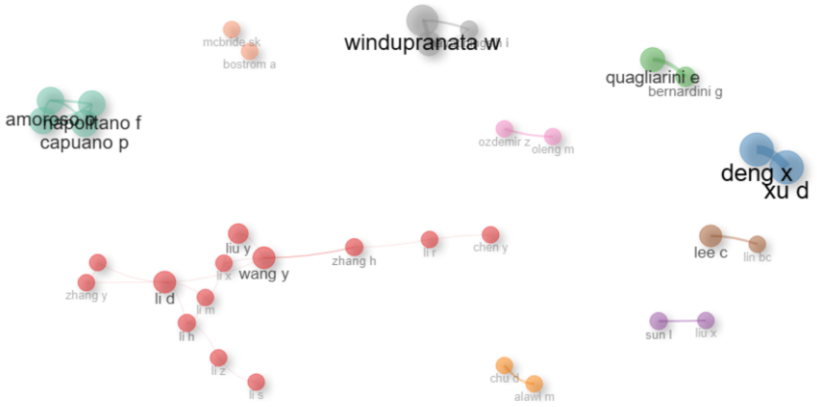

Figure 29. Collaboration network

The collaboration network analysis of authors in disaster management research reveals a single main cluster of connected researchers. Within this network, Li D and Wang Y emerge as central figures, exhibiting the highest betweenness (35.5 and 33.0, respectively) and PageRank values (0.050 each), indicating their key role in connecting different collaborators and influencing the flow of knowledge. Other authors, such as Li H and Zhang H, also hold moderate centrality positions, contributing to the network's connectivity. Meanwhile, several authors, including Liu Y, Li S, Zhang Y, and Chen Y, show low betweenness and PageRank, suggesting more peripheral roles with fewer bridging connections. Overall, the network highlights a core group of highly influential authors supported by a wider set of collaborators, reflecting a structured but concentrated pattern of co-authorship in this research field.

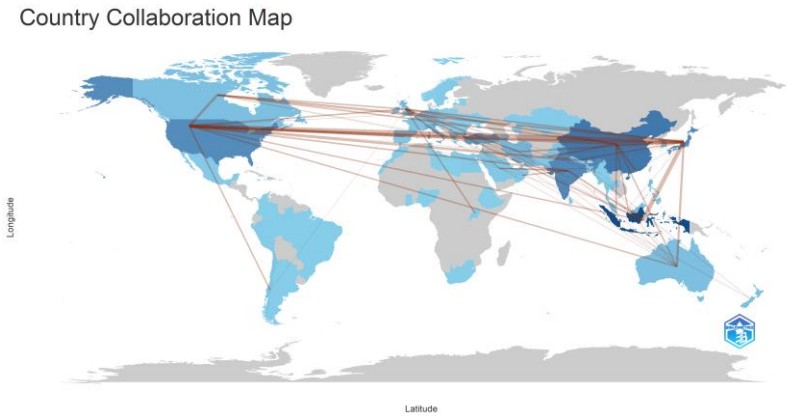

Figure 30. Countries' collaboration world map

The countries' collaboration network in disaster management research shows strong international partnerships concentrated among a few key nations. New Zealand emerges as a central hub, collaborating extensively with Germany, Japan, the United Kingdom, and the USA, each with a collaboration frequency of approximately 171.5. Japan also plays a significant role, forming notable partnerships with China, India, and Indonesia, with frequencies around 138.0. Similarly, Australia is a major collaborator, particularly with China, India, and Indonesia, showing slightly lower collaboration frequencies of about 134.5. This pattern highlights a network where research collaboration is highly interconnected across Asia, Oceania, and Western countries, emphasizing the global nature of disaster management studies and the key bridging role of New Zealand, Japan, and Australia.

Discussion

The The bibliometric analysis of research at the intersection of earthquake technologies, physics education, and Education for Sustainable Development (ESD) offers a comprehensive overview of the field's current state. The findings confirm the study's primary objective to address a significant research gap by mapping the literature from 2021 to 2025 (Rodríguez et al., 2019; Paredes et al., 2020). While existing studies often focus on technological tools or sustainability education separately, this analysis is the first to systematically combine these three areas. The results underscore a growing academic interest, as evidenced by an annual growth rate of 8.2% in publications (Harris et al., 2019). This growth is particularly notable between 2023 and 2024, when the number of articles rose from 122 to 198, indicating a recent surge in scholarly attention (O'Neill et al., 2021). The analysis confirms that educational technologies like virtual reality (VR) simulations and mobile applications are seen as vital tools for enhancing earthquake preparedness and teaching the fundamental physics behind seismic activities within the framework of ESD (Tanaka et al., 2020; Kuo et al., 2021).

The findings regarding the most relevant sources and authors highlight the intellectual structure of the field. The International Journal of Disaster Risk Reduction is the leading publication, contributing 90 articles and indicating its role as a core source for this research (Schwarz & Weber, 2020). The concentration of publications in a few core journals, as identified by Bradford's Law, demonstrates a well-established and focused research community (Müller et al., 2018). The analysis of author productivity further reinforces this pattern, showing that a small number of authors, like Deng X and Xu D, are highly productive and influential, while the majority contribute minimally (Liu et al., 2021). This suggests that although the field is expanding, a core group of researchers is driving its development and shaping key research directions (Bucchi, 2019).

The geographical distribution of research output reveals a strong concentration in Asian countries, with Indonesia, China, and India leading in both publication volume and total scientific production. This is likely due to the high frequency of seismic events in these regions, which necessitates a strong focus on disaster preparedness and education (Chavez et al., 2020). However, the analysis of citation impact shows a different trend. While Asian countries are the most productive, nations like Italy, Iran, Australia, and Canada have a higher citation impact relative to their output (Jiang et al., 2021). The high rate of international collaboration for countries like Australia (88.2%)

and Canada (60.0%) also highlights their significant role in bridging global research networks despite a smaller overall output (Rojas et al., 2021).

