



VIRTUAL VISIONS FOR TANGIBLE TREASURES: A BIBLIOMETRIC ANALYSIS OF EXTENDED REALITY'S ROLE IN URBAN HERITAGE SAFEGUARDING

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Abstract

This paper presents a bibliometric analysis of published research on Extended Reality (XR), encompassing Virtual Reality, Augmented Reality, and Mixed Reality, in the field of urban heritage preservation. The study maps research trends, key contributors, geographical distribution, thematic clusters, and collaboration patterns within this emerging interdisciplinary domain. The findings indicate substantial growth in XR related heritage studies between 2020 and 2024, reflecting increasing scholarly attention to immersive technologies in conservation, interpretation, and public engagement. The analysis further shows that research output is dominated by a limited number of countries and authors, while Malaysia remains an emerging contributor. Thematic clustering reveals that current scholarship extends beyond technological experimentation to include educational applications, human centered design, and heritage interpretation. These findings suggest strong potential for XR to support urban heritage safeguarding in Malaysia through context sensitive innovation, strategic collaboration, and improved institutional support. The study contributes a structured overview of the field and offers practical insights for policymakers, researchers, and heritage practitioners seeking to strengthen digitally enabled preservation strategies.

Keywords: Extended reality; Virtual reality; Augmented reality; Heritage preservation; Urban conservation; Bibliometric analysis; Cultural heritage; Digital technologies

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INTRODUCTION

Extended Reality (XR) technology includes Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). It creates immersive experiences by blending physical and digital environments. The global XR market is growing rapidly from US\$33.8 billion in 2021 to an expected US\$125.2 billion by 2026. This growth spans various sectors including education, healthcare, entertainment, and cultural heritage.

In Malaysia, the adoption of XR technology has gained considerable momentum, driven by government policies such as the Malaysia Digital Economy Blueprint and the National Policy on Industry 4.0. Educational institutions across Malaysia have established dedicated XR laboratories and research centers to develop local expertise and innovation capacity in immersive technologies. Despite growing interest and investment, XR applications in Malaysia remain predominantly concentrated in the entertainment, education, and manufacturing sectors. Conversely, cultural heritage applications represent an emerging but still underdeveloped domain. They have specifically identified XR technologies as key enablers for enhancing tourism experiences through the digitalization of cultural assets, creating opportunities for innovative approaches to heritage preservation. Notably, Universiti Sains Islam Malaysia (USIM) has launched initiatives exploring XR for the preservation of Islamic architectural heritage. On the other hand, immersive XR experiences have been piloted in George Town's Armenian Street and Melaka's Stadthuys area to preserve colonial-era architecture and enhance digital tourist engagement. These efforts, although still emerging, reflect a growing recognition of XR's role in preserving Malaysian culture.

Urban heritage preservation is an emerging application area for XR technologies in Malaysia, where rapid urbanization poses a threat to the sustainability of historical sites and cultural landmarks (Hassan & Ismail, 2024). XR offers potential solutions for documenting, preserving, and demonstrating urban heritage by creating digital twins, enabling virtual reconstructions of degraded structures. It also provides immersive educational experiences that foster cultural appreciation and understanding. Recent initiatives in Malaysian, United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage Sites, such as Melaka and George Town, have demonstrated XR's capacity to enhance conservation efforts while also improving accessibility and tourism engagement. However, implementation challenges persist, including technical limitations, cost barriers, and the need for specialized expertise to develop culturally accurate and contextually relevant XR experiences. This bibliometric analysis aims to systematically map the research landscape of XR technologies in urban heritage preservation, with particular focus on Malaysian applications, to identify key trends, research clusters, and opportunities for future

development. For example, the George Town World Heritage Incorporated (GTWHI) has expressed interest in leveraging immersive storytelling and XR-based interpretation to attract younger audiences. In this regard, such local applications validate the relevance of the global trends identified in this bibliometric analysis.

