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Review

Innovative Methodologies Based on Extended Reality and Immersive Digital Environments in Natural Risk Education: A Scoping Review

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Abstract: Faced with the rise in natural disasters, studies on disaster risk reduction education (DRRE) first emerged in the 1990s, predominantly employing a transmissive teaching approach; the literature advocates for interactive models, including extended reality (XR) simulations, which offer cost-effective solutions. This scoping review explores XR in DRRE for teachers, students, and citizens aiming to discern its pedagogical affordances. The databases search identified 34 papers published between 2013 and 2023. The majority centered on seismic events and floods, with Asia, notably Japan, as a primary source. Methodologically, 26 were empirical, using various research designs, and 8 were non-empirical. While XR-based tools demonstrated pedagogical affordances in teaching risk management, the lack of specific educational frameworks and a predominant focus on the acquisition of procedural knowledge and skills indicate that a broader approach is needed, by the incorporation of uncertainty education and complex competences, including attitudes like risk perception.

Keywords: natural risk education; extended reality; disaster risk reduction education (DRRE); scoping review

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1. Introduction

The scoping review examines innovative educational methodologies, exploring the pedagogical affordances of XR and immersive digital environments in preparing teachers, students, and the general public through education about environmental risks, natural disasters, and their mitigation, with a specific focus on climate-related events.

The primary objective is to scrutinize scientific studies addressing the question: how are XR technologies and immersive digital environments utilized in the training of educators, students, and the wider community regarding environmental risks?

In the face of the increasing natural disasters [1], linked to climate change [2], and the resulting need for more effective disaster risk reduction education (DRRE) [3], the integration of XR technologies and immersive digital environments can offer citizens a vicarious experience of catastrophic situations. This approach can provide citizens with a realistic perception of a risk and offer an opportunity to practice emergency procedures without exposing them to actual threats [4–8]. Consequently, this study intentionally avoids focusing on the technical training undertaken by professionals in risk management sectors, such as firefighters, healthcare personnel, military personnel, and the like. Instead, the focal point is to scrutinize educational, didactic, and training methodologies aimed at fostering a "culture of environmental risk management" that encompasses all members of society. Therefore, attention is channeled towards initiatives implemented within both formal education and training systems and informal education settings.

The scoping review has been undertaken within Multi-Risk sciEnce for resilienT commUnities undeR a changiNg climate (RETURN), a three-year project funded by the

National Recovery and Resilience Plan (NRRP), involving 26 Italian entities, including universities, research institutions, companies, and the Department of Civil Protection. The main objective of RETURN is to strengthen the research chains on environmental, natural, and anthropogenic risks at the national level and promote their participation in strategic European and global value chains.

Prior to describing the methodology and the results of the scoping review, we provide the background of the study with an overview of the field of natural hazard education.

1.1. Natural Disaster and Climate Change

The escalation in the frequency of natural disasters has been a longstanding and increasingly prominent issue, destined to attract even more attention in the years to come. As early as 2009, the United Nations had estimated that the average number of recorded natural disasters had doubled over the preceding two decades [1]. The Centre for Research on the Epidemiology of Disasters (CRED), custodian of the Emergency Events Database (EM-DAT) since 1988, reported that "The total of 387 catastrophic events in 2022 is slightly higher than the average from 2002 to 2021 (370)" [9] (p. 2). Notably, the Global Risk Report by the World Economic Forum asserts that the next decade

> will be characterized by environmental and societal crises, driven by underlying geopolitical and economic trends. 'Cost-of-living crisis' is ranked as the most severe global risk over the next two years, peaking in the short term. 'Biodiversity loss and ecosystem collapse' is viewed as one of the fastest deteriorating global risks over the next decade, and all six environmental risks [1. Extreme weather events, 2. Failure to implement climate actions, 3. Biodiversity loss, 4. Environmental disasters from pollution, 5. Water crises, 6. Extreme climate events linked to energy transition.] feature in the top 10 risks over the next 10 years [10] (p. 7).

The role of climate change in the increase in natural disasters appears to be well-established. According to the Intergovernmental Panel on Climate Change (IPCC) report, the rise in the frequency and intensity of extreme weather phenomena such as floods, droughts, storms, and sea-level rise is directly correlated with climate change [2].

1.2. What Education Can Do?

In the prospect of an increase in natural risks, how can education contribute to facing these scenarios? The United Nations' 2030 Agenda, under Goal 13.3 of the Sustainable Development Goal 13 on Climate Action, recognizes the power of education to reduce the impact of climate change [11]. But how does this work in practice? A brief exploration of the literature reveals that environmental risk education appears to be closely linked to scientific education. For instance, Mereli et al. [12] advocate for environmental disaster education programs that integrate STEAM (Science, Technology, Engineering, Arts, and Mathematics) disciplines. Similarly, Canlas and Karpudewan [13] reflect on the role of disaster risk reduction education in promoting scientific literacy. However, a study by Cahapay and Ramirez [14] suggests that scientific education alone may not be correlated with disaster preparedness or risk perception.

Certainly, and generally, the more educated a community is, the better it can confront environmental risks and natural disasters [15].

Cerulli et al. [16] also investigated the relationship between a community's education level and its ability to manage natural risks. Analyzing 15 countries representing a wide range of natural risks, they found that "countries at low risk tend to be over-aware while countries at high risk are under-aware of natural hazards. Education can significantly increase awareness of natural hazards and reduce their impact" [16] (p. 1).

However, a more in-depth exploration of the scientific literature on education focused on natural disaster preparedness reveals a specific educational approach, called disaster risk reduction education (DRRE), which emerged in the 1990s and is currently supported by a substantial body of research [13].

1.3. Disaster Risk Reduction Education (DRRE)

Studies within the academic domain of DRRE employ diverse expressions to refer to the field often encapsulated by the term "disaster risk reduction education" (DRRE). As stated by Canlas and Karpudewan [13] (p. 1), "DRRE in the United Nations (UN) may have begun with the International Decade for Natural Disaster Reduction declaration in 1990". Since then, international attention to the subject has steadily grown, and from 2014 onwards, the number of publications on DRRE has increased, albeit with a limited number of scholars dedicated to this theme, and a notable absence of studies evaluating the effectiveness of the designed strategies [13]. The issue of DRRE effectiveness is also addressed by Nakano and Yamori [3], who, after analyzing the literature on the subject, argue that most studies rely on a transmissive teaching approach and measure knowledge only in the short term, without accounting for a sustained change in the behavior of those receiving risk reduction training.

As Rohrmann [17] noted, there are four factors influencing emergency management behavior: risk perception (individual assessment of the magnitude of a risk), risk attitude (propensity for risk-taking or caution), risk communication (information about the risk available to individuals), and risk management (procedures to follow in case of danger). Therefore, in line with Rohrmann's framework [17], to promote effective citizen behaviors in the face of natural risks, action must be taken on each of these four factors.

Nakano and Yamori [3], aiming for a lasting change in student behavior, propose and experiment with a "new 'proactive attitude paradigm' which consists of the (1) instructor/learner fusion approach, (2) participation in a community of practice approach, and (3) long-term commitment evaluation approach" [3] p. 1). Kagawa and Selby [18] (p. 207) also advocate for an educational approach that is "interactive, experiential and participatory".

1.4. Environmental Risk Education with XR Technologies

In response to the necessity for a more interactive, experiential, and participatory DRRE, some scholars [4–8] have proposed the idea that XR technologies can provide citizens with a vicarious experience of catastrophic situations, fostering a realistic perception of risk and the opportunity to practice without actual threats to their safety. This offers the advantage of learning the most effective procedures for managing such situations.

David et al. [5] argue that integrating VR applications into disaster preparedness programs can bridge the gap between theoretical knowledge and its practical application by providing students with an opportunity to practice their lessons in a controlled, simulated setting. Similarly, [7] contends that AR presents an engaging, non-intimidating, and memorable way to introduce crisis terminologies and scenarios to younger audiences, laying down a foundation of basic knowledge.

The importance of prior experience in risk perception is also highlighted in a meta-analysis conducted by Theodorou et al. [19]. Contrary to Wachinger et al. [20], who argued that previous experience cannot influence risk perception unless the experience was severe, these authors demonstrate that both previous experience and the severity of the experience show the same positive effect on risk perception. Therefore, perhaps even vicarious experience can influence risk perception.

Another advantage of XR technologies is its cost-effectiveness. Caballero and Niguidula [4] highlight that training for natural disaster management, if carried out interactively and experientially in a real situation, can be very costly (as well as dangerous). Therefore, they advocate for simulation-based training, which employs computer-generated environments to replicate real-world scenarios, allowing individuals to practice responding to disasters like earthquakes, typhoons, tsunamis, and fires in a virtual setting.

In the same vein, Yoshida et al. [8] suggest that while physically exploring one's surroundings and learning from the disaster experiences of others could enhance awareness, such an approach is time-consuming and logistically challenging. They propose a system that simulates disaster experiences, enabling learners without prior exposure to disasters to grasp the potential impacts on their communities and commuting routes.

In summary, as Hsu et al. [6] highlight, the emergence of technology-driven approaches to disaster preparedness, particularly through VR environments, shows great promise in filling the gaps left by traditional training methods, potentially revolutionizing how we prepare for and understand disasters.

In conclusion, natural disasters pose a threat to humanity and our countries, with no sign of diminishing, partly due to climate change. Education can play a role not only because a more educated community can manage environmental risks better, but also because specific educational initiatives can be implemented to improve the preparation and management of natural disasters, as evidenced by the growing literature on disaster risk reduction education (DRRE). Nevertheless, there are still only a few studies focusing on this area, and there is a scarcity of research works evaluating the effectiveness of adopted educational approaches. This lack of studies may be due to the fact that environmental risk education, to be effective, must be "interactive, experiential and participatory" [18] (p. 207), but this can be expensive and hazardous. Therefore, considering all the possible advantages identified so far (immersion, practice, safety, engagement, cost-efficiency), a possible response to the need for human communities' preparedness for natural disaster management could be an educational approach based on simulations using XR. Based on the analytical examination of the literature, this study aims to identify the most effective methodologies for environmental risk education with a focus on the use of XR technologies and immersive digital environments for disaster management preparedness. So, despite the limited research on XR's role in DRRE, its significance warrants a comprehensive review. Given the escalating threat of natural disasters and the potential of immersive education, exploring XR's efficacy in disaster management preparedness is crucial.

2. Methodology

As outlined in the introduction, the scoping review explores and analyzes relevant and recent literature, specifically from the last ten years. It focuses on the role that XR technologies and immersive digital environments can play in the education of various target groups, including teachers, students, and the general public.

The primary goal is to examine how these technologies can be utilized to enhance the understanding of environmental risks and natural disasters, including those linked to climate change. The decision has been made not to consider the technical training received by professionals in risk management sectors, such as firefighters, healthcare personnel, military personnel, etc. The aim is to explore educational, didactic, and training methodologies to promote a "culture of environmental risk management" that involves all citizens. Hence, attention is directed towards initiatives implemented both within the formal education and training system and within informal education.

The study will explore both existing and potential use of XR in the educational contexts of environmental risk training, looking at how immersive experiences can enhance the learning process, entailing a better assimilation of knowledge related to environmental risks, while strengthening the preparedness and response capabilities of communities.

2.1. The Identification of Research Questions

A primary research question was formulated, taking into account the context, target audience, and key concepts.

> *RQ: What educational, instructional, and training methodologies based on the use of extended reality (XR) and immersive digital environments can be proposed to develop*

> *better knowledge of environmental risks and natural disasters, including those related to climate change, and their management in teachers, students, and citizens?*

This general research question was articulated into five specific research questions (RQs) aimed at further clarifying and outlining the different types of evidence available in the literature.