The thematic analysis confirms that the literature is centered on disaster management and earthquake-related terms, as seen in the high frequency of these words and their dominance in the visualizations. The thematic clusters further break this down, showing a strong focus on prevention, prediction, and technology, as well as human and educational aspects (Bucchi, 2019). The factorial analysis of keywords provides a crucial insight into this duality, revealing a spectrum of research from social and human-centered approaches to data- and technology-driven methods like machine learning and forecasting. This confirms the study's initial observation that the existing literature, while fragmented, touches upon both the technological tools and the sustainability principles of disaster preparedness (Schwarz & Weber, 2020; Tanaka et al., 2020).

Despite the growth in scholarly output, the analysis confirms that a significant gap remains in research that cohesively integrates earthquake technologies, physics education, and ESD. While studies on technology-enhanced learning and disaster preparedness exist, they often fail to bridge these areas within a single, comprehensive framework (Harris et al., 2019). The fragmentation of the literature limits the understanding of how educational technologies can be optimized to teach both the scientific principles of earthquakes and their broader implications for sustainable development (Rodríguez et al., 2019). The lack of a consolidated view of relevant studies also hinders the development of effective curricula and informed educational strategies (Paredes et al., 2020).

The results of this study serve as a foundational reference for addressing these gaps. By systematically mapping the field, the research provides a clear roadmap for future investigations (Liu et al., 2021). The identified core authors, institutions, and journals can guide new researchers in identifying key collaborators and publication venues. Furthermore, the analysis of emerging trends and topic evolution points to areas that require further exploration. For instance, future research could focus on empirical studies that evaluate the effectiveness of specific technologies, such as mobile apps and VR, in improving both physics comprehension and disaster response skills in students (O'Neill et al., 2021).

This study's findings also have significant implications for educators and policymakers. The identified gaps highlight the need for a new generation of curricula that effectively merge physics principles with sustainable development concepts in the context of real-world applications (Tanaka et al., 2020). Policymakers can use this research to create informed educational strategies that promote the adoption of technology-enhanced learning tools for disaster preparedness (Jiang et al., 2021). For example, given the strong research output from Indonesia, China, and India, these countries could lead the way in developing and implementing such curricula, particularly in regions with high seismic activity (Müller et al., 2018). By leveraging the insights from this bibliometric analysis, stakeholders can move beyond fragmented research and build a cohesive, technology-driven approach to physics education for sustainable development.

CONCLUSION

Fundamental Finding : This study reveals growing research, particularly in Asia, but with significant fragmentation. Specific technologies like VR simulations, mobile apps, and disaster management are discussed, but there is a lack of holistic studies. Key publications, influential authors, and hotspots have been identified, showing potential for creating resilient communities. **Implication :** Future research should focus on empirical studies evaluating integrated, technology-enhanced curricula. Educators and policymakers need to develop strategies to teach earthquake physics and Education for Sustainable Development (ESD), especially in high-seismic regions like Indonesia and China. **Limitation :** The study is limited to publications from 2021-2025 and specific keywords, possibly missing relevant articles. The bibliometric approach may overrepresent older research. **Future Research :** Future studies should include systematic reviews, longitudinal studies, and qualitative research on technology-enhanced disaster preparedness programs, expanding the keyword search and analysis period.

AUTHOR CONTRIBUTIONS

Hanan Zaki Alhusni was responsible for methodology development, data analysis, sourcing references, and drafting the manuscript. **Binar Kurnia Prahani** contributed to the conceptual framework. **Titin Sunarti** contributed to research design. **Madlazim** handled validation process. **Salma Hasna Hamiyda** handled data management, project coordination, and assisted in the manuscript drafting.

CONFLICT OF INTEREST STATEMENT

The authors declare that there are no conflicts of interest, either financial or personal, that could have influenced the content or the results of this study.

ETHICAL COMPLIANCE STATEMENT

This manuscript complies with established standards of research and publication ethics. The authors affirm that the work presented here is original, conducted with academic integrity, and free from any form of unethical practices, including plagiarism and data manipulation.

STATEMENT ON THE USE OF AI OR DIGITAL TOOLS IN WRITING

The authors declare that this manuscript was prepared entirely without the use of artificial intelligence (AI) or other digital tools. The research process, data processing, analysis, writing, and editing were conducted manually by the authors, and full responsibility for the authenticity and content of the article rests solely with them.

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***Hanan Zaki Alhusni (Corresponding Author)**
Postgraduate Physics, Universitas Negeri Surabaya
Jl. Ketintang, Ketintang, Kec. Gayungan, Surabaya, Jawa Timur 60231
Email: hanan.20068@mhs.unesa.ac.id

Binar Kurnia Prahani
Postgraduate Physics, Universitas Negeri Surabaya
Jl. Ketintang, Ketintang, Kec. Gayungan, Surabaya, Jawa Timur 60231
Email: binarprahani@unesa.ac.id

Titin Sunarti
Postgraduate Physics, Universitas Negeri Surabaya
Jl. Ketintang, Ketintang, Kec. Gayungan, Surabaya, Jawa Timur 60231
Email: titinsunarti@mhs.unesa.ac.id

Madlazim
Postgraduate Physics, Universitas Negeri Surabaya
Jl. Ketintang, Ketintang, Kec. Gayungan, Surabaya, Jawa Timur 60231
Email: madlazim@mhs.unesa.ac.id

Salma Hasna Hamiydah
Al-Azhar University
Youssef Abbas, Gameat Al Azhar, Qesm Thani, Nasr City,Cairo, Egypt
Email: salma.isna2145@gmail.com