Recent scholarship demonstrates that XR is increasingly used in heritage documentation, digital reconstruction, interpretation, museum mediation, and immersive learning. International studies highlight the ability of XR technologies to visualize inaccessible environments, reconstruct lost or damaged heritage elements, and improve public understanding of cultural assets. However, this literature remains uneven in geographic and institutional distribution, with stronger representation from technologically advanced contexts that benefit from greater financial support, digital infrastructure, and specialist expertise. Consequently, less attention has been devoted to how XR can be meaningfully implemented in developing countries where heritage documentation systems, institutional coordination, technical readiness, and conservation priorities may differ significantly. This gap is important in the Malaysian context, where urban heritage sites such as George Town and Melaka face increasing pressure from tourism, urban change, and long term preservation demands. Situating Malaysia within these broader international developments helps clarify both the relevance of XR and the need for context specific adaptation.

Theoretical Framing of XR in Urban Heritage Preservation

This study is guided by a conceptual framing of XR in urban heritage preservation in Figure 1. First, the technological dimension considers XR as a medium for documentation, simulation, visualization, and interactive access to heritage environments. Second, the cultural dimension emphasizes that digital heritage technologies must support authenticity, contextual interpretation, and the safeguarding of heritage values rather than merely producing visually attractive representations. Third, the educational dimension highlights the role of XR in immersive learning, accessibility enhancement, and public engagement. Together, these dimensions provide an interpretive lens for understanding why XR research in heritage preservation increasingly spans technical innovation, cultural meaning, and human experience. This framing also helps explain why the relevance of XR in Malaysia depends not only on the availability of technology, but also on institutional readiness, cultural appropriateness, and educational value.

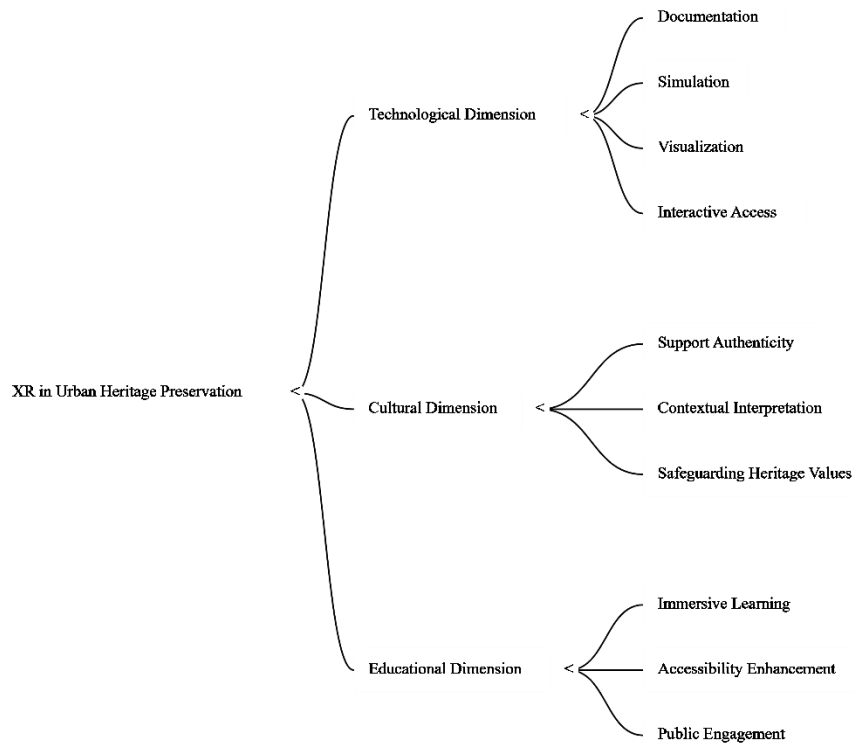


Figure 1: The three core dimensions of the theoretical framing of XR in urban heritage preservation: technological, cultural and educational

RESEARCH QUESTION

The main questions and objectives, along with the envisioned deliverables and target audience, inform the data discovery, collection, and presentation methods in any review. This document explores multiple questions to determine their findings.

- What are the research trends in XR technology according to the year of publication?
- Who are the key authors advancing XR research in heritage preservation?
- How is XR heritage research distributed across countries and regions?
- What are the main thematic clusters in XR applications for heritage?
- How do researchers and countries collaborate in XR heritage studies?