> *RQ1: In which geographical contexts and for what types of environmental risks and natural disasters have educational activities based on XR technologies been advanced or validated in the scientific literature over the last 10 years?*
>
> *RQ2: What types of studies (methodology, target audience, and limitations) are present in the scientific literature over the last 10 years on the use of XR technologies for education on environmental risks and natural disasters?*
>
> *RQ3: What learning objectives do the proposals in the scientific literature over the last 10 years on the use of XR technologies for education on environmental risks and natural disasters pursue?*
>
> *RQ4: What teaching/training methods based on the use of XR technologies have been proposed and/or validated by the scientific literature over the last 10 years for education on environmental risks and natural disasters?*
>
> *RQ5: What results (in terms of achieved learning or methodological–instructional reflection) have been highlighted by the scientific literature over the last 10 years on the use of XR technologies for education on environmental risks and natural disasters?*

2.2. Research Method

The method adopted to carry out the current study is the scoping review. To increase its reliability and minimize subjectivity, the review process involved three researchers. The process was iterative, refining inclusion/exclusion criteria and the data collection tool, and involved discussions among the researchers to ensure a holistic, objective, and coherent view and to promote consensus on interpretations and results analysis.

To guide the scoping review, the checklist developed by Tricco et al. [21] for the PRISMA extension for scoping reviews (PRISMA-ScR) was used. Additionally, the PRISMA flowchart [22,23]) in its updated version was used to track and visually clarify the review process (see Section 2.6).

To effectively address the RQs, it was essential to identify specific keywords in English. The decision to use English not only represents a coherent choice in terms of disciplinary alignment but also aims to ensure a more extensive and representative data collection.

The process of selecting keywords resulted from a collaborative approach characterized by brainstorming among the research team members. This synergistic approach allowed the identification of an effective set of keywords, ensuring broad and balanced coverage of the research's areas of interest. The identified keywords were divided and organized, based on the context, target audience, and concepts present in the general research question, into three areas:

1. Education and target;
2. Environment;
3. Technologies.

Each area indicates a specific topic, semantically consistent and clearly different from the further conceptual elements characterizing the other areas. This segmentation methodology was adopted to optimize the internal uniformity of each area. This strategy aims to facilitate and make the analysis and interpretation of data more effective, enhancing the understanding of thematic connections and conceptual differences among the various areas.

Specifically, the keywords in the Environment area were extrapolated following the definitions of the United Nations contained in *The Sendai Framework for Disaster Risk*

Reduction 2015–2030 [24], in *Hazard Information Profiles: Supplement to UNDRR-ISC Hazard Definition & Classification Review* [25]. In total, 66 keywords were identified. For an organized visualization and grouping of these keywords in the three distinct areas, refer to Table 1.

Table 1. Keywords tested and organized by areas.

Area	Keywords
Education/Target	adult education; citizen awareness; community; communit*; education; informal education; learning; school; teacher training; training
Environment	avalanche; climate change; cold wave; disaster risk; drought risk; drought; earthquake risk; earthquake; environmental risk; extreme event; fire; flood risk; flood; forest fire; heat wave; hurricane; hydrogeological risk; hydrogeological; landslide; lightning risk; multislide; natural disaster; natural hazard; natural risk; natural threat; precipitation extreme; rockslide risk; rockslide; sea level rise risk; sea level rise; seismic risk; seismic; storm risk; storm; thunder risk; thunder; tidal wave risk; tornado risk; tornado; tsunami risk; tsunami; typhoon risk; typhoon; volcan*; volcan* risk; volcanic; weather hydro risk
Technology	XR; 360 degree video; 360 video; augmented reality; immersive; metaverse; mixed reality; simulation; virtual reality

Notes: In some keywords aimed at identifying content that includes similar or correlated words, the asterisk (*) has been employed as a wildcard character.

The sixty-six keywords were combined and tested in at least one of the 12 search strings characterized by different purposes and scopes, such as the following: general exploration of themes; focus on the educational context and target audience; framing of the nature of environmental risks; verification of the technological scope.

This preliminary phase was crucial for the development and definition of the final search string. The string was further refined through a collaboration with colleagues involved in the project.

The composition of the final search string expression, formulated with parentheses and Boolean operators, reflects the three areas (Education/Target; Environment; Technology) in which the keywords were organized:(education OR school OR training OR “citizen awareness” OR communit*) AND (“climate change” OR “natural disaster” OR “natural hazard” OR “natural threat” OR “disaster risk” OR “environmental risk” OR “extreme event” OR “natural risk” OR earthquake OR hydrogeological OR flood OR drought OR fire OR volcan* OR landslide OR tsunami OR rockslide OR hurricane OR avalanche OR “precipitation extreme” OR seismic OR storm OR multislide OR tornado OR typhoon OR “cold wave” OR “heat wave” OR “sea level rise” OR thunder OR lightning) AND (“extended reality” OR “augmented reality” OR “virtual reality” OR immersive OR metaverse)

From a technical standpoint, the expression of the final search string has been designed to be compliant with major scientific databases. This means it can be used directly in databases without the need for substantial modifications or with only slight syntax adjustments required to conform to the specific input fields of different search interfaces.

2.3. Database and Import of Research Results

On 21 June 2023, the final search string was executed across five databases (Table 2). The selection of these databases combined a broad and generalist approach, typical of Scopus and Web of Science, with a specific focus on the fields of psychoeducational and technological scientific literature, characteristic of EBSCOhost, PubMed, and IEEE Xplore. This combination allowed access to a wide range of studies.

On EBSCOhost, the following databases were selected as more relevant to the research objectives Education Source; APA PsycInfo; APA Psyctest; GreenFILE; Library, Information Science & Technology Abstracts.

The filter settings used for the search, where allowed by the databases, were limited to the time frame of the last ten years (2013–2023) and the English language.

The research results for each database are reported in Table 2.

Table 2. Results of the search for each database.

Databases	Results
EBSCOhost	638
IEEE Xplore	335
PubMed	235
Scopus	767
Web of Science	744
Total	2719

The 2719 research results were imported in the .ris format into Rayyan (https://www.rayyan.ai/ accessed on 23 June 2023), a web-based automated screening tool that uses text-mining methods and machine learning algorithms to facilitate the semi-automatic screening of records. Even in its free version, Rayyan facilitates collaboration among multiple reviewers, a significant advantage for research teams working together on a review. It allows easy sharing of work and decisions made, offering a blind review mode where reviewer decisions and labels remain hidden from others.

2.4. Inclusion and Exclusion Criteria

The research team collaboratively established initial inclusion criteria, followed by further refinement and fine-tuning of exclusion criteria, to delineate the scope and boundaries of the scoping review. This process aimed to identify key aspects for addressing the research questions. These criteria guided the selection of abstracts and subsequent full-text articles for in-depth analysis.

2.4.1. Inclusion Criteria

The definition of the inclusion criteria also played a role in setting two parameters used in the filters (temporal scope and English language) as described in the previous section of the database search masks.

The chosen timeframe for studies published in the last decade (2013–2023) was motivated by the rapid development of XR technologies [26–29]. During this period, XR technologies began to be widely utilized in educational settings [30–34]. Several events occurred in this timeframe that facilitated the adoption of these technologies in schools, including the following: the spread of increasingly accessible and high-performing hardware and software devices, which is accompanied by the growth of the XR technology market, with new enterprises emerging and a broad expansion of product and service offerings. Educational institutions and international organizations are paying greater attention to educational innovation, increasingly recognizing the potential benefits of using XR technologies in learning. Additionally, during the COVID-19 pandemic, there was a significant increase in interest in XR technologies in the educational context, highlighting the growing importance of these technologies in education.

Given the broad scope of the research question and thematic focus, no geographic restrictions were applied in article selection, and reviews (including systematic reviews) on the topic were also included.

2.4.2. Exclusion Criteria

Exclusion criteria for article selection were defined as follows:

- Articles solely focused on technical design and the development of prototypes or applications using XR technologies, without a concrete educational analysis.
- Research exclusively centered on usability tests of XR-technology-based application interfaces, without an educational focus.
- Topics or technological tools not directly related to the scope of the research, such as the following: Artificial Intelligence (AI); Internet of Things (IoT); Wearable Devices.
- Specific technical training for professionals in risk management sectors, for example, firefighters, healthcare personnel, military, etc.
- Studies unrelated to the thematic focus, not addressing environmental risks, natural disasters related to climate change, but exclusively focusing on, for instance, health risks, descriptions of simulations and safety analyses in escape routes during evacuations, and fires not related to wildfires.
- Studies where the educational purpose is declared but, in practice, no information is extracted on teaching methods, learning outcomes, or affordance.
- Studies directed at sectors other than education, such as communication, cultural heritage, health, psychology, and tourism.
- Studies not available in full-text format.

The initial dataset was analyzed following the inclusion and exclusion criteria. To minimize subjectivity in the review process, three research group members read the abstracts of all collected articles (N = 2719), evaluating their suitability for the next phase, which involved reading the full text. After the import of the 2719 results, Rayyan identified 998 potential duplicates. To verify their actual duplication, each case was examined considering the title, authors, and the first sentence of the abstract. In the presence of matches among these elements, duplicates were removed (N = 562). Five were labeled by Rayyan as non-duplicates; however, after manual verification, two turned out to be duplicates. Another two duplicates were manually identified through additional verification by sorting potential duplicates by titles. In this phase, papers without abstracts were also eliminated (N = 1). At the end of this process, 567 articles were removed. Consequently, the number of articles in the final dataset, after removing duplicates and papers without abstracts, amounts to 2152.

In these phases, the use of Rayyan proved crucial to expedite the process, particularly due to an automatically generated tag cloud on "Topics", facilitating analysis of each topic, starting with those less relevant or less relevant to the research scope; custom labels to motivate decisions for the exclusion or inclusion of studies; and an automatic language detection system for abstracts, allowing the immediate exclusion of 23 studies not in English.

Before identifying relevant studies, extensive discussions within the research group were conducted to achieve consensus on defining the corpus. Doubts about study inclusion were primarily resolved by considering abstracts, titles, and keywords. Explicit references to XR technologies and immersive digital environments in combination with education on environmental risks, specific technical training for professionals in risk management sectors, analyses of escape routes, and fires other than wildfires were considered crucial. This evaluation further refined the selection process, ensuring that studies included in the final dataset were closely aligned with the research objectives. At the conclusion of this review process, 90 studies were identified for in-depth analysis through the reading of their full texts.

2.5. Analysis of Full Text

The analysis of full texts was conducted using an ad hoc analytical grid, providing a systematic guide to examine each article. The grid's design and application are described in the "Data Collection Tool" section.

To find all full-text relevant studies, the researchers used various methods:

- Electronic databases accessed through academic accounts;
- Direct author contact via email;
- Academic social networks like Academia.edu and ResearchGate;
- Collaboration with colleagues at other institutions for additional database access.

As explained in Table 3 below, 56 papers were eliminated after reading the full text. The 34 articles resulting from the full-text analysis process are reported in the references [4,5,7,8,35–64]

Table 3. Reasons for exclusion of full texts.

Reason for Exclusion	Number of Articles
Non-availability in full-text	10
Non-English language	2
Not related to wildfires	26
Non-educational focus	11
Technical training	4
Usability testing	2
Not related to environmental risk	1
Total	56

2.6. PRISMA-ScR Checklist and PRISMA Flowchart

Table 4 presents the checklist developed by Tricco et al. [21] for the PRISMA extension for scoping reviews (PRISMA-ScR). For each item on the checklist, the paragraph and section of this review where the content is addressed are indicated.

Table 4. PRISMA-ScR checklist.

