Virtual, Augmented, and Extended Reality Applied to Science Communication: A Systematic Literature Review

Juan Romero-Luis, José Luis Rubio-Tamayo, Alberto Sanchez-Acedo, Daniel Wuebben, and Valeri Codesido-Linares

***Abstract*—Extended reality (XR)—which includes virtual reality (VR) and augmented reality (AR)—is becoming increasingly popular for sharing scientific knowledge. This research evaluates the state-of-the-art in XR for scientific communication. Our two-phase methodology began with a Systematic Literature Review, identifying 94 relevant articles and conference papers from the last decade (2013-2023) sourced from the Web of Science and SCOPUS databases. These publications show scholars and practitioners using XR to convey scientific findings, foster awareness, ignite interest, shape opinions, and enhance understanding. In the second phase, we applied data clustering and analysis. Our findings highlight a significant increase in XR studies over the last decade, with the XR technologies used for communication (N = 24), dissemination (N = 23), educational/training (N = 21), and decision-making (N = 10). Our results indicate the need to establish clearer guidelines for aligning science communication and to create more possibilities to publish peer-reviewed research in.**

***Index Terms*—Scientific communication, public understanding of science, extended reality, XR, virtual reality, VR, augmented reality, AR, Mixed Reality, MR.**

I. Introduction

SCIENCE communication is a multidisciplinary field that involves using various skills, media, and dialogic approaches to foster public awareness, enjoyment, interest, and understanding of science [1]. The discipline emphasizes personal and societal engagement with scientific knowledge, serving as a critical bridge between science communities and broader publics [2]. In today's digital age, emerging technologies like "virtual reality" (VR), and "augmented reality" (AR) are encompassed by the umbrella term "extended reality" (XR). Emerging XR technologies represent advanced media tools; they also form entirely new communication systems with the potential to transform how knowledge is generated, curated, disseminated, and democratized. Aspects of "immersiveness," "embodiment," and "presence," reveal some of the new dimensions of modern XR communication tools and frameworks [3], [4], [5], [6].

In addition to providing exciting opportunities to represent cutting-edge research and concepts within the scientific community, XR technologies are inspiring pedagogical innovations in various fields such as education, training, and data visualization [7], [8]. Immersive, engaging learning experiences can bring scientific concepts to life and foster a deeper understanding and appreciation of scientific principles. Indeed, applying XR tools to science communication can foster scientific literacy and promote a culture of scientific inquiry.

Despite growing recognition of XR's potential to transform how scientific content is disseminated and understood, there has been limited systematic analysis of its application within the domain of science communication. Previous literature reviews have been limited to identifying overall applications of XR (36) or how it has been used for education [9], citizen engagement [10], museum experiences for cultural heritage [11], Industry 4.0 [12], immersive journalism [13]. This fragmented approach underscores the need for a comprehensive, systematic review that shows how XR technologies have been applied and evolved within science communication.

The primary objective of this study is to explore the current state and potential developments of XR as a subject of study for communication researchers and means for disseminating scientific content. To fulfill this primary objective, we conduct a systematic literature review with three specific objectives:

- (SO1) Chart the evolution of publications in the field over time.
- (SO2) Identify and categorize the technologies employed to research XR both as a medium and as an outcome of scientific communication.
- (SO3) Assess the methodologies, data collection techniques, and sample sizes employed in these studies.

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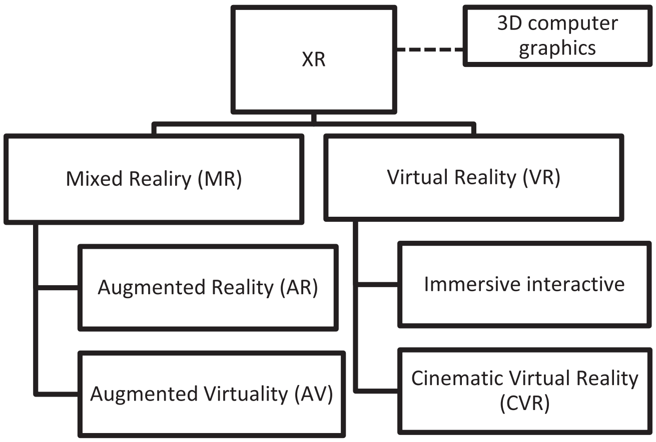

Fig. 1. Typology of the concepts related to XR was considered to help conduct the literature review.

II. Background on VR, AR, and XR Research

From a communications perspective, VR (Virtual Reality), AR (Augmented Reality), and XR (Extended Reality) represent transformative media technologies defined by their immersive and interactive capabilities—attributes that distinguish them from traditional media. These technologies have been employed across various research domains and content development contexts. Originating in the early 1990s, pioneers such as Biocca [14], Lanier ([15], and Machover & Tice [16] explored the potential of VR, while contemporaries such as Drascic [17] and Caudell [18] advanced AR technologies. Biocca's work [14] draws a compelling analogy between VR and the advent of television in the 1940s, explaining that each evolved from a technical innovation to become a cultural phenomenon.

In terms of education and training, scholars such as Bricken [19], Helsel [20], and Pantelidis [21] have examined the capacity of XR and VR to craft immersive and interactive learning environments. Studies by other authors, such as Heinonen [22] also emphasize this benefit, and [23] Feibush also highlights the opportunities of the extended reality medium for scientific visualization. The terms "training environment" and "learning environments" frequently arise in discussions about the educational applications of VR, AR, and the rest of XR technologies [24], [25], [26], [27]. These studies underscore the unique potential of XR technologies facilitating hands-on, experiential learning that traditional methods cannot replicate.

More recent advancements in XR technologies have also transformed scientific communication, offering new modes of abstraction and representation. For example, Trench's analytical framework for science communication [28] highlights how XR might convey complex scientific concepts. concepts. Furthermore, Çöltekin et al. [29] investigates the challenges and future projections in this area and Rubio-Tamayo et al., [30] have proposed a framework for establishing XR development standards. However, these guidelines and recommendations are recent and need to be put into practice in the development of research in this area.

Science communication theories offer further insights for designing and evaluating XR-based interventions. For instance, the deficit model, which traditionally views the public as lacking scientific knowledge, can be reimagined through XR as an opportunity to create interactive and engaging educational experiences that bridge knowledge gaps. The public understanding of science (PUS) framework emphasizes accessibility, aligning well with XR's potential to present complex information through immersive simulations. Additionally, science engagement approaches highlight the importance of dialog and participatory experiences, suggesting that XR applications should prioritize interactivity and audience feedback. These theoretical foundations provide a crucial lens through which we can critically examine the practical implementations and technological characteristics of XR tools designed to enhance scientific communication and engagement.

III. Definition of Terms and Constructs

For a comprehensive understanding of existing research and future trends, it is imperative to acquaint oneself with the following terminologies: XR, VR, Mixed Reality (MR), AR, CVR, and 3D computer graphics. These terminologies form the foundation of the research's analytical framework. Detailed elucidation of these terms, provided henceforth, is essential to grasp the research findings and to appreciate the analytical perspective adopted by the authors.