METHODOLOGY

Bibliometrics refers to the synthesis, management, and analysis of bibliographic data derived from scientific publications (De Sousa et al., 2024). In addition to standard descriptive data, such as publishing journals, publication year, and primary author categorization (Langlais, 2023), it also encompasses sophisticated methodologies, including document co-citation analysis. An iterative sequence of selecting appropriate keywords, conducting a literature search, and analyzing the results is essential for conducting a thorough literature review, constructing a comprehensive bibliography, and generating trustworthy findings (Costa et al., 2023). Furthermore, this section encompasses the adoption of search terms, preliminary screening of search results, and refining of search results. Journals that indicate Moreover, to ensure the incorporation of premier publications, only papers published in rigorously peer-reviewed and high-caliber academic journals were selected, excluding books and conference proceedings (Costa et al., 2023). Although Scopus encompasses a vast array of journals, its impact is limited to recent publications (Tennant, 2020). Articles from the Social Science Citation Index (SSCI), Science Citation Index Expanded, and Arts and Humanities Citation Index, spanning from 2020 to December 2025, were examined for analysis.

Data Search Strategy

Study employed a screening sequence to determine the search terms for article retrieval. Study was initiated by querying Scopus database with online TITLE-ABS-KEY (extended AND reality AND technology) AND PUBYEAR > 2019 AND PUBYEAR < 2026 AND (LIMIT-TO (SRCTYPE , "j") OR LIMIT-TO (SRCTYPE , "p") OR LIMIT-TO (SRCTYPE , "b")) AND (EXCLUDE (DOCTYPE , "er") OR EXCLUDE (DOCTYPE , "tb") OR EXCLUDE (DOCTYPE , "no") OR EXCLUDE (DOCTYPE , "le") OR EXCLUDE (DOCTYPE , "ed")) AND (EXCLUDE (SUBJAREA , "VETE")) , thereby assembling 4,334 articles. Afterwards, the query string was revised so that the search terms "extended reality technology" OR "XR technology" should focus on urban heritage preservation. This process yielded 3,248 results, which were further scrutinized to include only research articles in English, and article reviews were also excluded. The final search string refinement included 2,885 articles, which were used for bibliometric analysis. As of December 2025, all articles from the Scopus database relating to XR technology and focusing on heritage preservation were incorporated into the study.

Researchers who perform bibliometric analysis typically focus on specific date ranges, which help detect modern trends alongside relevant and manageable bibliographic data (İri & Ünal, 2024). The 2020-2025 period fulfills three key strategic roles by emphasizing modern XR advancements and rapid

technological adoption, while maintaining sufficient data points (2,885 articles) to prevent excessive inclusion of outdated sources. The recency filter enables researchers to identify top institutions and authors, as well as their advanced XR applications in heritage contexts (Herlina et al., 2024). Research progress from 4,334 articles was narrowed down to 2,885 scholarly works through language, subject domain, typing, and research type filters.

Data Analysis

The analysis utilized PlainText format data sets that included the study publication year, publication title, author name, journal, citation, and keywords. These data were extracted from the Scopus database between 2020 and December 2025 using VOSviewer software version 1.6.15. The VOS clustering method, in combination with mapping techniques, was the primary functionality of this software during map generation and data analysis. Furthermore, VOSviewer serves as an alternative to the Multidimensional Scaling (MDS) approach (Van Eck and Waltman, 2010). Both methods share the same goal of positioning items in low-dimensional spaces to accurately represent item similarity through distance measurements between them (Appio et al., 2014). According to Van Eck and Waltman (2010), the normalization of co-occurrence frequency calculation in VOS differs from M, which focuses on computing similarity measures through Jaccard indexes and cosine similarity.

$$\frac{AS_{ij}}{W_{ij}} = \frac{1}{4} C_{ij}$$

The measure exists as "the ratio between on the one hand co-occurent frequencies of observations *i* and *j* and on the other hand co-occurrence frequencies *i* and *j* under independence" (Van Eck & Waltman, 2010). Using this index, VOSviewer transforms data into a map by applying weighted sum reduction on all item pair distances. It implemented LinLog/modularity normalization (Appio et al., 2014). Additionally, the analytical techniques provided by VOSviewer generated visual outputs from the mathematical patterns within the data, enabling the execution of keyword co-occurrence, citation, and co-citation analysis reports (Dubey et al., 2023).