Section	Item	Prisma-Scr Checklist Item	Reported On
Title			
Title	1	Identify the report as a scoping review.	Title
Abstract			
Structured summary	2	Provide a structured summary that includes the following (as applicable): background, objectives, eligibility criteria, sources of evidence, charting methods, results, and conclusions that relate to the review questions and objectives.	Abstract
Introduction			
Rationale	3	Describe the rationale for the review in the context of what is already known. Explain why the review questions/objectives lend themselves to a scoping review approach.	Sections 1.1–1.4
Objectives	4	Provide an explicit statement of the questions and objectives being addressed with reference to their key elements (e.g., population or participants, concepts, and context) or other relevant key elements used to conceptualize the review questions and/or objectives.	Section 1.4, final paragraph

Methods			
Protocol and registration	5	Indicate whether a review protocol exists; state if and where it can be accessed (e.g., a Web address); and, if available, provide registration information, including the registration number.	Section 2.7
Eligibility criteria	6	Specify the characteristics of the sources of evidence used as the eligibility criteria (e.g., years considered, language, and publication status) and provide a rationale.	Section 2.4
Information sources	7	Describe all information sources in the search (e.g., databases with dates of coverage and contact with authors to identify additional sources), as well as the date the most recent search was executed.	Section 2.3
Search	8	Present the full electronic search strategy for at least 1 database, including any limits used, such that it could be repeated.	Section 2.3.
Selection of sources of evidence	9	State the process for selecting sources of evidence (i.e., screening and eligibility) included in the scoping review.	Sections 2.4–2.7
Data charting process	10	Describe the methods of charting data from the included sources of evidence (e.g., calibrated forms or forms that have been tested by the team before their use, and whether data charting was conducted independently or in duplicate) and any processes for obtaining and confirming data from investigators.	Section 2.7
Data items	11	List and define all variables for which data were sought and any assumptions and simplifications made.	Section 2.7
Critical appraisal of individual sources of evidence	12	If conducted, provide a rationale for conducting a critical appraisal of included sources of evidence; describe the methods used and how this information was used in any data synthesis (if appropriate).	Section 2.7
Synthesis of results	13	Describe the methods of handling and summarizing the data that were charted.	Section 3
Results			
Selection of sources of evidence	14	Give the numbers of sources of evidence screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally using a flow diagram.	Section 2.6
Characteristics of sources of evidence	15	For each source of evidence, present the characteristics for which data were charted and provide the citations.	Section 3
Critical appraisal within sources of evidence	16	If conducted, present data on critical appraisal of included sources of evidence (see item 12).	Section 3.2
Results of individual sources of evidence	17	For each included source of evidence, present the relevant data that were charted that relate to the review questions and objectives.	Section 3
Synthesis of results	18	Summarize and/or present the charting results as they relate to the review questions and objectives.	Section 4
Discussion			
Summary of evidence	19	Summarize the main results (including an overview of concepts, themes, and types of evidence available), link to the review questions and objectives, and consider the relevance to key groups.	Section 4
Limitations	20	Discuss the limitations of the scoping review process.	Section 5, first paragraph

Conclusions	21	Provide a general interpretation of the results with respect to the review questions and objectives, as well as potential implications and/or next steps.	Section 5
Funding			
Funding	22	Describe the sources of funding for the included sources of evidence, as well as the sources of funding for the scoping review. Describe the role of the funders of the scoping review.	Section 1, final paragraph

In addition, to provide a clear, structured, and summary view of the various steps in the process leading to the composition of the final dataset, we utilized the graphical synthesis of the PRISMA workflow (Figure 1), generated using the R package [65], which is also suitable for scoping reviews [23].

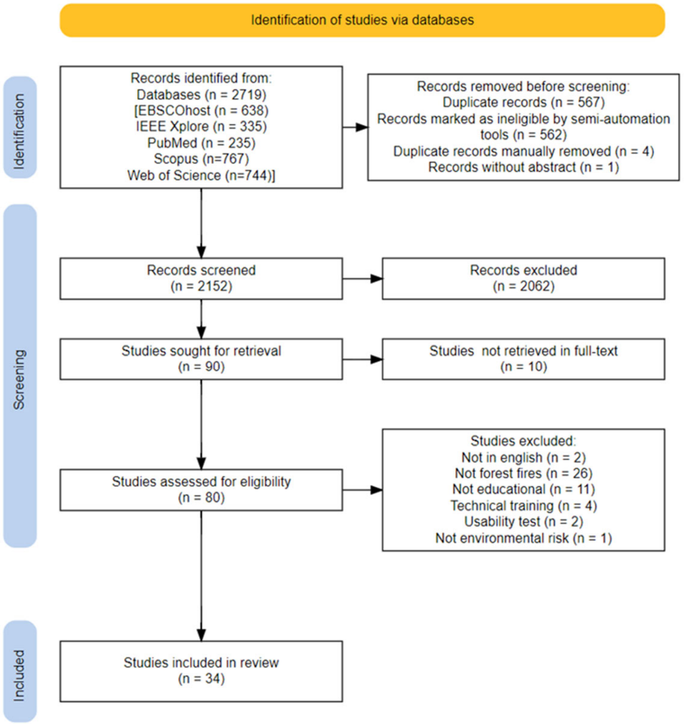


Figure 1. Prisma flowchart.

2.7. Information Extraction Tool

The information extraction tool (Table 5) is based on theories and notions presented in the conceptual background and aims to address the research questions comprehensively. It was, therefore, designed to gather information on how XR technologies are used in education; understand how XR technologies can improve the learning of teachers, students, and citizens on environmental risks, natural disasters linked to climate change, and strategies for managing these global challenges.

The information extraction tool is structured into different sections including the following: 1. Bibliographic Information; 2. Study Type and Methodology; 3. Environmental Risk or Natural Disaster; 4. Target Audience; 5. Learning and Teaching with XR Technologies; 6. Study Findings.

Table 5. Information extraction tool.

1. Bibliographic Information	
Label	Description of the Label
Authors	Authors' names
Title	Article title
Year	Year of publication of the article
Source of the title	Title of the journal, conference, or book
Document type	Journal article, conference article, book chapter
Number of citations	Number of citations as indicated on Google Scholar
APA-formatted bibliographic reference	Complete bibliographic reference in APA format retrieved from Google Scholar
Abstract	Copy of the abstract from the article
Keywords	Copy of the keywords provided in the article
Geographic area of the corresponding author	Geographic area of the corresponding author (Africa, Asia, Europe, North America, Oceania, South America).
2. Study Type and Methodology	
Label	Description of the Label
Study Type	Indicate whether the study is empirical or non-empirical
Methodology Type	Specify the type of research methodology adopted in the study (e.g., quantitative, qualitative, mixed methods, theoretical proposal, applied concepts, personal opinions/observations, reflections on current events/authority, review, meta-analysis)
Sample	Report details of the study sample (number, gender, age, prior experience)
Study Limitations	Copy the limitations as stated in the article
3. Environmental Risk or Natural Disaster	
Label	Description of the Label
Environmental Risk or Natural Disaster Type	Specify the type of environmental risk or natural disaster as stated in the article
Detailed Description of Environmental Risk or Natural Disaster Type	Only if explicitly mentioned in the article, copy the specific details of the type of risk
4. Recipients (Target)	
Label	Description of the Label
Audience (Target)	Recipients of the educational intervention (teacher, student, citizen, anyone)
Educational level of the target audience (Target)	Determine the educational level of the recipients (higher education, kindergarten, primary school, secondary school, adult learning, any level)
5. Learning and Teaching with XR Technologies	
Label	**Description of the Label**
Learning objectives	Identifying learning objectives (knowledge acquisition, problem-solving, learning procedures, etc.)
Teaching methodology	Identifying teaching methodologies (e.g., cooperative learning, peer-to-peer training, flipped classroom, laboratory teaching, etc.)
XR technologies are employed for...	Specifying the use of XR technologies (e.g., simulation, exploration, virtual tours, virtual field trips, serious games, etc.)

Educational use of XR technologies	Identifying the educational context in which XR technologies are utilized (e.g., in-class/group settings, in-class/individual settings, at home, etc.)
Type of XR technology	Identifying the type of XR technology (Augmented Reality, Mixed Reality, Virtual Reality, 360° video)
6. Study Findings	
Label	Description of the Label
Study outcomes	Copy the findings exactly as they are written in the article
Learning affordances with XR technologies	Extract from the article the pedagogical added value of learning with XR technologies

The dataset collected using the information extraction tool is available upon request in the Open Access repository Zenodo, at the following link: https://doi.org/10.5281/zenodo.11102094, accessed on 02/05/2024.

The information collected regarding the first group of variables (1. Bibliographic Information) serves to contextualize the analyzed literature on spatial–temporal coordinates, identifying the geographic areas or countries with higher or lower scientific production on the subject and any trends of increase or decrease in the number of publications over the years. Concerning the variables in the second group (2. Study Type and Methodology), they provide useful information to determine whether certain methodological approaches are more prevalent than others; furthermore, analyzing the research designs used is essential to identify the limits within which the findings of the analyzed studies have internal validity [66] and potentially external validity, i.e., can be generalized to similar contexts. The information collected on the third group of variables (3. Environmental Risk or Natural Disaster) is crucial to check if the literature focuses on certain types of risks over others; moreover, this information, when combined with the geographic context of the studies, can verify the hypothesis of a relationship between the most frequent type of risk in a specific geographical area and the development of scientific literature on the use of XR technologies for education on reducing that particular risk. For example, it is expected that studies published in countries like Japan would primarily focus on earthquakes. The information gathered on the variables related to the fourth (4. Recipients) and fifth group (5. Learning and Teaching with XR Technologies) helps to define, from an educational standpoint, the processes within which XR technologies were used for disaster risk reduction education: their learning objectives, the teaching strategies adopted, the type and age of the recipients, the type of technologies used, and how they were utilized. This information is necessary to outline the existing literature on the topic of the scoping review and to make any recommendations for future educational research in this area. Finally, regarding the last group of variables (6. Study Findings), the information collected is used to define the state of the art on the effectiveness of using XR technologies for disaster risk reduction education, within the internal and external validity limits delineated based on the analysis of the research designs adopted.

3. Results

In this section, the results of the scoping review are presented. Based on the research questions, they focus on the following aspects: context and type of addressed risk, types of studies found (methodology, target audience, and limitations), learning objectives, teaching/training methods and tools, findings (in terms of achieved learning outcomes or methodological–didactic reflections, including the pedagogical affordances of XR technologies).

3.1. Contexts and Treated Environmental Risks

The scoping review, spanning from 2013 to 2023, explores the historical–geographical context of literature on XR technologies in disaster risk reduction education. Analyzing factors such as publication year, geographic focus, and publication type reveals a surge in publications from 2016 onward (Figure 2). This trend is attributed to increased accessibility of advanced software and hardware, heightened awareness of XR's educational benefits, and intensified focus during the COVID-19 pandemic [29]. It is worth noting that the lack of meaningful data for 2023 is due to the fact that the database search was conducted until June 21, 2023. By that date, only one article had been published in 2023.