Extended reality (XR): XR encompasses advancements in VR, AR, and MR, serving as an overarching term for these technologies. Defined by scholars like Chuah [31] and Andrews et al. [32] traced back to Milgram and Kishino's [33] "continuum of virtuality." Milgram and Kishino's model has inspired the reality-type taxonomy with XR at the top (Fig. 1). XR represents a broad spectrum of reality technologies and here, we primarily adopt XR as the means of examining the innovative technologies applied to scientific communication.

Virtual reality (VR): The definition of VR has evolved over the last few decades, with contributions from various authors [5], [14], [34], [35]. Broadly, VR can be defined as a 3D, immersive experience created with computer graphics, which simulates a physical space with varying levels of realism. The term "virtual reality" includes the subcategories of interactive virtual reality, which allows interaction with objects, and cinematic virtual reality (CVR) [36], [37] CVR is an immersive film presented in 3 degrees of Freedom (3doF), and it blends features from the video medium while offering limited interactivity. Access to virtual reality is common, though not exclusively, through a head-mounted display (HMD).

Mixed reality (MR): MR merges real and virtual worlds to produce new environments where physical and digital objects co-exist and interact in real time. Grounded in the works of Milgram and Kishino [33], it includes AR and, to a lesser extent, augmented virtuality (AV). AR, as detailed by Feiner [38] and Azuma [39], overlays digital content onto the real world via devices like smartphones or HMDs. MR is integral to XR studies, building on the virtuality continuum concept.

3D computer graphics: This term is closely related to virtual reality [40], [41], particularly its potential for generating immersive and interactive content. Technically, 3D computer graphics

TABLE I
RELATIONSHIP BETWEEN SO AND RQ

SO	RQ
SO1	What is the number of publications registered in the last 10 years? What is the predominant format for publication of this research?
SO2	What is the most used XR technology in the studies? What is the purpose of the extended reality (XR) products conceived for scientific communication? What has been the evolution of studies according to the technology studied? Are there any common features in the XR technology used in the research?
SO3	What kind of approaches do the studies take when addressing the subject of study? What are the sampling techniques used in the studies? What is the size of the samples? Are the information-gathering techniques pertinent to the objectives of the studies?

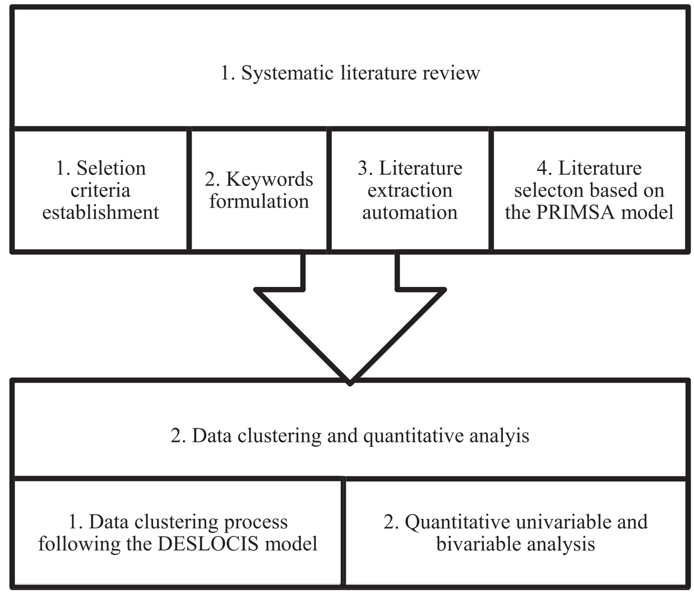

Fig. 2. Phases carried out in the thesis development.

involves artificially generated graphics, represented digitally on a device or in a medium such as XR.

Data visualization in the context of XR: Data visualization transforms information, often presented in numerical formats, into visual shapes and colors. Data visualization predates digital technologies, and not all XR technologies practice data visualization; however, the concept of data visualization is significant to this study because the remediation of information into 3D, interactive, or immersive formats, distinguishes some of the *scientific* aspects of the XR content. Following research by Kageyama et al. [42], Bayyari & Tudoreanu [43], and Archambault et al. [44], our review hopes to show how XR can and should incorporate data visualization to enhance understanding and engagement.

IV. MATERIAL AND METHODS

This research employs two methods: a systematic literature review (SLR) and qualitative and quantitative synthesis. The former corresponds to the data collection technique, while the latter pertains to the analysis phase (Fig. 2).

The SLR was conducted following several steps: (1) establishing the selection criteria, (2) formulating the keywords, (3) automating the extraction of literature, and (4) selecting the literature based on the PRISMA model. PRISMA, an acronym for Preferred Reporting Items for Systematic Reviews and Meta-Analyses, is a widely accepted method that offers a checklist of 27 items, designed to assist researchers in conducting systematic literature reviews. It encompasses four phases: Identification, Screening, Eligibility, and Inclusion [45].

The data clustering and quantitative analysis were necessary for the development of results. This process is further detailed in the upcoming subsections.

A. Systematic Literature Review

An SLR is a comprehensive analysis of all available and relevant research on a specific topic [46]. The following subsections thoroughly explain the process used to conduct it.

Initial Approach and Selection Criterion

Initially, the authors convened to establish the selection criteria. The investigation begins with the research question: What is the current state of scientific literature addressing the concept of XR within the context of scientific communication? In this first stage, we established a series of review questions (RQ) about the specific objectives (Table I).

The scope was limited to publications from the last 10 years (2013-2023) found in the Web of Science (WOS) and SCOPUS databases. These databases were selected due to their significance as search systems for researchers and professors [47] and their significance and quality across various disciplines. It was also decided that only scientific articles and conference papers would be selected to be analyzed in this study. Despite our initial decision to solely include articles in English, upon the conclusion of the screening process (see *Screening phase*), we revised our criteria to encompass articles in other languages as well. The non-English articles that were encountered were exclusively in Spanish and Portuguese. Fortunately, these languages were within the linguistic competencies of several authors, enabling them to conduct the necessary analysis.

Additionally, a content selection criterion was established for inclusion or exclusion. While the association of the XR product with science may encompass any scientific discipline [48], we only selected publications that focus on XR as a science-related communicative product designed to evoke one or more of the following responses to science: Awareness, Enjoyment, Interest, Opinion-forming, or Understanding. This aligns with the definition of science communication provided by Burns et al. [1].

To further enhance the selection criteria and reduce potential biases, we limited our scope to articles that referenced XR technologies as communication tools. We included studies where the XR products were used as a stimulus for data collection, but we did exclude studies that only referenced XR as instruments for data collection and did not consider them as tools for science communication.