During specific periods, researchers have successfully employed keyword co-occurrence analysis to study the dynamics of field development as described by Dubey et al. (2023). The evaluation of cited works through citation analysis helps identify essential research problems and technical patterns, as well as a history of discipline-specific topics (İri & Ünal, 2024). Notably, the regularly used bibliometric method, known as document co-citation (Robledo-Giraldo et

al., 2023; Rossini, 2024), follows principles of network theory and decipher relevant data structures through its mapping process (Rossini, 2024).

FINDINGS

1. What are the research trends in XR technology according to the year of publication?

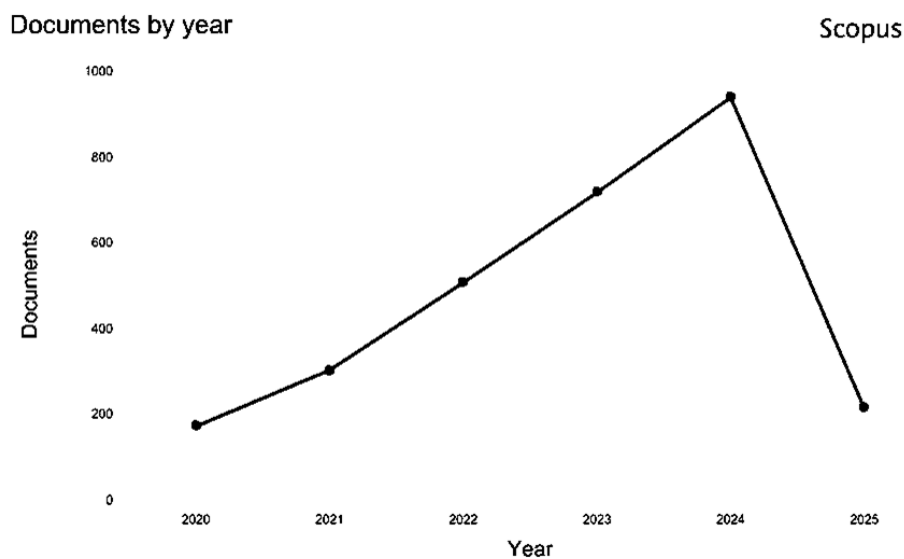


Figure 2: Trend of research in extended reality technology by years
Source: Scopus

The bibliometric data presented in Figure 2 illustrates a clear trend in publications on XR technology research in urban heritage preservation from 2020 to 2025. The line graph in Figure 1 depicts a consistent and significant upward trajectory in publication volume from 2020 to 2024, followed by a sharp decline in 2025. Starting with just 170 publications in 2020, the field experienced steady growth with 300 publications in 2021, 505 in 2022, and 716 in 2023. The research output peaked dramatically in 2024 with 937 publications, representing a 452% increase from the 2020 baseline.

However, 2025 demonstrates a substantial drop to only 213 publications. This decline may be explained by several factors: the data collection may have occurred early in 2025 (capturing only a partial year), there could be indexing delays in the Scopus database, or possibly a genuine decline in research interest.

Furthermore, the overall pattern suggests that XR technology in heritage preservation experienced rapid growth and mainstream research adoption through 2024, potentially reaching market saturation or research maturity before the apparent decline. Hence, this publication trajectory aligns with typical technology adoption curves, where initial enthusiasm leads to a peak in research output, followed by stabilization or decline as the technology becomes established and matures. This growth trend indicates that XR has become an increasingly important research area in heritage studies, although the relatively limited Malaysian contribution suggests a need for stronger local research investment.