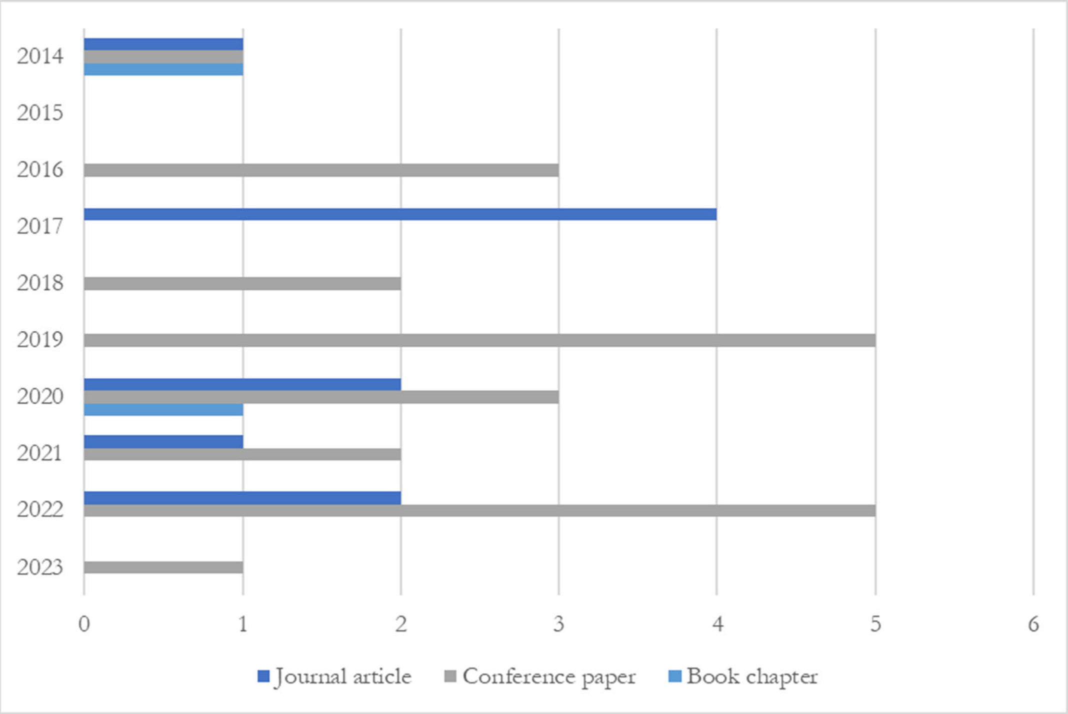


Figure 2. Number of papers per year divided by document type. The color shows the details of the document type.

Figure 3 highlights Asia as the leading continent, with 18 publications, followed by North America, with 10. South America and Africa had no publications.

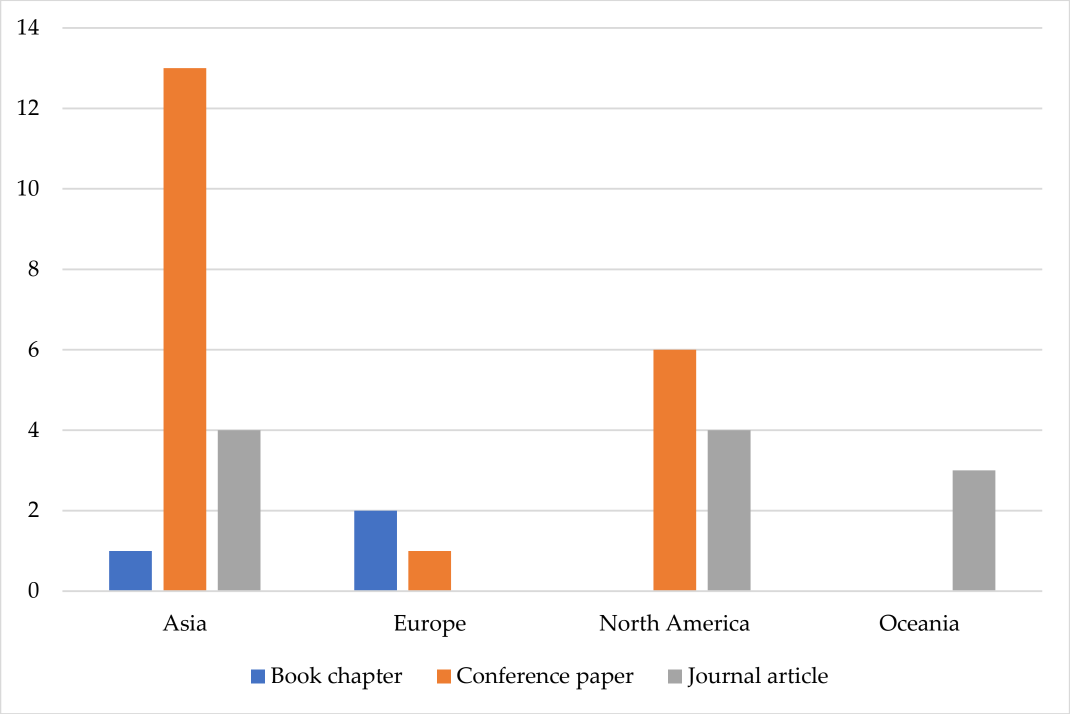


Figure 3. Number of papers per geographical area divided by document type. The color shows the details of the document type.

Analyzing paper content, Figure 4 reveals a focus on earthquakes (N = 12) and floods (N = 9). In the multi-risk category (N = 5), the studies addressed three or more types of risks, including cyclones, earthquakes, floods, fires, landslides, tsunamis, and typhoons. There is no correspondence between the total number of articles (N = 34) and the number of types of risks, as some articles address two or three types of risks.

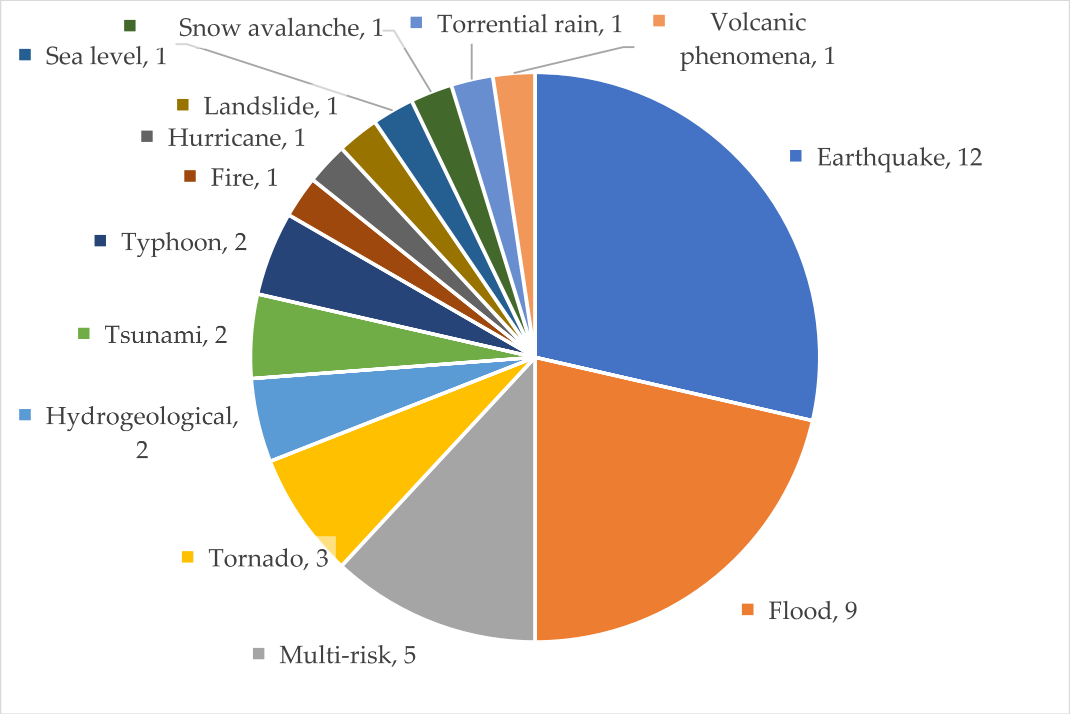
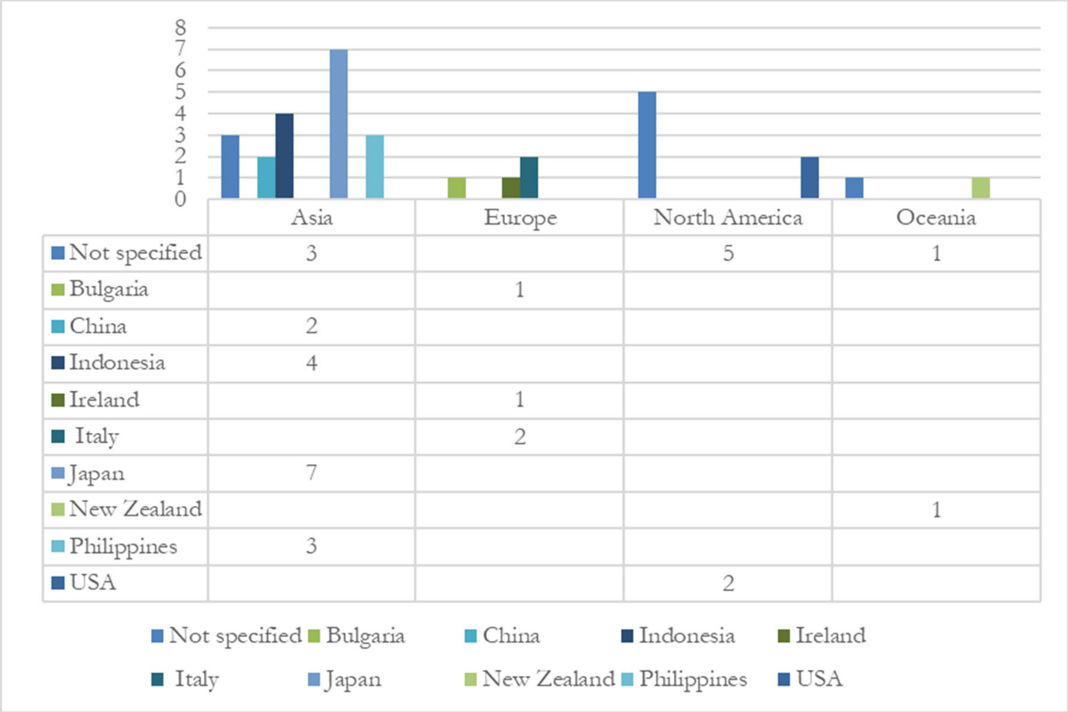


Figure 4. Number of papers per type of risk addressed.

Figure 5 underscores Asia's prominence (N = 19), notably Japan (N = 7), due to its technological advancements and seismic vulnerability, as hypothesized in Section 2.7. Japan's significant role arises from its advanced technology sectors, including robotics and XR, coupled with its geographically precarious position atop tectonic plates and the active Nojima fault. This geographical susceptibility makes Japan prone to earthquakes, occasionally leading to tsunami alerts. The study by [55] is a systematic literature review and, therefore, does not contain specific information about the geographical area considered in the study.



	Asia	Europe	North America	Oceania
Not specified	3		5	1
Bulgaria		1		
China	2			
Indonesia	4			
Ireland		1		
Italy		2		
Japan	7			
New Zealand				1
Philippines	3			
USA			2	

Figure 5. Number of papers per examined geographic area and country.

3.2. Research Methodologies

To analyze the papers from a research methodology perspective, they were initially categorized into empirical and non-empirical studies. The empirical studies involved users or experts in the educational tool design or usage process, either to validate their effectiveness or conduct usability tests. The non-empirical studies, in contrast, excluded user groups from these processes.

Subsequently, the papers were grouped based on three methodological approaches: predominantly quantitative, qualitative, and mixed-method. The studies were predominantly quantitative if they employed closed-ended questionnaires, structured observation, statistical analyses, and standardized research designs. Predominantly qualitative studies involved small groups, utilized non-standardized data collection tools like interviews or continuous feedback, and had less-standardized research designs, such as case studies. The mixed-method studies integrated both approaches.

Efforts were made during the full-text analysis to explicitly identify limitations outlined by the studies themselves. Figure 6 illustrates the distribution of the 34 included studies, with 26 adopting an empirical approach, and eight being non-empirical.