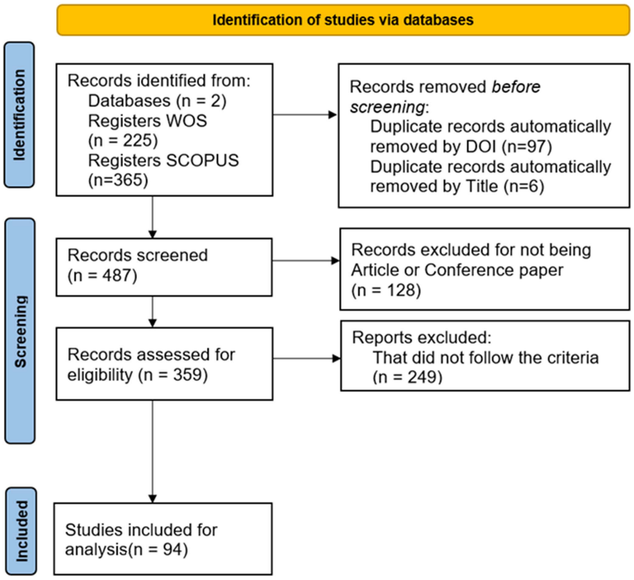

Fig. 3. Studies identification process based on the PRISMA model.

Keywords selection

The next phase involved collaboratively establishing a series of keywords. The keyword selection process was guided by several key criteria:

- Relevance: Keywords were chosen to address both XR and scientific communication fields.
- Alignment with prior research: The selection was informed by keywords used in previous related systematic literature review [13].
- Expert consensus: The selection process involved collaborative discussions among authors through face-to-face meeting discussions.

To compile literature pertinent to both scientific communication and XR, distinct sets of keywords were devised for each category. This strategic keyword creation later facilitated the construction of Boolean operators which were then employed in the ensuing phase of the research process.

Literature Extraction (Identification phase)

After developing our set of keywords, we conducted automated literature extraction from the SCOPUS and WoS databases using Harzing's Publish or Perish version 7.33. [49]. This phase coincides with the PRISMA identification phase (Fig. 3).

A complex boolean was created for the extraction:

("science communication" OR dissemination OR "scientific communication" OR "science engagement" OR "citizen science" OR "scientific journalism" OR "public engagement" OR "data representation" OR "data visualization" OR audiovisual OR "digital content" OR "social media" OR "social network" OR dissemination) AND ("virtual reality" OR "VR" OR "extended reality" OR "XR" OR "augmented reality" OR "AR" OR "volumetric video" OR "metaverse" OR "360° video" OR "360-degree video" OR "360 video" OR 360video OR 360 OR immersive OR immersion OR transmedia OR "virtual environment")

TABLE II
RESULTS OF SEARCHES CONDUCTED WITH HARZING'S PUBLISH OR PERISH SOFTWARE

Searches	WOS results	SCOPUS results
Search 1 (2020-2023)	129	189
Search 2 (2013-2019)	96	176
TOTAL	225	365
TOTAL SUM	590	

To avoid the request rate limitation imposed by databases for literature collection using *Harzing's Publish or Perish* tool, four searches were conducted whose results can be seen in Table II. A total of 590 items were retrieved. The search was conducted in two batches, with two searches in SCOPUS and two in WOS, limited by years. It's important to note that the search was performed on July 18, 2023.

During this phase, all articles identified as duplicates were discarded. The elimination process was automated and executed in two parts. Initially, duplicates were identified and removed via the DOI field, resulting in 97 duplicates. Subsequently, a second automation round identified records with identical titles, leading to the identification of 6 duplicate records. Consequently, a total of 487 records were retained for the screening phase.

Screening Phase

During the screening phase, all abstracts were thoroughly reviewed. In some cases, it was necessary to read the entire work (not just the abstract) to determine whether it met the criteria.

Records not classified as either an 'Article' or a 'Conference Paper' were discarded at this stage, resulting in the elimination of 128 studies. This left a total of 359 entries, consisting of 199 articles and 160 conference papers.

During the eligibility phase, 359 records were thoroughly evaluated. This resulted in the exclusion of 140 articles and 109 conference papers, a total of 249 records, as they didn't meet the pre-set content criteria, meaning they clearly were not related to both science communication and XR. Consequently, 115 records, consisting of 54 articles and 61 conference papers, met the criteria and were advanced to the analysis phase.

Records Included

Initially, 115 records were selected for the analysis phase. However, full text for 16 of these records was unavailable, reducing the final number of studies included in the analysis to 94. These consisted of 46 articles and 48 conference papers.

B. Data Clustering and Quantitative Analysis

After compiling the records, the clustering phase was initiated. Here, articles were established as the unit of analysis, and qualitative analysis was performed through analytical inference, guided by the 'Descriptors for a Systematic Literature

Review on Social Science' (DESLOCIS) [50]. In other words, the authors (1) read all included articles individually and (2) entered information into an online form, —using the Microsoft Forms platform— based on the openly available DESLOCIS model, meaning they use the criteria determined by the model that can be checked on the internet [50], to carry out the analytical process. This model is specifically designed to evaluate scientific literature within the realm of social sciences. Its main goal is to identify and analyze the research design, data collection techniques, and analytical methods employed in these studies. Doing so aids in distinguishing between the different approaches and theoretical frameworks used in both well-established and emerging research fields.

In addition to the variables established by the DESCLOCIS model, we decided to cluster additional information that is closely related to our object of study and was not considered by the model:

- XR is categorized into various types based on its expression in the research. These categories include interactive and immersive virtual reality, cinematic virtual reality, augmented reality, and 3D computer graphics.
- Additionally, we created a variable to identify how many studies are using data visualization in the context of XR. The analysis pinpointed articles that incorporated data visualization, either in the application's development and testing phase or in the theoretical approach or analysis. However, representations and reconstructions of varying realism levels were not classified as articles that use data visualization.

To ensure consistency in the data clustering phase, all authors participated in the process, and at the end of the clustering process, the first two authors conducted a second review to check the consistency of the data extracted from the articles.

After clustering the information, a data table was downloaded in Excel format. Subsequently, a quantitative synthesis was carried out, which produced the results detailed in the following section. Through the results obtained in the clustering process, the following clusters were thoroughly analyzed: publication year, language, type of publication (article or conference paper), XR technology type, XR technology purpose, focus on data visualization, type of research, data gathering methods, sample size, data gathering techniques, number of data gathering techniques, and sample size.

V. Results

The total number of articles is 94, of which 92 are in English, 1 in Spanish, and 1 in Portuguese. The authors, native Spanish or English speakers and one with proficiency Portuguese, conducted the selection and analysis without language restrictions. All items are available in Table III.

A. Publication Per Year

Fig. 4 shows the relationship of publications by year, segmented into conferences and research articles. An increasing trend of publications can be observed over the last 10 years with a spike in 2019 reaching a peak in 2021. However, a reduced number of publications is observed in 2020, which is notable as it precedes two years with a high number of publications. The year 2023 cannot be considered in the same way as the others, as data was collected in the second half of that year and therefore did not include all articles published before the end of the calendar year.