2. Who are the key authors advancing XR research in heritage preservation?

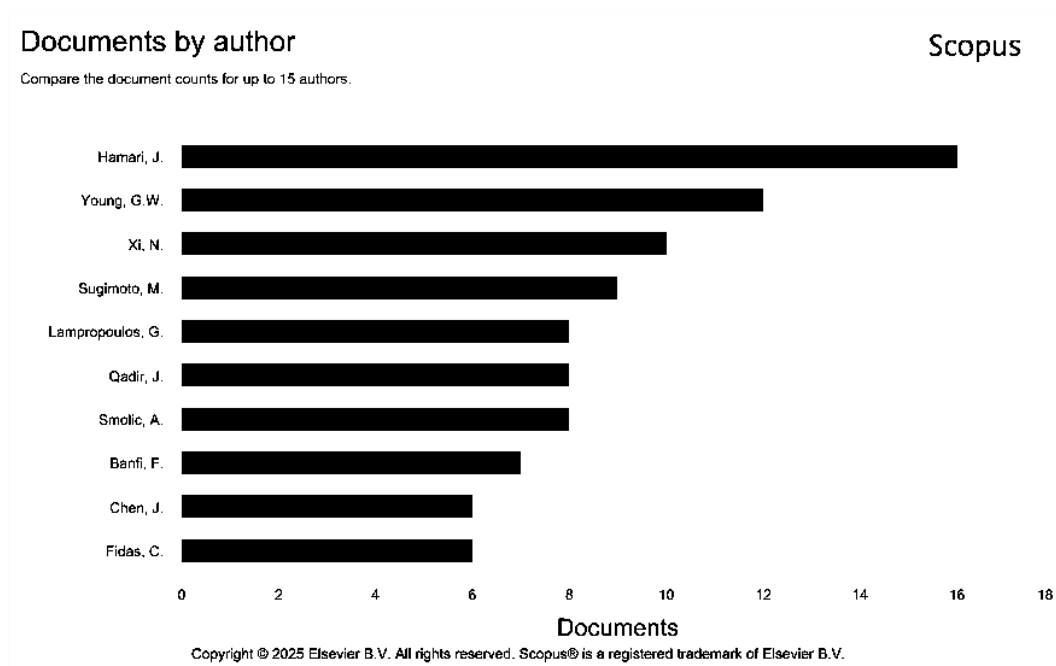


Figure 3: Top authors
Source: Scopus

The bibliometric analysis, as illustrated in the horizontal bar chart in Figure 3, displays the publication productivity of the top authors in the field of XR technology for urban heritage preservation. The data reveals a clear hierarchy in research output, with Hamari, J. leading significantly with 16 publications, establishing this researcher as the dominant contributor to the field. In comparison, Young, G.W. follows with 12 publications, while Xi, N. has

produced 10 documents. The middle tier of prolific authors includes Sugimoto, M., with 9 publications, followed by three researchers (Lampropoulos, G., Qadir, J., and Smolic, A.) who have each contributed 8 documents. Finally, Banti, F. rounds out the top tier with 7 publications.

Notably, the visualization displays only 8 of the possible 15 authors mentioned in the chart's subtitle, suggesting these represent the most productive researchers in this specific domain. This concentration of publications among a relatively small group of authors indicates that the field has established expertise clusters. Moreover, Hamari's substantial lead (33% more publications than the second-most productive author) suggests potential thought leadership or pioneering work in applying XR technologies to heritage preservation contexts. The concentration of highly productive authors indicates that the field is shaped by a relatively small set of knowledge leaders, creating opportunities for emerging scholars to build strategic collaborations.