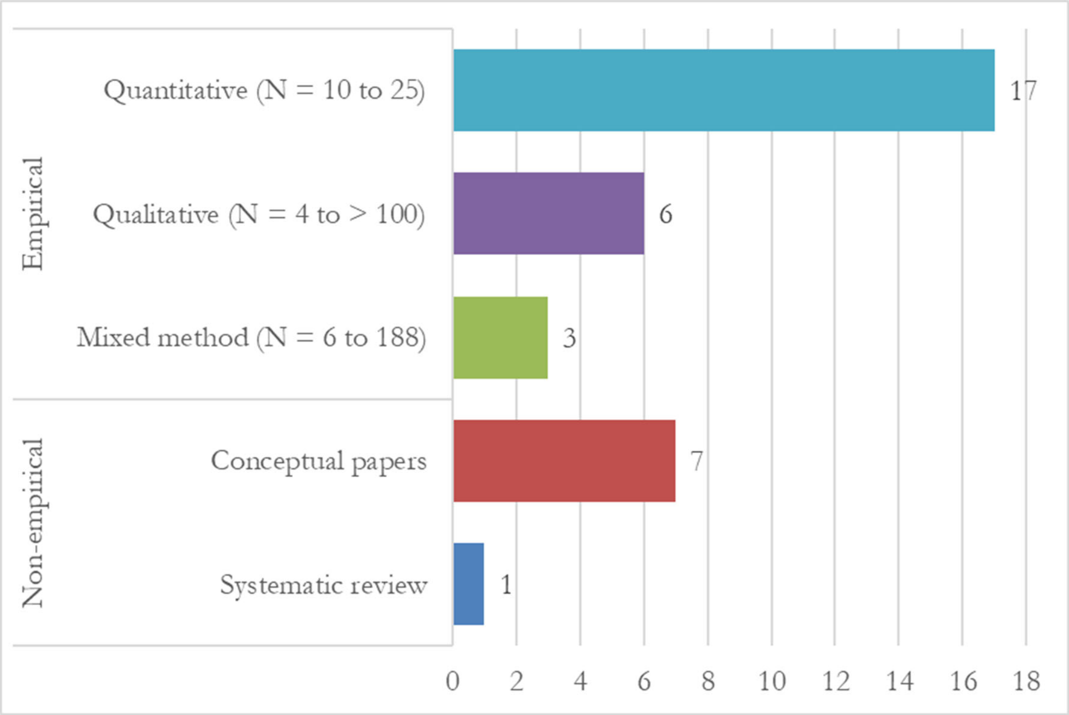


Figure 6. Number of studies by type (empirical–non empirical) and methodological approach.

Before examining the methodological approaches of the studies, it is important to remember that they vary greatly in internal validity, which we define as the extent to which changes in the dependent variable are due to manipulations in the independent variable [66]. Indeed, some studies boast high internal validity, employing experimental designs, while others, adopting quasi-experimental or qualitative approaches, have limited internal validity, though supported by empirical verification.

Starting from non-empirical studies, they include a systematic review [55] and seven studies proposing educational applications of XR technologies for disaster risk reduction education (DRRE) without undergoing experimental validation or usability testing. It is worth noting that the search string used did not yield papers solely discussing theoretical reflections on the use of XR for DRRE without proposing specific applications or simulations.

3.2.1. Empirical Studies

To analyze the 20 empirical studies employing predominantly quantitative or mixed-method approaches, various research designs were deduced and categorized into seven types, as illustrated in Figure 7.

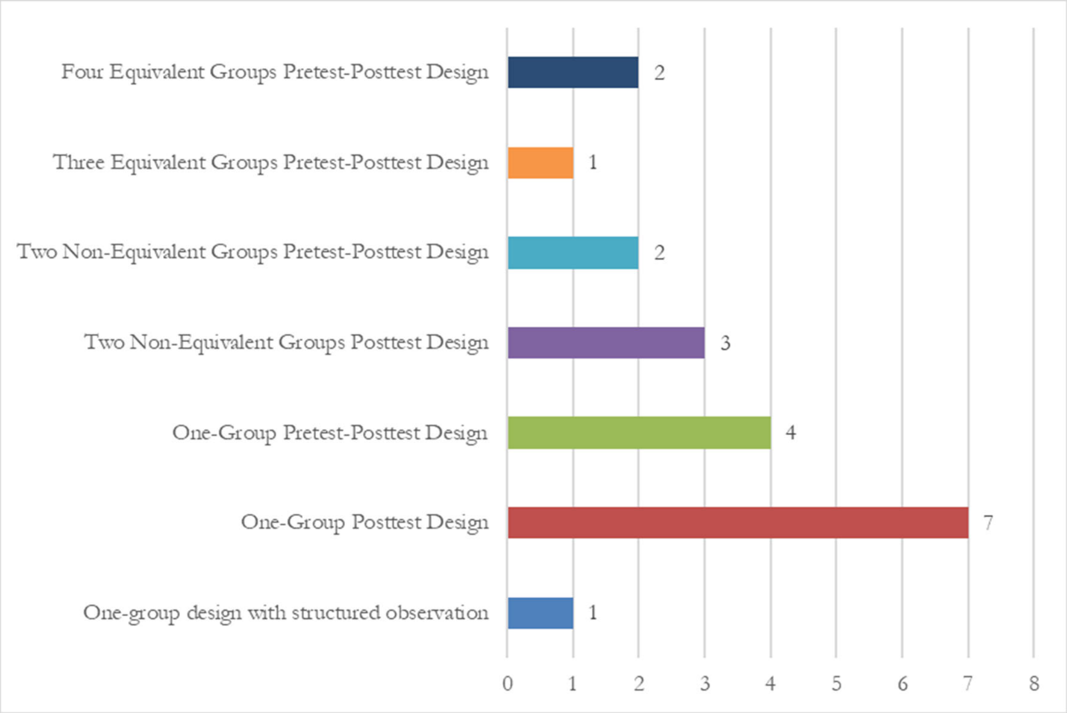


Figure 7. Number of empirical studies per research design.

The most prevalent design is the one-group post-test, which was adopted by seven studies. Critically, this quasi-experimental design is deemed non-interpretable due to potential confounding factors, as cautioned by Cook et al. [67]. These studies typically employ a brief structured questionnaire post XR application use, focusing on usability and occasionally probing perceived educational effectiveness.

The second most frequent design is the one-group pre-test–post-test, which was used in four studies [39,48,54,61]. Structured assessments are conducted before and after XR application implementation to gauge formative impacts.

Five studies employ a quasi-experimental design involving two groups (experimental and control), with three featuring only post-tests, and two incorporating pre-tests. Among these, Liang et al.'s study [51] uniquely evaluates a VR-based system for earthquake evacuation training through structured tests, while others include perceived effectiveness questions in usability questionnaires.

Three studies adopt an experimental design, employing random assignment to experimental and control groups [46,47,50]. These research designs encompass both pre-test and post-test assessments, comparing multiple experimental groups against a control.

Qualitative empirical studies involve small numbers of participants (ranging from approximately 10 to 24), with the exception of Dutto et al. [44], likely reaching over 100 individuals. Three studies engaged expert groups as in Caballero et al.'s [38] immersive virtual reality training for government experts. Bodzin et al. [37] proposed a flood preparedness virtual reality game, involving 24 participants in a usability test, while Posluszny et al. [58] presented a case study to be further discussed in the educational methodologies section.

3.2.2. Limitations of the Studies

While examining the research designs of the identified studies, two recurring limitations were found. Firstly, only three studies are strictly experimental, therefore making questionable the possibility to consider educational methodologies as determinant factors for the results of the study. When reading below the paragraph on the findings emerged from the reviewed studies, this important limitation must be kept in mind. Secondly, most studies prioritize usability over educational effectiveness, often measuring outcomes through participant perceptions. This focus, of course, prevents the generalization of conclusions on the best teaching and training strategies for DRRE.

It is also worth remembering that the seven studies classified as non-empirical advance simulations activities for DRRE, without including any validation of the educational effectiveness of the activity itself. Therefore, it can be stated that the majority of studies lack robust research designs and focus less on evaluating the educational impact of XR-based uses for disaster risk reduction education.

The lack of methodological elaboration is also proven by the scarce attention given to the analysis and discussion of limitations (only 10 studies out of 34). On the contrary, the studies based on a stronger experimental research design go deeper in the examination of limitations, providing useful insight. For instance, Feng et al. [46] acknowledge their study's failure to measure long-term knowledge retention and its reliance solely on a comparison between immersive virtual reality serious games (IVR SGs) and traditional instruction, suggesting the integration of both approaches would be beneficial. Other studies highlight simulation-specific limitations, such as the exclusion of building collapse scenarios [50] and the cumbersome process of selecting and collecting items in the proposed game [39]. Liuwandy [52] identifies the main limitation of his educational activity in the inability to select more than one room for earthquake simulation. Hirokane et al. [48] recommend broadening the variety of disaster scenarios and increasing participant numbers. Lastly, some studies emphasize the need for validating the educational effectiveness of their interventions, indicating a future direction for research to confirm whether VR experiences can motivate action or behavior change regarding issues like climate change [58] and the necessity for a quantitative evaluation to ascertain training effects [60].

3.3. Educational Methodologies Utilizing XR Technologies

In examining the studies from an educational methodology perspective, attention was directed towards specific aspects as follows: (1) the target audience for XR-technology-based educational activity and their educational level, (2) the pursued learning objectives, and (3) the educational uses of XR technologies.

3.3.1. Target Audience and Their Educational Level

The studies examined herein address two primary target groups (Figure 8). Nineteen studies target formal educational settings, focusing on either students or teachers. Among these, 16 studies concentrate on educational simulations for students across various educational levels, primarily secondary and higher education. Noteworthy, four studies specifically cater to primary school students, with Abdulhalim et al. [55] notably considering Deaf and Hard of Hearing (DHH) children in earthquake preparedness.

In the second group, fifteen studies target the general public. While Bodzin et al. [37] and Rismayani et al. [53] propose immersive simulations for adults and all age groups, respectively, 13 studies lack information on educational levels. Noteworthy, only Caballero et al. [38] focuses on disability, designing a simulated training system for disaster risk management tailored to individuals with hearing impairments.

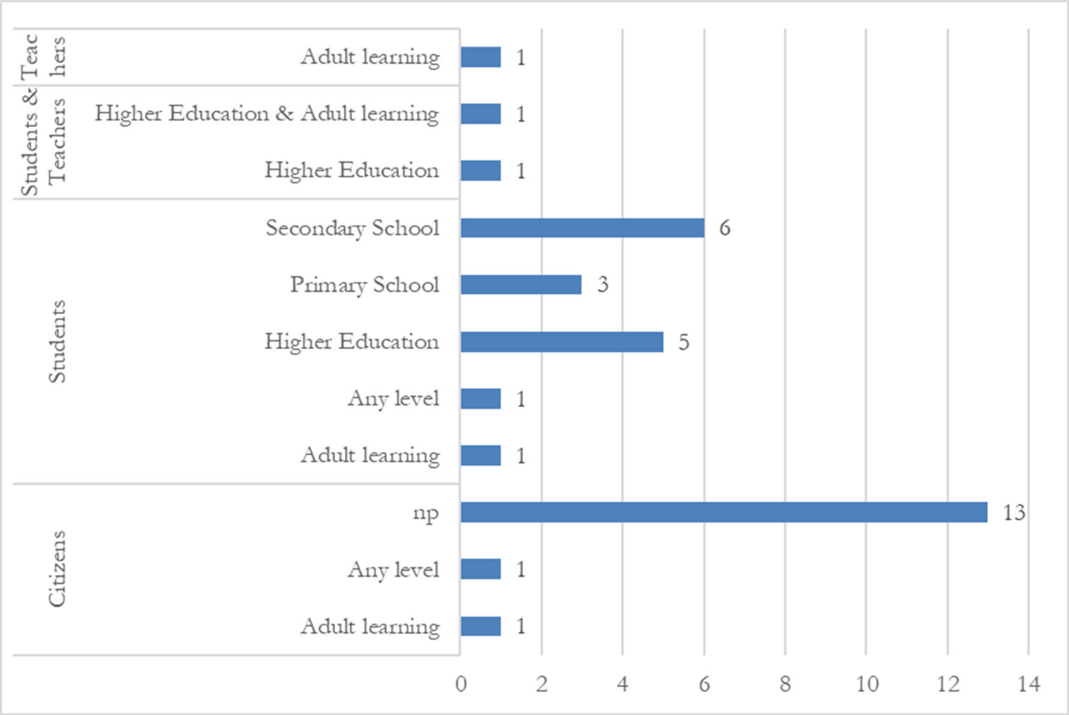


Figure 8. Number of studies per target audience and their educational level (Each study may encompass objectives falling within multiple categories, thus exceeding the total of 34 occurrences corresponding to the studies analyzed).