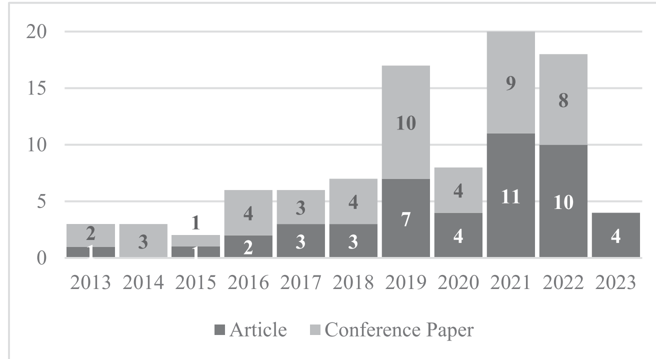

Fig. 4. Conference paper and research article publications by year.

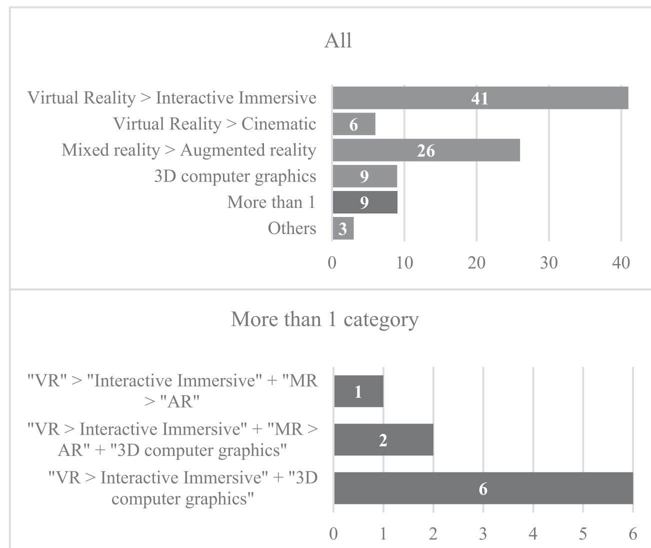

Fig. 5. Relationship between type of XR technology and the number of articles in which it is studied.

According to the annual segmentation presented in Fig. 4, it is not observed that either of the two formats analyzed (conference paper or article) predominates substantially. This trend seems uniform over the years, except for 2014. In general, an increase in publications is observed, although it is not excessive.

B. XR Technology Type and Purpose, and its Connection to Data Visualization

Upon detailed examination of the variable that identifies the type of XR technology used in each study (Fig. 5, top), it is observed that "immersive interactive VR" (N = 41) is predominant. "AR" (N = 26), which is classified under MR technologies, is identified as the second most common, with "3D computer

TABLE III
REFERENCES INCLUDED IN THE ANALYSIS

Authors	Title	Year
Wuebben, D., Rubio-Tamayo, J.L., Gertrudix, M., Romero Luis, J.	360° Video for Research Communication and Dissemination: A Case Study and Guidelines	2023
Lampropoulos, G., Barkoukis, V., Burden, K., & Anastasiadis, T.	360-degree video in education: An overview and a comparative social media data analysis of the last decade	2021
Dong, H., Liang, X., Liu, Y., & Wang, D.	5G Virtual Reality in the Design and Dissemination of Contemporary Urban Image System under the Background of Big Data	2022
Ledwidge M.	A Clever Label: Multi-sensory VR data visualization for art, productivity and communication	2022
Gandhi, K., Miller, J. A., Spatharioti, S. E., Apte, A., Fatehi, B., Wylie, S., & Cooper, S.	A Comparison of Augmented Reality and Browser Versions of a Citizen Science Game	2021
Fanini, B., & d’Annibale, E.	A framework for compact and improved panoramic VR dissemination	2016
Nisiotis, L., Alboul, L., & Beer, M.	A prototype that fuses virtual reality, robots, and social networks to create a new cyber-physical-social eco-society system for cultural heritage	2020
Macedo, M. C., Apolinário, A. L., Souza, A. C., & Giraldi, G. A.	A Semi-automatic markerless augmented reality approach for on-patient volumetric medical data visualization	2014
Lee, S.-H., Kang, H.-C., Kim, J.-S., & Lee, C.-K.	A Study on the Effects of Immersive Content Use on Positive affect, Self-esteem, and Psychological Happiness of Disabled Persons: To advocate the dissemination of immersive content facilities in island areas	2022
Zhang, N., Wan, A., Huang, J., & Cao, P.	A System Design of Virtual Reality Enabled Chinese Ancient Books for Enhancing Reading Promotion and Culture Dissemination	2022
Francese, R., Frasca, M., Risi, M., & Tortora, G.	An Augmented Reality Mobile Application for Skin Lesion Data Visualization	2020
Dinis, F. M., Guimarães, A. S., Carvalho, B. R., & Martins, J. P. P.	An immersive Virtual Reality interface for Civil Engineering dissemination amongst pre-university students	2017
Rodil, K., Fly, M., Sigmer, K. T., & Løvig, N.	An Investigation of Dissemination and Retention of Non-verbal Information About the Cultural Heritage of Rock Art in a Virtual Reality Simulation	2022
Collodel, G., Masini, M., Signorini, C., Moretti, E., Castellini, C., Noto, D., ... & Innocenti, A.	Antioxidants, Dietary Fatty Acids, and Sperm: A Virtual Reality Applied Game for Scientific Dissemination	2019
Joeres, F., Black, D., Razavizadeh, S., & Hansen, C.	Audiovisual AR concepts for laparoscopic subsurface structure navigation	2021
Casaca, A. F., Alturas, B., & Rodrigues, R.	Augmented Reality and User Experience (UX) in the dissemination of digital content from Portuguese Museums	2021
Cárdenas, M. I. Z.	Augmented reality application for dissemination of cultural heritage	2016
Harrington, M. C., Tatzgern, M., Langer, T., & Wenzel, J. W.	Augmented Reality Brings the Real World into Natural History Dioramas with Data Visualizations and Bioacoustics at the Carnegie Museum of Natural History	2019
Baker, F., & Karnapke, M.	Beyond stereoscopic: Combining spatial acquisition technologies in real-time engines to produce immersive virtual reality expereinces for the dissemination of archaeological research	2016
Natephra, W., & Motamedi, A.	BIM-based live sensor data visualization using virtual reality for monitoring indoor conditions	2019
Bibic, L., Druskis, J., Walpole, S., Angulo, J., & Stokes, L.	Bug off Pain: An Educational Virtual Reality Game on Spider Venoms and Chronic Pain for Public Engagement	2019
Berger, C., & Gerke, M.	COMPARISON OF SELECTED AUGMENTED REALITY FRAMEWORKS FOR INTEGRATION IN GEOGRAPHIC CITIZEN SCIENCE PROJECTS	2022
Díaz, M. J., Mantell, C., Caro, I., de Ory, I., Sánchez, J., & Portela, J. R.	Creation of Immersive Resources Based on Virtual Reality for Dissemination and Teaching in Chemical Engineering	2022
Li, X., & Hu, X.	Current Status of Ceramic Industry and VR Technology Used in Ceramic Display and Dissemination	2021
Reehl, A., & Sharma, S.	Data Visualization of Crime Data using Immersive Virtual Reality	2022
Harrington, M. C., Bledsoe, Z., Jones, C., Miller, J., & Pring, T.	Designing a virtual arboretum as an immersive, multimodal, interactive, data visualization virtual field trip	2021
Rubio Tamayo, J. L., Barro Hernández, M., & Gómez Gómez, H.	Digital data visualization with interactive and virtual reality tools. Review of current state of the art and proposal of a model	2020
Weiss, P. L. T., Raban, D. R., Geifman, D., & Keshner, E. A.	Dissemination of research in virtual reality-based rehabilitation: Journal publication profiles	2019
Trindade, Y., Rebelo, F., & Noriega, P.	Dissemination of São Tomé and Príncipe Culture Through Virtual Reality: Comparative UX Study Between Potential Tourists from Portugal and Santomean Inhabitants	2022
Comes, R., Neamțu, C., Buna, Z. L., Bodi, Ș., Popescu, D., Tompa, V., ... & Mateescu-Suciu, L.	Enhancing accessibility to cultural heritage through digital content and virtual reality: A case study of the sarmizegetusa regia unesco site	2020
Fatta, F., & Fischnaller, F.	Enhancing cultural heritage exhibits in Museum Education: 3D Printing Technology : eo mapping and 3D printed models merged into immersive audiovisual scenography (FSJ-V3D Printing+MM Installation)	2018