3. How is XR heritage research distributed across countries and regions?

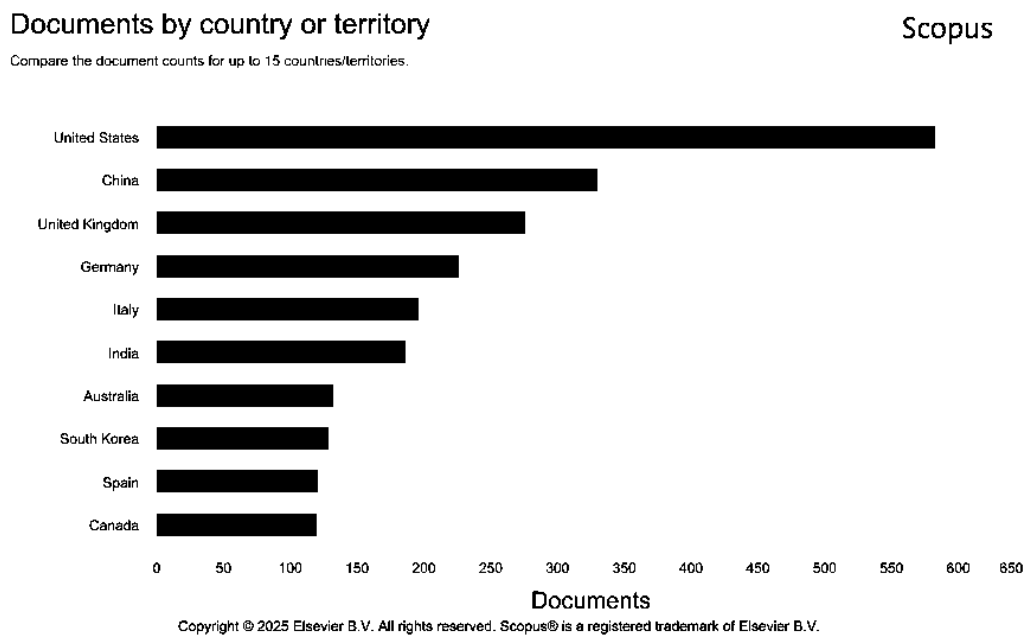


Figure 4: Geographical distribution of publications
 Source: Scopus

The bibliometric data presented in both the horizontal bar chart in Figure 4 and accompanying Table 1 illustrate the geographical distribution of

research publications on XR technology for heritage preservation across countries. The United States dominates the research landscape with 583 documents, almost twice the output of the second-ranked country, China, which contributed 330 publications. In comparison, the United Kingdom follows in third position with 276 documents, while Germany (226) and Italy (196) round out the top five countries. At the same time, the middle tier of contributing nations includes India (186), Australia (132), and South Korea (129), while Spain (121) and Canada (120) complete the top ten with nearly identical outputs.

Table 1: Geographical distribution of publications by country/ territory

Country/Territory	Documents
United States	583
China	330
United Kingdom	276
Germany	226
Italy	196
India	186
Australia	132
South Korea	129
Spain	121
Canada	120

Source: Scopus

Consequently, this distribution reveals a clear Western dominance in the field, particularly from North America and Europe, which collectively account for six of the top ten positions. However, the significant presence of Asian countries (China, India, and South Korea) indicates that research in XR technology for heritage preservation has global reach. Furthermore, the substantial gap between the United States and other countries suggests that it may have earlier adoption and greater funding resources. It may also indicate a more established research infrastructure in this interdisciplinary domain, where technology intersects with the preservation of cultural heritage. These thematic clusters suggest that XR research in heritage preservation is no longer limited to technical experimentation but increasingly addresses education, interpretation and human centered experience.