3.3.2. Learning Objectives

The learning objectives and related educational methodologies are analyzed as the second aspect. Figure 9 classifies the objectives into four categories: risk awareness, survival skills, risk preparedness and management, and human–nature interaction knowledge.

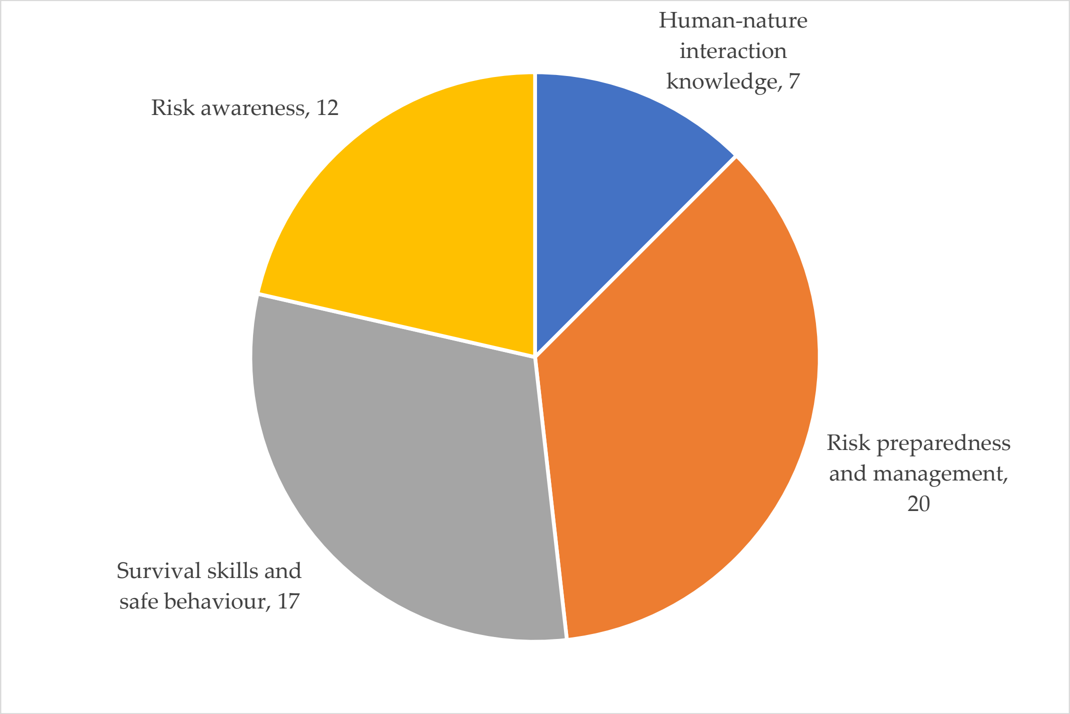


Figure 9. Number of studies per learning objectives pursued.

Twenty studies focus on objectives related to risk preparedness and management. For example, Bodzin et al. [37] aim to enhance understanding of flood preparation and mitigation, while Purnomo et al. [59] seek to improve community understanding of flood disaster preparedness for swift and appropriate responses.

The second most common category of learning objectives (17 studies out of 34) focuses on the specific skills and behaviors required to survive natural disaster emergencies. Typically, these studies employ evacuation simulations. For example, Liang et al. [51] aim to provide knowledge on safe evacuation during earthquakes, while Liuwandy [52] intends to guide people on appropriate steps during earthquakes at home without jeopardizing safety. Similarly, Ooi et al. [54] seek to enhance knowledge about evacuation behavior and disaster prevention awareness.

Less frequent are learning objectives related to risk awareness (12 studies), entailing not only knowledge and skills but also attitudes towards natural risks in a specific area. For example, Caro et al. [39] stress the importance of hazard perception and risk awareness, while Pamenang et al. [56] look at raising awareness of earthquake risks. Similarly, Yoshida et al. [8] focus on disaster awareness and preparation, allowing individuals to take detailed disaster-avoidance measures.

Lastly, seven studies tackle the issue of developing knowledge about the natural phenomena leading to potential disasters and the impact of human actions on them, categorized as "human–nature interaction knowledge". For instance, Demir [43] proposes a simulation to educate students about hydrological processes and the effects of human activity on floodplains.

3.3.3. Educational Use of XR Technologies

To analyze the educational methodologies adopted by the reviewed studies, full texts were scanned for words related to possible teaching methodologies, strategies, or techniques, such as cooperative learning, peer education, flipped classroom, laboratory teaching, etc. This exploration yielded minimal results, indicating that most papers presented XR tools (prototypes or applications) without providing a detailed description of the educational methodologies implemented. Figure 10 shows the types of XR technologies used (AR, VR, MR) and their application with individuals or groups. Immersive VR was the most frequent technology, primarily for individual use.

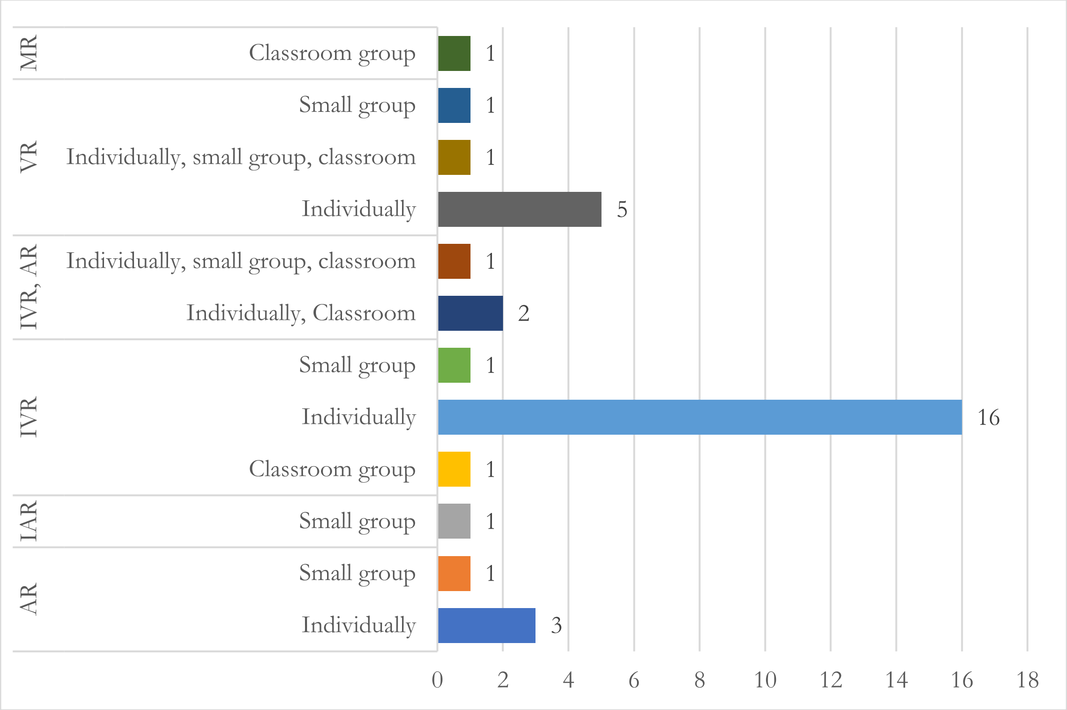


Figure 10. Number of studies per type of XR utilized and their application.

Figure 11 summarizes the learning strategies employed. All studies used simulations, with two groups identified. The first (14 studies) focused solely on simulations, while the second (20 studies) incorporated simulations within a game-based learning approach.

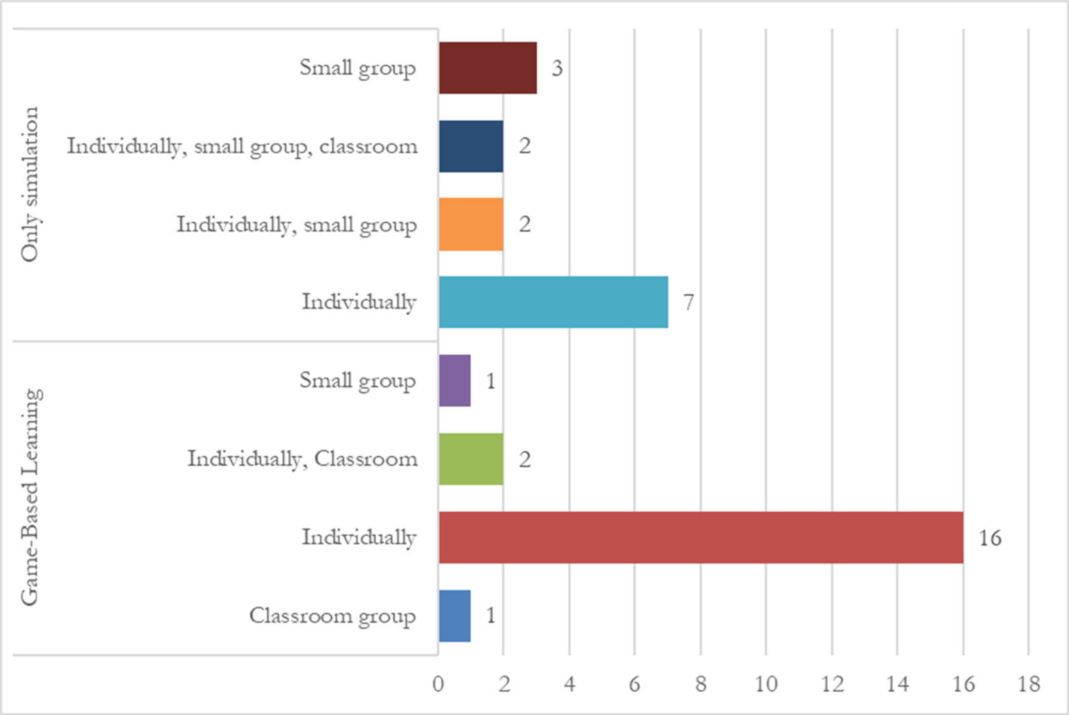


Figure 11. Simulation or game-based learning per type of group.

As emerged from Figure 11, most studies design activities for individual learners, with a limited focus on small groups or entire classrooms. While all studies suggest specific educational uses for their XR tools, no one presents a comprehensive pedagogical framework. Elements like context, learning objectives, assessment tools, and activity durations are often missing. One exception was the study by Dai et al. [42], which clearly defines the context and learning materials for a flood management simulation game. It includes a virtual science education room, an immersive flood experience room, and a game room for practicing escape strategies.