TABLE III
(CONTINUED)

Authors	Title	Year
Ehab, A., Burnett, G., & Heath, T.	Enhancing Public Engagement in Architectural Design: A Comparative Analysis of Advanced Virtual Reality Approaches in Building Information Modeling and Gamification Techniques	2023
Tyurina, A.	Enhancing Science Communication through AR Driven Visual Storytelling: Suggested Approach and Study	2021
Bayle, P., Armand, D., Bessou, M., Cochard, D., Couture, C., Deguilloux, M. F., ... & Bordes, J. G.	Enhancing the learning of evolutionary anthropology skills by combining student-active teaching with actual and virtual immersion of Master's students in fieldwork, laboratory practice, and dissemination	2022
Sacramento, P., Deligant, A., Loekken, S., & Mathieu, P. P.	EO space and multi-source data visualization using Virtual Reality in the ESA Φ-Lab	2022
Pérez-Aldana, C. A., Lewinski, A. A., Johnson, C. M., Vorderstrasse, A. A., & Myneni, S.	Exchanges in a virtual environment for diabetes self-management education and support: social network analysis	2021
Powley, B. T.	Exploring Immersive and Non-Immersive Techniques for Geographic Data Visualization	2020
Mallavarapu, A., Lyons, L., & Uzzo, S.	Exploring the Utility of Social-Network-Derived Collaborative Opportunity Temperature Readings for Informing Design and Research of Large-Group Immersive Learning Environments	2022
DiBenigno, M., Kosa, M., & Johnson-Glenberg, M. C.	Flow Immersive: A Multiuser, Multidimensional, Multiplatform Interactive Covid-19 Data Visualization Tool	2021
Merchán, M. J., Merchán, P., & Pérez, E.	Good practices in the use of augmented reality for the dissemination of architectural heritage of rural areas	2021
Donalek, C., Djorgovski, S. G., Cioc, A., Wang, A., Zhang, J., Lawler, E., ... & Longo, G.	Immersive and collaborative data visualization using virtual reality platforms	2015
Mircică, N.	Immersive and Engaging Digital Content, Data Visualization Tools, and Location Analytics in a Decentralized Metaverse	2022
Diolaiuti, G., Maugeri, M., Senese, A., Panizza, M., Ambrosini, R. O. B. E. R. T. O., Ficetola, G. F., ... & Pelfini, M.	IMMERSIVE AND VIRTUAL TOOLS TO SEE AND UNDERSTAND CLIMATE CHANGE IMPACTS ON GLACIERS: A NEW CHALLENGE FOR SCIENTIFIC DISSEMINATION AND INCLUSIVE EDUCATION	2021
Antinozzi, S., di Filippo, A., & Musmeci, D.	Immersive Photographic Environments as Interactive Repositories for Preservation, Data Collection and Dissemination of Cultural Assets	2022
de Farias Macedo, M. C., & Apolinario, A. L.	Improving On-Patient Medical Data Visualization in a Markerless Augmented Reality Environment by Volume Clipping	2014
Kosa, T., Bennett, L., Livingstone, D., Goodyear, C., & Loranger,	Innovative Education and Engagement Tools for Rheumatology and Immunology Public Engagement with Augmented Reality	2019
Chen, X., Wang, H., Zhu, Y., Wang, H., Su, M., Bao, S., & Wu, Y.	Interactive Geological Data Visualization in an Immersive Environment	2022
Ünal, F. C., & Demir, Y.	Location based data representation through augmented reality in architectural design	2018
Šendula-Jengić, V., Šendula-Pavelić, M., & Hodak, J.	Mind in the Gap Between Neural and Social Networks - Cyberspace and Virtual Reality in Psychiatry and Healthcare	2016
Hayden, S., Ames, D. P., Turner, D., Keene, T., & Andrus, D.	Mobile, Low-Cost, and Large-Scale Immersive Data Visualization Environment for Civil Engineering Applications	2015
Yiu, C. P. B., & Chen, Y. W.	Molecular Data Visualization with Augmented Reality (AR) on Mobile Devices	2021
Liu, R., Wang, H., Zhang, C., Chen, X., Wang, L., Ji, G., ... & Yang, D.	Narrative scientific data visualization in an immersive environment	2021
Boutsi, A. M., Verykokou, S., Soile, S., & Ioannidis, C.	PATTERN-BASED AUGMENTED REALITY APPLICATION for the DISSEMINATION of CULTURAL HERITAGE	2021
Tang, J. J., Maroothynaden, J., Bello, F., & Kneebone, R.	Public Engagement Through Shared Immersion: Participating in the Processes of Research	2013
Colegrove, P. T., & Mikel, M.	Radical inclusion: immersive 360-degree video capture, dissemination, and use of emerging technology in support of traditional archival roles at a university library	2018
Cardenas, I. S., Powlison, K., & Kim, J. H.	Reducing cognitive workload in telepresence lunar - Martian environments through audiovisual feedback in augmented reality	2021
Law, Y. C., & Weyers, B.	Social Media and Virtual Reality for Risk Communication in case of Volcanic Eruptions	2016
Fan, Z., Dai, R., Xu, Y., Wang, X., & Chen, S.	The display and dissemination of Qiantang River poetry road culture based on Virtual Reality and Human-computer Interaction	2021
Paul, S., & Hamad, S.	The role of virtual reality in story telling and data visualization for motivating students in learning programming	2020
Hruby, F.	The Sound of Being There: Audiovisual Cartography with Immersive Virtual Environments	2019
Gonizzi Barsanti, S., Malatesta, S. G., Lella, F., Fanini, B., Sala, F., Dodero, E., & Petacco, L.	The WINCKELMANN300 project: Dissemination of culture with virtual reality at the Capitoline Museum in Rome	2018
Martínez, B., Casas, S., Vidal-González, M., Vera, L., & García-Pereira, I.	TinajAR: An edutainment augmented reality mirror for the dissemination and reinterpretation of cultural heritage	2018
Kline, J. L., & Volegov, P. L.	Toward 3D data visualization using virtual reality tools	2021