4. What are the main thematic clusters in XR applications for heritage?
- 5.

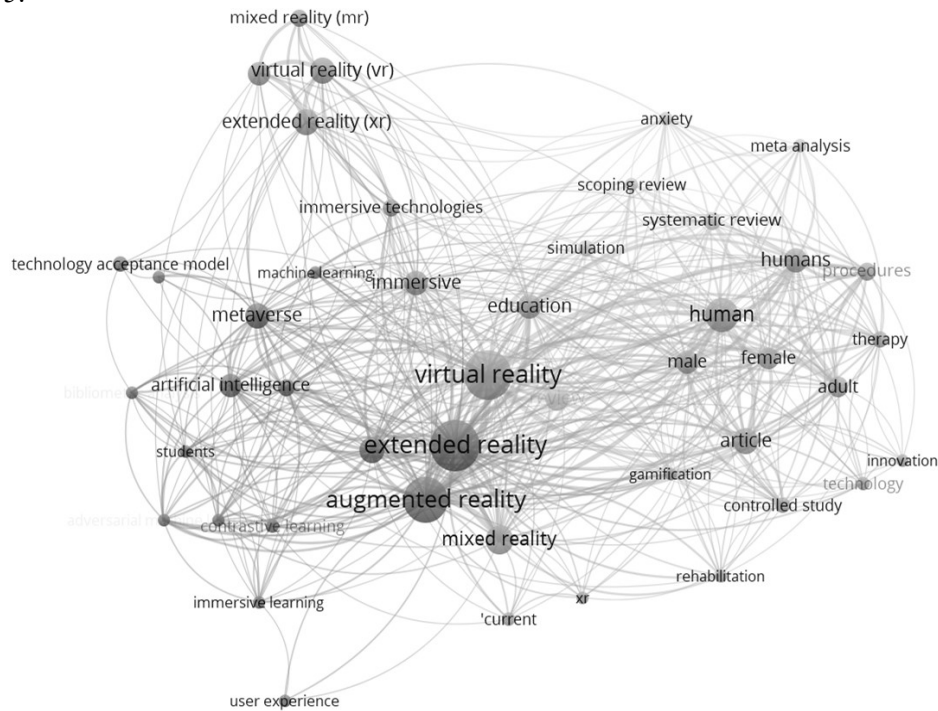


Figure 5: Cluster 1 themes
 Source: VOSviewer

The network visualization presents a keyword co-occurrence cluster analysis of research related to XR technology in heritage preservation. The diagram reveals five distinct thematic clusters differentiated by color. To begin with, the red cluster centers on technological foundations, connecting "extended reality," "augmented reality," "metaverse," and "artificial intelligence" with educational applications such as "constructive learning" and "students." In contrast, the green cluster focuses on human elements and impact, linking "human," "therapy," "rehabilitation," and demographic factors like "male," "female," and "adult." Conversely, the blue cluster represents core XR technologies, demonstrating relationships between "mixed reality," "virtual reality," and "immersive" applications. The yellow cluster, on the other hand, emphasizes research methodologies and assessment, connecting terms such as "systematic review," "meta-analysis," "anxiety," and "simulation." Finally, the purple cluster appears to highlight current trends in mixed reality applications. The size of nodes corresponds to keyword frequency, with "extended reality,"

"virtual reality," and "augmented reality" being most prominent, indicating their centrality to the research domain. Hence, the dense interconnections between clusters suggest a highly interdisciplinary field. Technological innovations are closely tied to human factors, educational applications, and rigorous research methodologies, collectively advancing XR applications in heritage preservation contexts.