Regarding formative assessment, studies employing a game-based educational approach within their simulation storyboards often encompass feedback mechanisms akin to formative evaluation, although not all studies explicitly state it. For example, Feng et al. [47] outline a game teaching earthquake behavior, offering formative feedback when players encounter problems. Caro et al. [39] discuss personalized learning in their game, adapting activities based on user characteristics.

Among game-based learning studies, Abdulhalim et al. [55] undertook a systematic review of Immersive Virtual Reality Serious Games for earthquake preparedness among Deaf and Hard of Hearing (DHH) children. The study found an unspecified number of papers, primarily directed toward vulnerable communities rather than specifically towards DHH children. After selecting the papers for inclusion, they were analyzed based on a disaster risk reduction education (DRRE) framework employed in New Zealand. This 4R framework includes four stages for DRRE, from the simplest to the most complex: Readiness, Reduction, Response, Recovery. Abdulhalim et al. [55] found that only a few studies progressed to the more complex stages (Response and Recovery).

In addition, interestingly, Abdulhalim et al. [55] present an educational framework for DRRE and analyze its functions and limitations in light of studies using Immersive Virtual Reality Serious Games for DRRE.

Among the 14 studies solely proposing XR technology-based simulations without a game-based learning approach, a few exceptions explore specific educational strategy aspects. For example, Chiou and Shen [41] adopt an augmented-reality-based tornado simulator, employing collaborative learning. Similarly, Chiou and Barrnaki [40] propose collaborative learning with virtual experiments and activities. In this cluster of studies, three stand out for their unique educational approaches. Firstly, Posluszny et al. [58] guided university students in designing a virtual reality story about sea-level rise using a user-centered instructional approach. Secondly, Takahashi et al. [60] developed a system to train teachers in emergency evacuations via an immersive earthquake simulation. Teachers undergo repeated simulations with various scenarios projected on large screens. Thirdly, Yoshida et al. [8] proposed a photo-based virtual experience system for learning disaster behavior. Users relive past experiences to learn from them, visualizing routes and environments to understand alternative actions.

3.4. Findings and Educational Affordances of XR Technologies for DRRE

Finally, the scoping review attempted to extract the authors' identified findings and educational affordances of XR technologies from the examination of the full-text articles.

3.4.1. Findings

While the evidence found was of varied quality in terms of methodological soundness and weight (see above "Research methodology" paragraph), in Figure 12, findings from the reviewed studies are classified into five categories.

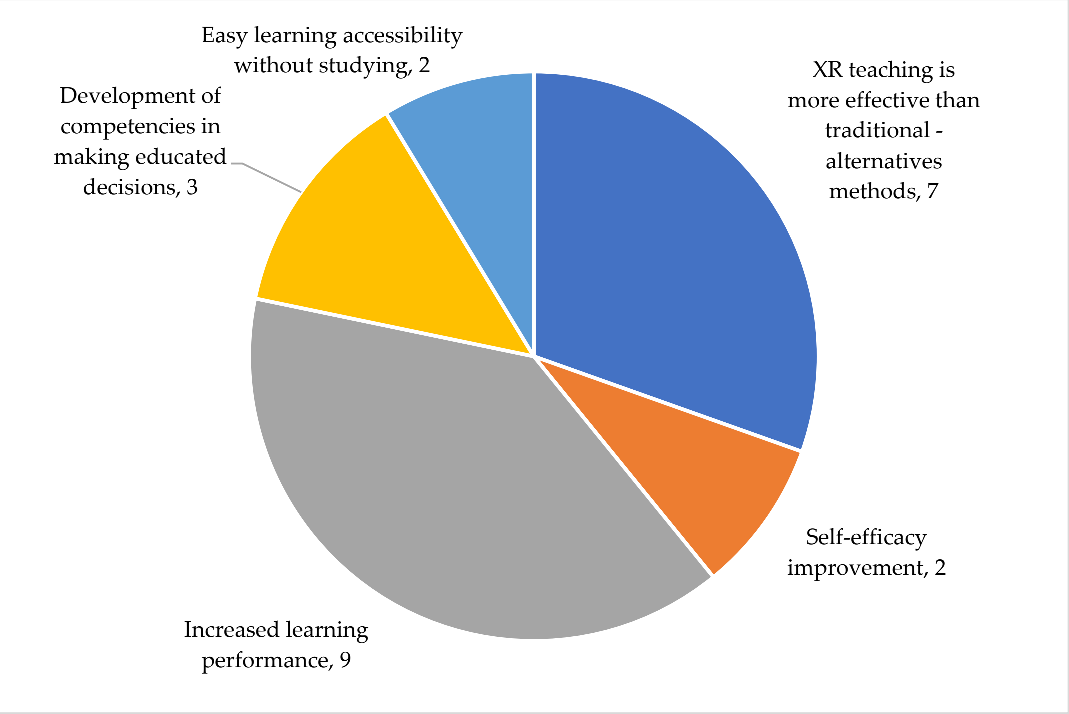


Figure 12. Number of studies per type of findings (Each study may identify outcomes across multiple categories, resulting in a sum of occurrences higher than 34, which is the number of studies analyzed).

The category with the highest occurrences is "increased learning performance". Within this category, nine studies suggest that immersive virtual or augmented reality is effective in achieving learning objectives (see above "Learning objectives" paragraph). Four of these studies assert that it is more effective than other methods. These studies employ experimental or quasi-experimental designs, except for Caballero and Niguidula [4], utilizing a qualitative approach.

The second most recurrent finding concerns the effectiveness of XR technology-based training compared to traditional methods. Seven studies emphasize this outcome, employing experimental or quasi-experimental designs, except for Caballero and Niguidula [4].

Other categories include the development of decision-making skills in natural disasters (two studies), such as Caballero et al. [38] confirming the utility of simulated disaster training for decision-making. “Self-efficacy improvement” was observed by Feng et al. [46] across all trainee groups. Lastly, easy accessibility to learning through XR technologies was highlighted by Liuwandy [52], stating that users can grasp virtual reality applications without prior study.

3.4.2. XR Educational Affordances

In Figure 13, the educational affordances highlighted by the examined studies have been categorized into seven categories.

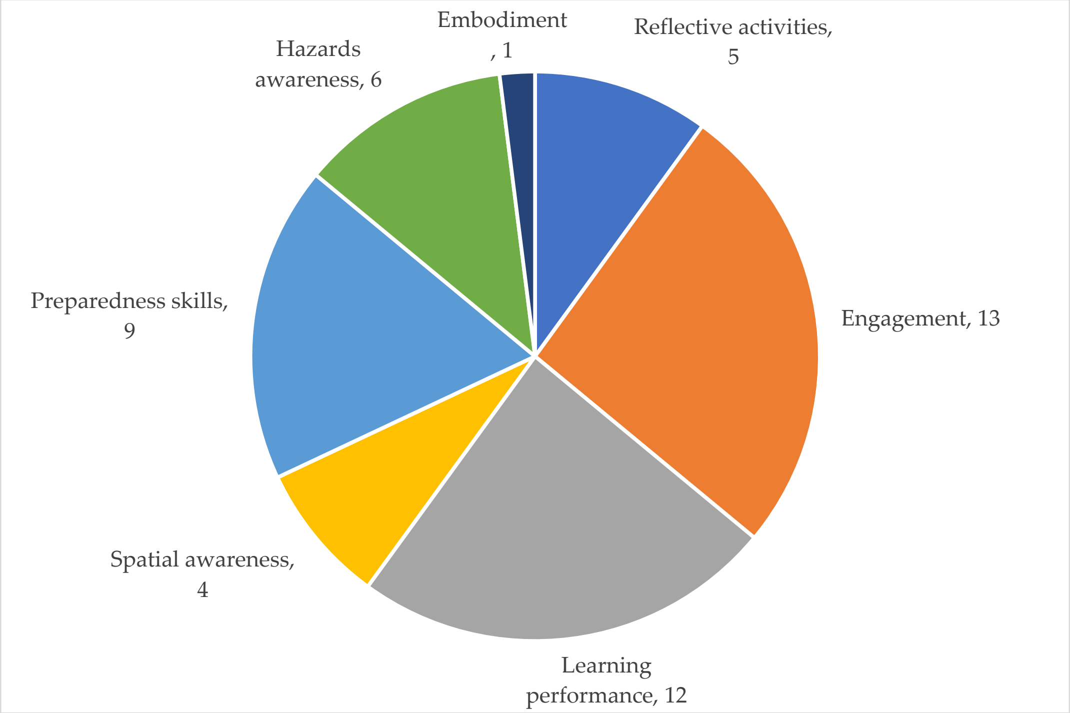


Figure 13. Number of studies by type of educational affordances identified for XR technologies (Each study may have identified affordances falling within one or more of these seven categories; thus, the sum of occurrences presented in the graph exceeds 34, which represents the number of studies analyzed).

Many categories align with the educational affordances of XR technologies already identified in the literature [31,68,69], namely spatial awareness, embodiment, reflective activities, and engagement. Engagement, in particular, stands as the category with the highest occurrences: 13 studies reported it as a specific affordance of XR technologies for DRRE. For instance, Pedersen and Irby [57] (p. 41) observe that “students were on-task, directed their own actions, and engaged in inquiry activities”.

The second most frequently occurring category (12 studies) involves learning performances. For example, Asgary et al. [35] (p. 552) argue that “the application can [...] enhance learning and training and improve preparedness and risk understanding”.

Other studies (9) identify an affordance which is more specifically linked to the learning skills necessary for reducing risks stemming from natural disasters. For example, Li et al. [50] write that through the proposed virtual environments in the event of an earthquake, "The user will learn to avoid and protect his head by his arms from dangerous falling objects in the training process" [50] (p. 3).

Lastly, an intriguing affordance is associated with the XR technologies' capability to develop an attitude termed "hazard awareness", closely related to risk perception. Six of the analyzed studies suggest that XR technologies can enhance awareness of how certain natural phenomena work, potentially increasing risk perception. For instance, Ooi et al. [54] (p. 30) state that "The system [...] gives awareness to the students themselves, improves consciousness of disaster prevention".

In conclusion, the studies identify results primarily related to learning outcomes achieved through an XR-based approach that appears more effective than traditional approaches. However, the validity of these conclusions is highly subject to the variability of the research designs used in the analyzed studies. In the few cases where the study is experimental, validity is greater, while in many other instances, the identified results are just hypotheses.

Regarding the educational affordances of XR technologies for DRRE, studies predominantly identify the same affordances already recognized in the specialized literature. Among these, the most recurrent is engagement, which undoubtedly plays a functional role in acquiring specific knowledge and skills for reducing risks associated with natural disasters.

4. Discussion

4.1. Key Insights from the Scoping Review

In the introduction, the field of environmental risk and natural disaster education was briefly outlined, emphasizing the potential use of XR technologies in this context. To identify educational methodologies, recently proposed or validated, that utilize XR technologies, a scoping review was conducted with the following main research question:

> *RQ: What educational, didactic, and training methodologies based on the use of extended reality and immersive digital environments can be suggested to enhance the preparedness of teachers, students, and citizens for environmental risks and natural disasters, including those related to climate change?*

This primary question was broken down into five secondary questions, each addressing various aspects analyzed in the 34 studies, published between 2013 and 2023, included in the scoping review (Table 6).

Table 6. Secondary research questions.

Secondary Question	Analyzed Aspects
RQ1	Context and Type of Addressed Risk
RQ2	Types of Studies Found (Methodology, Target Audience, and Limitations)
RQ3	Learning Objectives
RQ4	Teaching/Training Methods and Tools
RQ5	Findings (in terms of achieved learning outcomes or methodological–didactic reflections, including the pedagogical affordances of XR technologies)

Firstly, regarding RQ1, the studies exhibited a rising trend in scientific production from 2016 onwards, with earthquakes (12 studies) and floods (9 studies) being the most addressed risks, primarily from Asia (18 studies), notably influenced by Japan's contributions (7 studies), due to its technological advancement and seismic vulnerability.