TABLE III
(CONTINUED)

Authors	Title	Year
Southall, H. V., Beever, L., & Butcher, P. W.	Traversing social networks in the virtual dance hall: Visualizing history in VR	2017
de los Ríos, S., Cabrera-Umpiérrez, M. F., Arredondo, M. T., Páramo, M., Baranski, B., Meis, J., ... & del Mar Villafranca, M.	Using augmented reality and social media in mobile applications to engage people on cultural sites	2014
Al Bondakji, L., Lammich, A. L., & Werner, L. C.	ViBe (Virtual Berlin)-Immersive Interactive 3D Urban Data Visualization Immersive interactive 3D urban data visualization	2019
Bartosh, A., & Krietemeyer, B.	Virtual Environment for Design and Analysis (VEDA): Interactive and Immersive Energy Data Visualizations for Architectural Design	2017
Woolley, S., Mitchell, J., Collins, T., Rhodes, R., Rukasha, T., Gehlken, E., ... & Cooke, A.	Virtual Museum 'Takeouts' and DIY Exhibitions–Augmented Reality Apps for Scholarship, Citizen Science and Public Engagement	2021
François, P., Leichman, J., Laroche, F., & Rubellin, F.	VIRTUAL REALITY AS A VERSATILE TOOL FOR RESEARCH, DISSEMINATION AND MEDIATION IN THE HUMANITIES	2021
Theart, R. P., Loos, B., & Niesler, T. R.	Virtual reality assisted microscopy data visualization and colocalization analysis	2017
Wei, T., Xing, Y., Wu, Y., & Kwan, H. Y.	Virtual Reality Design in Reading User Experience: 3D Data Visualization with Interaction in Digital Publication Figures	2022
Fischer, R., Chang, K. C., Weller, R., & Zachmann, G.	Volumetric Medical Data Visualization for Collaborative VR Environments	2020
Reinoso-Gordo, J. F., Barsky, D., Serrano-Ramos, A., Solano-García, J. A., León-Robles, C. A., Luzón-González, C., ... & Jiménez-Arenas, J. M.	Walking among mammoths. remote sensing and virtual reality supporting the study and dissemination of pleistocene archaeological sites: The case of fuente nueva 3 in Orce, Spain	2020
Hou, J. X., Wu, Y. D., Xu, Y. J., Li, X. J., Wang, S., Wang, F. P., & Zhang, X. R.	3D data visualization system of immersive underground laboratory	2019
Miranda, B. P., Queiroz, V. F., Araújo, T. D., Santos, C. G., & Meiguins, B. S.	A low-cost multi-user augmented reality application for data visualization	2022
Jamaludin, N. A., Mohamed, F., Chan, V. S., Sunar, M. S., Selamat, A., Krejcar, O., & Iglesias, A.	Answering Why and When? A Systematic Literature Review of Application Scenarios and Evaluation for Immersive Data Visualization Analytics	2023
Suresh, P., Kiran, M., Shetty, B. B., Nagasree, G. D., & Kavya, M.	Augmented Reality as a data visualization tool	2017
Sicat, R., Li, J., Choi, J., Cordeil, M., Jeong, W. K., Bach, B., & Pfister, H.	DXR: A Toolkit for Building Immersive Data Visualizations	2019
Barrile, V., Fotia, A., Candela, G., & Bernardo, E.	Geomatics techniques for cultural heritage dissemination in augmented reality: Bronzi di riace case study	2019
Yanzhen, W., Xiaofen, W., & Lihua, H.	Research on Great Wall section protection and user VR experience innovation based on GIS data visualization	2023
Keefe, D.F. & Laidlaw, D.H.	Virtual reality data visualization for team-based STEAM education: Tools, methods, and lessons learned	2013
Baltabayev, A., Gluschkow, A., Blank, J., Birkhölzer, G., Büsche, J., Kern, M., ... & Sommer, B.	Virtual reality for sensor data visualization and analysis	2018
Zhang, L., Qi, W., Zhao, K., Wang, L., Tan, X., & Jiao, L.	VR games and the dissemination of cultural heritage	2018
Uhr, M., Haselmann, S., Steep, L., Bretschneider, C., & Eickhoff, J.	Vroadworks - Interactive data visualization for coordinating construction sites in virtual reality	2019
Cherukuru, N. W., & Calhoun, R.	Augmented Reality Based Doppler Lidar Data Visualization: Promises and Challenges	2016
Natephra, W., & Motamedi, A.	Live data visualization of IoT sensors using augmented reality (AR) and BIM	2019
Pester, A., & Sulema, Y.	Multimodal Data Representation Based on Multi-image Concept for Immersive Environments and Online Labs Development	2021
Fischnaller, F., & Fatta, F.	3d printing technology, video mapping and immersive audiovisual scenography for heritage museum exhibits: Case study: FSJ-3D printing + mixed media installation in the MuCEM	2019
Daniil, R., Wohlgenannt, G., Pavlov, D., Emelyanov, Y., & Mouromtsev, D.	A New Tool for Linked Data Visualization and Exploration in 3D/VR Space	2019
Hirve, S. A., Kunjir, A., Shaikh, B., & Shah, K.	An approach towards data visualization based on AR principles	2017
Gomes Costa, M. A. F., Serique Meiguins, B., Carneiro, N. S., & Gonçalves Meiguins, A. S.	Prisma-Mar: An architecture model for data visualization in augmented reality mobile devices	2013
Perfetti, L., Teruggi, S., Achille, C., & Fassi, F.	RAPID AND LOW-COST PHOTOGRAMMETRIC SURVEY OF HAZARDOUS SITES, FROM MEASUREMENTS TO VR DISSEMINATION	2022
Lugmayr, A., Lim, Y. J., Hollick, J., Khuu, J., & Chan, F.	Financial Data Visualization in 3D on Immersive Virtual Reality Displays: A Case-Study for Data Storytelling and Information Visualization of Financial Data of Australia's Energy Sector	2019
Rahman, Y., Asish, S. M., Khokhar, A., Kulshreshth, A. K., & Borst, C. W.	Gaze data visualizations for educational VR applications	2019

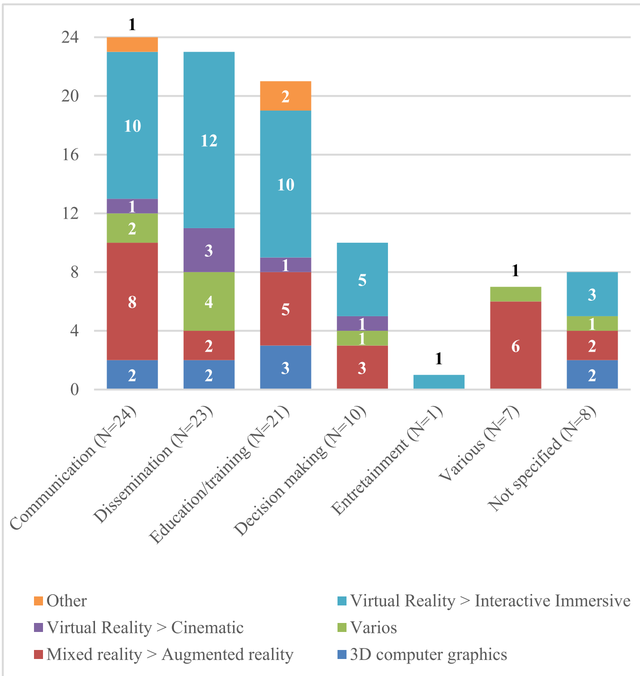

Fig. 6. Purpose of XR technology use.