Secondly, regarding RQ2, the research methodologies were categorized into empirical (26 studies) and non-empirical (8 studies). The empirical studies involved user or expert validation, while the non-empirical studies lacked user involvement, often presenting conceptual proposals. Among the empirical studies, various approaches were utilized, including predominantly quantitative, qualitative, or mixed-method designs, with the majority favoring quasi-experimental designs. Only a few studies employed fully experimental designs, and the findings have both internal validity (the hypotheses are verified) and external validity (the findings are generalizable); when the studies are quasi-experimental, the results have good internal validity but are not generalizable; in all other cases, the identified findings remain hypotheses to be further verified.

Thirdly, regarding RQ3 and RQ4 from an educational standpoint, 20 studies target students (primarily in secondary or tertiary education), while 15 aim at the general public. The learning objectives focus mainly on risk preparedness (20 studies) and survival skills (17 studies), with 12 studies addressing attitudinal shifts, like risk awareness. However, the selected research designs rarely allow for a valid assertion of achieving these objectives. The XR technologies are predominantly used for disaster simulations in all the studies, with 14 employing a game-based learning approach. Only a few studies explicitly outline educational strategies, like personalized learning [39] or collaborative learning [41], or offer comprehensive frameworks, such as the 4R framework by [58].

Finally, concerning the findings highlighted by the studies (RQ5), they are primarily related to learning outcomes achieved through an XR-based approach that appears more effective than traditional approaches. Regarding the educational affordances of XR technologies for DRRE, the studies predominantly identify the same affordances already recognized in the specialized literature. Among these, the most recurrent is engagement, which undoubtedly plays a functional role in acquiring specific knowledge and skills for reducing risks associated with natural disasters.

4.2. Strengths

The literature on the educational use of XR technologies for environmental risk and disaster preparedness reveals notable strengths and weaknesses. Its primary strength lies in providing a wealth of ideas, prototypes, and applications for simulations or serious games, facilitating the design and development of instructional programs for disaster risk reduction education (DRRE). These solutions cover various risks and disasters, offering detailed device descriptions for inspiration.

Another strength is the diversity of research methodologies employed. This complexity reflects the nature of educational challenges [70] and draws from various research approaches, including case studies, experimental validations, usability checks, conceptual proposals, mixed-method studies, and systematic reviews. However, while the methodological approaches show the highlighted limitations (see above “Limitations of the studies” paragraph), they also showcase a variety of perspectives that reflect the complexity of the topic under examination, enriching the scientific discourse on the use of XR for DRRE.

The third strength is linked to the potential of using XR technologies for DRRE. While the literature still has limited studies (34) on the subject, the findings of this scoping review highlight the pedagogical affordances of using XR for DRRE and indicate potential avenues for further research. Specifically, many studies highlight, among their findings, the opportunity to develop, through XR technologies, knowledge and skills for managing emergencies derived from natural disasters, without exposing individuals to real risks. XR technologies ensure a high level of engagement among users, allowing them to experience simulated scenarios. It has been observed how prior experience tends to increase risk perception, which is important insofar as moderate risk perception helps adopting protective behaviors [20]. Therefore, one could conclude that simulated experiences may also elevate risk perception. However, given the type of evidence for this conclusion, it still needs to be confirmed, which bring us to the recurrent and already-mentioned weaknesses found within the analyzed literature.

4.3. Weaknesses

There are some important weaknesses in the examined research on the educational use of XR technologies for disaster preparedness. Firstly, the body of studies on this topic is limited to just 34 studies published in 10 years. However, as observed in the results' section, it is a growing field of study, and it is likely that, in the future, more students will be involved in activities based on the use of XR technologies. Consequently, there is a likelihood of increased research in this area, necessitating the synthesis of evidence, as conducted in the present scoping review.

Secondly, a notable deficiency is associated with the absence of comprehensive educational frameworks surrounding the proposed XR tools. While studies highlight the potential educational benefits of XR simulations, none provide a structured framework outlining specific objectives, learner prerequisites, materials, timelines, or assessment methods.

Thirdly, the literature reveals methodological weaknesses, as detailed in Section 3.2.2. Here, we add that the five studies with a more rigorous research design only aim to teach knowledge and skills. However, developing competencies requires focusing on three components: knowledge, skills, and attitudes [71]. Among the most crucial attitudes for managing natural disasters is risk perception, which is essential for adopting protective behaviors [20]. These five studies do not target attitude change. Consequently, none of the 34 studies can assert, with good internal validity, that the use of XR-based educational activities can lead to attitude changes toward environmental risks and disasters. This highlights the need for research on XR-based educational programs that target not just knowledge and skill acquisition but also changes in attitudes, such as risk perception, to build competencies for risk reduction, disaster management, and community resilience.

4.4. DRRE and Education on Uncertainty

From a pedagogical standpoint, it is essential to broaden disaster risk reduction education (DRRE) beyond merely teaching about risk to include education on uncertainty and complexity. Vignoli et al. [72] draw a distinction between risk, where the probability of future events is known, allowing for outcomes to be estimated, and uncertainty, where outcomes are too unpredictable for probability calculations or completely unknown. They identify three sources of uncertainty: social interactions that affect personal decisions; the quality and amount of information available for making decisions; and fundamental uncertainty, arising from these sources, characterized by an inability to predict outcomes. The authors explore how economic uncertainty, exacerbated in the globalized era by the information and technology revolution, influences decisions such as having children, but in the Western world, things have changed in recent decades: globalization intensifies economic uncertainty through increased worldwide social connections and the information revolution, where growing information does not necessarily enhance clarity [72] (p. 29).

Regarding natural hazards, it can be argued that a similar process is underway. Natural risks and disasters have always been present [9], but recent climate change is increasing their frequency and intensity while diminishing predictability [2]. Therefore, it seems necessary not just to prepare citizens (starting from children) to manage emergencies caused by natural disasters (earthquakes, floods, etc.) through protocol-based knowledge or skills. It appears crucial to focus on raising awareness that disasters can be more frequent, intense, and unforeseen. In other words, it is essential to work not only on knowledge and skills but also on attitudes, such as risk perception.

As outlined in the introduction, a recent meta-analysis on variables influencing natural risk perception (Theodorou et al., submitted) revealed three factors that carry significant weight in determining risk perception: (1) awareness of climate change, (2) the presence of negative emotions (like environmental concern, worry about flood risk or adverse weather conditions, anxiety, anger, fear, depression), and (3) the perceived probability of the event (such as floods, tsunamis, droughts, deforestation).

The studies reviewed in this scoping review, particularly the five methodologically robust studies, demonstrate that it is possible, through educational activities based on XR technologies, to enhance knowledge of the functioning of certain natural phenomena. However, these studies only partially address awareness of climate change. Educational interventions based on XR technologies targeting all three factors identified in the literature on risk perception remain to be designed. Additionally, future research on this topic should consider the "risk perception paradox" because a high perceived risk often is not associated, or even negatively associated, with protective behaviors [20]. To account for this, it would be useful to measure, after designing an educational intervention for a specific group, the risk perception of each individual. This could allow adjustments in the intervention only for those with low perception to avoid increasing risk perception in those already perceiving it adequately (or excessively), potentially reducing the inclination to adopt protective behaviors. Therefore, future research on the use of XR technologies in disaster risk reduction education (DRRE) can benefit from the knowledge acquired so far. Starting from the wealth of ideas present in the literature, it is possible to design a comprehensive educational program, subsequently evaluating its effectiveness with a robust research design that incorporates the variables highlighted by research as relevant.

5. Limitations

This scoping review has revealed a variety of educational activities based on extended reality (XR) for disaster risk reduction education in the literature. The limitation is mainly due to the small number of studies examined (only 34 articles). On the other hand, the authors' choice is related to restricting the field to articles in English published in the last 10 years. The authors are, therefore, aware that what is reported here is a partial view and primarily refers to the Western world. In this regard, we point out that although there are many contributions from Asia (see Section 3.1), the majority come from Japan, which, from a geopolitical standpoint, can be considered closely aligned, at least regarding the subject of the present study, with the Western world.

6. Conclusions

Despite the limited corpus of studies analyzed, the growing threat of natural disasters and immersive education's potential clearly emerges, in particular the increase in student engagement through XR technologies. The 34 studies examined demonstrate a growing field of research addressing this topic with diverse methodological approaches. Collectively, they show how XR-based educational activities promote the engagement of students and teachers, facilitating the acquiring of knowledge and skills critical for the prevention and management of natural disasters.

In summary, this scoping review analyzed the English-language scientific literature from the past ten years on the use of XR technologies for disaster risk reduction education (DRRE). The analysis focused on several areas, corresponding to different sub-research questions: context and type of addressed risk, study methodologies, educational and/or didactic approach, and findings. For each aspect, the results can be summarized, and recommendations for future research can be derived.

First, regarding the context of publication and the type of risk addressed, research is particularly prolific in countries like Japan, which are characterized by both exposure to disasters and high technological development. However, many countries have the former characteristic but lack the latter; therefore, scientific communities should collaborate to make knowledge and technological tools available where they are needed, leveraging their potential for DRRE.

Second, concerning the methodology of the analyzed studies and the highlighted findings, it would be beneficial to strengthen empirical studies with experimental or quasi-experimental designs to increase internal validity. This would allow for more robust claims that certain educational practices based on the use of XR technologies are effective in achieving specific learning outcomes. Qualitative and mixed-method approaches can undoubtedly contribute to the research on XR technologies for DRRE by providing a more comprehensive understanding of their educational impact.

Finally, from an educational standpoint, current studies mainly focus on the knowledge and skills necessary for survival. Future research should develop and evaluate comprehensive educational frameworks that also include promoting attitudes such as risk perception among their learning objectives.

Despite the limitations stated above, this paper aims to offer the reader some original contributions.

The first original contribution of this scoping review is the identification of the strengths in recent research on the use of XR technologies for DRRE. These strengths include a wide range of ideas, mostly simulations or serious games, produced from various methodological perspectives (quantitative and qualitative), highlighting the affordances of XR technologies for DRRE. Among these affordances, engagement stands out, as already widely demonstrated by the literature on the use of these technologies in other educational fields [31,68,69].

The second original contribution lies in identifying the weaknesses in the research on XR technologies for DRRE. First, it outlines a field that still comprises a limited number of studies, although it is growing. Second, the analyzed research rarely relies on comprehensive educational frameworks that include objectives beyond the acquisition of knowledge and skills for DRRE, such as promoting attitudes favorable to risk management, like risk perception. This aspect relates to another weakness of the analyzed research corpus: there are no experimental or quasi-experimental studies demonstrating, with good internal validity, the effectiveness of XR technologies in promoting attitudes useful for risk management.

The final and most significant original contribution is the hypothesis that DRRE can be conceived as part of a broader education on uncertainty and complexity, aiming at ambitious educational goals, such as the development of competencies, rather than just the acquisition of knowledge or skills. To address the growing uncertainty of the contemporary world and the increasing disaster risks accompanying this uncertainty [1], it is necessary to develop “well-made” heads, as Morín [73] would say. These are heads not only full of knowledge but also capable of using their knowledge and skills in new contexts, driven by attitudes functional to managing new problematic situations.

In summary, it is essential to develop competencies based on knowledge, skills, and attitudes with a central role given to risk perception [20]. In this sense, this review suggests that XR technologies could be a valuable tool for developing this attitude, while future research should propose ideas, simulations, and educational experiences to be experimentally tested, within a sound educational design, to verify this hypothesis.

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