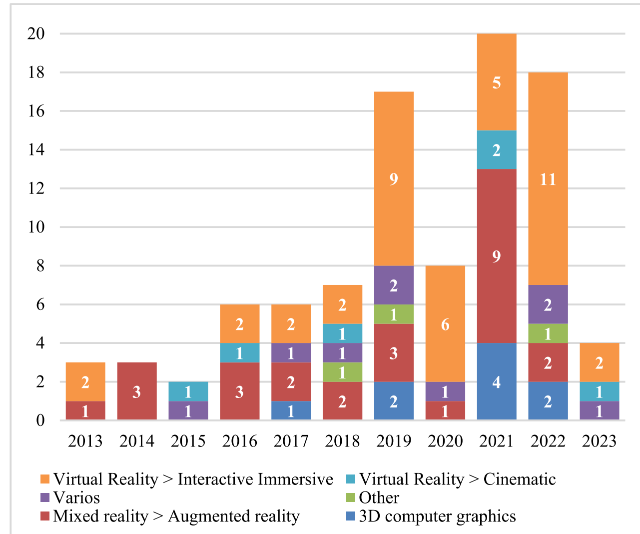

Fig. 7. XR technology studies over the past decade.

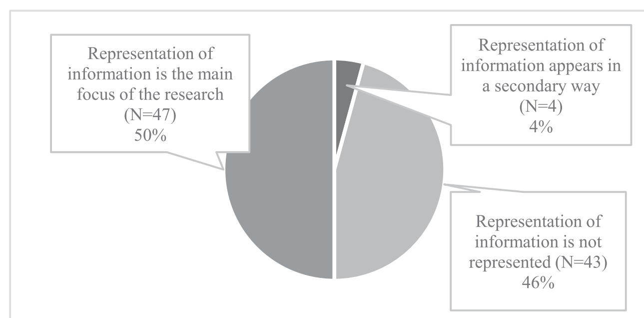

Fig. 8. Publications that focus on data visualization.

graphics” (N = 9) coming next. On the contrary, “cinematic VR” (N = 6) is found to be the least common.

A notable observation is the presence of articles that examine several distinct technologies (N = 9). As illustrated in Fig. 5 (bottom), publications that study more than one technology are predominantly focused on both “VR (interactive immersive)” and “3D computer graphics” (N = 6). This is not surprising given the versatility of both technologies, which can be utilized via an XR headset or a computer screen. Conversely, studies that investigate three technologies simultaneously (N = 2), and those examining VR and AR together (N = 1), are less common.

In terms of the purpose for which XR technology (Fig. 6) is used in the studies, the two that stand out the most are “Communication” (N = 24) and “Dissemination” (N = 23), and “Education/Training” (N = 23). VR interactive immersive technology is the most used for these three purposes (N = 10, N = 12, and N = 10 respectively). The use of AR technology with a communicative purpose (N = 8) and an educational purpose (N = 5) also stands out.

When reviewing the timeline of XR technology studies, it is evident that there has been a growing emphasis on virtual reality (VR) research since 2019. In contrast, augmented reality (AR) peaked as the most researched technology in 2021, as illustrated in Fig. 7. Despite this, AR has maintained a steady presence in research over the past decade, even though there were no publications on AR in 2015.

Regarding data visualization in the studied research (Fig. 8), half of the analyzed articles have a main focus on data visualization, understood as detailed in section *E. Data Clustering and Quantitative Analysis*. Notably, 46% (N = 43) of the articles do not reflect any use or approach to data visualization. On the other hand, in a smaller number of articles data visualization is a secondary factor (N = 4).

C. Research Type, Sample Size, and Method

The analysis of the publication’s research type reveals that most articles are Descriptive (N = 44), followed by Comparative (N = 24), and Analytical (N = 19),. Participatory (N = 5) and Explanatory (N = 2) articles are the least common.

Fig. 9 illustrates the relationship between the types of publications (articles and conference papers) and the sample size, according to the sampling method used in the studies. The most common sampling method is intentional or convenience sampling, with the most frequent sample size ranging from 1 to 50.

D. Data Gathering Techniques

Out of the analyzed research, it is observed that 77 studies use only one type of collection technique in their methods, while 17 employ multiple techniques or mixed methods to gather data.

In the analysis of studies that employed a single method of data collection, information gathering utilizing documents is the most frequently used technique, implemented in 46 studies (Fig. 10, top). This indicates a substantial reliance on existing literature,

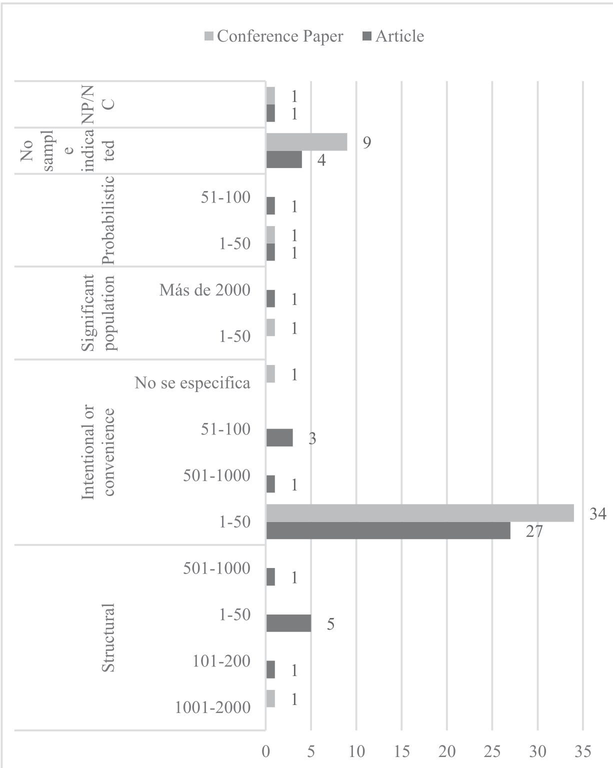

Fig. 9. Gathering method and sample size.

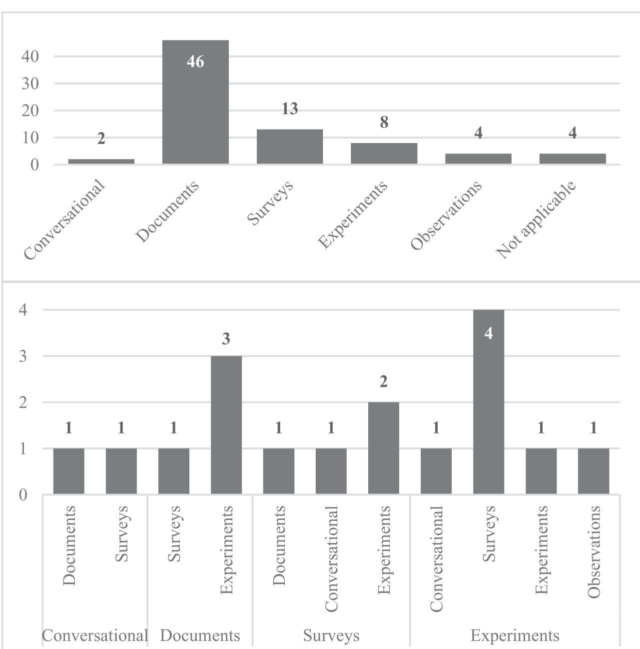

Fig. 10. Top: data gathering techniques in publications that only use one. Bottom: Data gathering techniques in publications that use more than one.

records, or various forms of documentation for information procurement. The second most common method is surveys (N = 13). The third most common technique is experimentation (N = 8). The least used methods are observation (N = 4) and conversational techniques (N = 1).

Concerning publications that employ multiple data collection methods and approaches, Fig. 10 (bottom) shows the most frequently used methods. At the bottom of each bar, the primary data collection method is indicated. This shows that the most common combination for a mixed method approach is "experiments" as the main method accompanied by "surveys" (N = 4).

VI. Discussion and Conclusion

Analysis of 94 papers and conference presentations highlights the emerging significance of XR technologies for science communication. We find that XR technologies are used for presenting information and data, conveying complex scientific ideas, and gamifying learning environments. Despite scientific examination and content development using these tools, clear guidelines for integrating 'science communication' theories into these immersive technologies are still missing and research on XR its diverse applications to scientific communication remains scant. Additionally, significant ethical concerns regarding privacy, accessibility, and digital divide need to be addressed.

XR technologies offer powerful solutions for bridging the science-public gap by creating immersive experiences that transform abstract scientific concepts into tangible, interactive visualizations. However, these technologies also present significant challenges. Cost barriers and technical requirements may limit accessibility, potentially widening the digital divide. There is a risk of cognitive overload if complex visualizations are not properly designed. Nevertheless, the opportunities are compelling: through virtual environments, users can actively participate in scientific phenomena rather than merely observing them. Features like interactive storytelling, personalized learning paths, and real-time data visualization work together to make complex information more accessible and engaging for diverse audiences. The key to success lies in developing inclusive, user-friendly applications while addressing ethical considerations and ensuring equitable access across different socioeconomic groups.

Returning to SO1, the results show an increasing trend of publications, which suggests that the subject is becoming more prevalent in academic research. The reduced number of publications in 2020 could be attributed to the global impact of the COVID-19 pandemic, which might have shifted research focus or caused delays in academic publishing related to this topic. In relation to S02 and the subsets of XR technologies, we see that VR is the subcategory that stands out, followed by AR. It is also important to note that terms such as CVR or 3D computer graphics are often used as intimately connected to the application of XR. The main purposes of using XR, as revealed in our review, span communication, dissemination, education, and decision-making, indicating XR's broad applicative spectrum beyond traditional educational settings into broader realms of public engagement and scientific discourse. For SO3, which determines scope and data collection techniques, we find most studies in this area have low study samples, between 1 and 50 subjects. In many technologies, usability studies are carried out with a convenience sample, partly because the technology used is experimental and in the process of evolution, and the applications are developed ad hoc with the means available. However, this cannot be extrapolated to all usability studies. This relatively small sample size might indicate the niche nature of the research topic or practical constraints such as resources and access to larger sample groups.

Despite these promising developments, our study, like those we reviewed, encounters several limitations that merit consideration. A significant constraint is the predominant reliance on text-based analysis. Current research, including ours, primarily reviews and synthesizes findings from textual publications such as journal articles and conference papers. This approach overlooks the practical demonstrations and applications of XR technologies, which are better showcased through interactive mediums like videos or virtual environments. Such limitations restrict the depth of analysis, particularly in understanding the user experience and the educational impact of XR technologies. Moreover, most existing studies do not delve into detailed examinations of XR innovations, choosing instead to focus on a more traditional academic practice of publishing textual analyses. This gap underscores a missed opportunity to explore the full potential of XR in scientific communication, where immersive and interactive experiences could offer richer, more engaging insights. The interdisciplinary *Journal of Video Research* (JoVE) provides an example of how new media technologies like XR could be used to publish results in multimodal formats. Moreover, XR technologies could help bridge the gap between scientists and the public by offering immersive, interactive experiences that show researchers conducting experiments or explaining scientific concepts for non-expert audiences.

Given these findings and limitations, we propose several directions for future research. First, there is a need for more empirical studies that not only discuss but also demonstrate XR applications. Such studies could utilize multimedia to provide a richer, more nuanced understanding of how XR technologies can be used effectively in real-world scientific communication. Of course, these studies or samples should, from the design phase, consider ethical concerns related to accuracy, privacy, and accessibility. Secondly, future research should aim to bridge the gap between traditional textual analysis and the innovative potential of XR technologies. This could involve developing new methodologies that incorporate XR products themselves as part of the research process, rather than merely as objects of study. By doing so, researchers can better capture the dynamic and interactive qualities of XR, offering deeper insights into its capabilities and limitations for science communication. Mixed methodological approaches combining qualitative and quantitative methods, including neuromarketing technologies, could provide more comprehensive insights into XR's impact on engagement and learning. Finally, there is a significant opportunity to explore the impact of XR on diverse audiences. Future research should investigate several critical questions about XR's impact on populations that may be typically marginalized from scientific discourse. While current studies primarily focus on academic settings, it is important to understand how XR effectiveness varies across different demographic groups (including citizens, policymakers, and other stakeholders), what barriers exist for non-academic audiences, and how these technologies can be optimized to deliver both engaging and socially responsible communication. We expect this review to contribute to the development of more comprehensive evaluation frameworks that measure educational and engagement outcomes across scientific disciplines and communicative contexts.

Conflict of Interests

The authors declare no conflict of interest.

Credit Author Statement

Juan Romero-Luis: Conceptualization, Methodology, Validation, Formal Analysis, Investigation, Data Curation, Writing – Original Draft, Visualization, Supervision, Project Administration, Funding Acquisition. Jose Luis Rubio-Tamayo: Conceptualization, Methodology, Validation, Formal Analysis, Investigation, Data Curation, Writing – Original Draft, Visualization, Supervision, Project Administration, Funding Acquisition. Alberto Sanchez-Acedo: Conceptualization, Methodology, Formal Analysis, Investigation, Writing - Review & Editing, Funding Acquisition. Daniel Lewis Wuebben. Investigation, Writing - Review & Editing. Valeri Codesido Linares: Investigation, Writing - Review & Editing.

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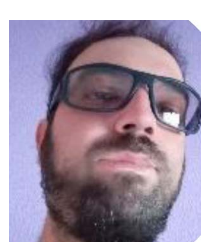

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