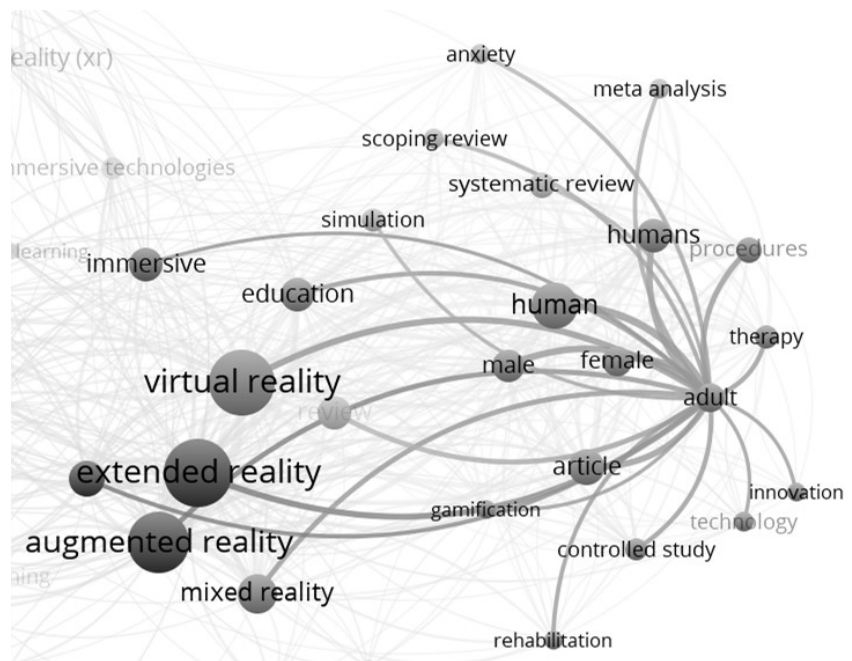


Figure 6: Cluster 2 themes
Source: VOSviewer

The network visualization in Figure 6: Cluster 2 themes provides an advanced view of how research keywords related to XR technology in heritage preservation studies are interconnected. In particular, the cluster analysis provides different thematic clusters through its use of color differentiation. XR technology dominates the field through its key components, which are displayed through the dense red central cluster. The human-centered research focus, which encompasses "human" with "therapy," "rehabilitation," "innovation," and demographic factors, is represented as a green cluster positioned on the right side. The blue nodes at the top represent technological base elements, which include the term "immersive" and various links to reality technology. Moreover, research evaluation methodologies establish systematic connections with applied educational applications and simulation applications, which are represented in the yellow cluster. Research conducted in XR technology is presented within a visual

framework that demonstrates how researchers undertake comprehensive investigations through strong academic connections between technical applications and human factors. Notably, it also highlights the connection between educational applications and evidence-based assessment approaches. Research involving multiple disciplines demonstrates that linking nearby research clusters facilitates the development of XR technology for heritage preservation, advancing innovative practices.

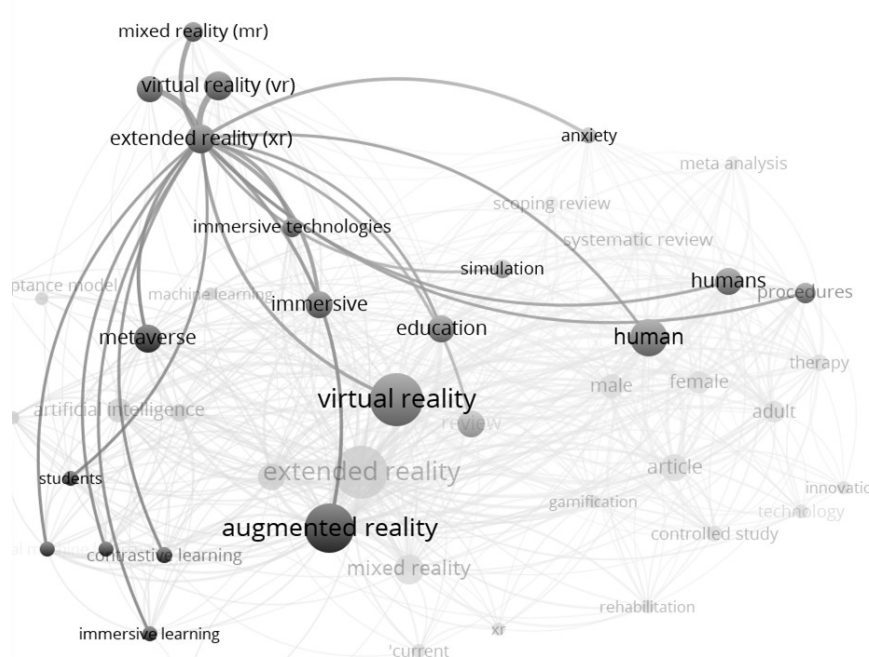


Figure 7: Cluster 3 themes
 Source: VOSviewer

This network visualization illustrates the keyword co-occurrence relationships in XR technology research for heritage preservation, organized into thematic clusters. The blue cluster at the top represents fundamental XR technologies, connecting "mixed reality," "virtual reality," and "extended reality" with "immersive technologies" and "immersive" applications. On the other hand, the red cluster on the left links advanced technological concepts, such as "metaverse" and "artificial intelligence," with educational applications including "constructive learning," "immersive learning," and "students," suggesting research focused on innovative teaching approaches. The yellow and purple central area highlights the core reality technologies ("virtual reality," "augmented

prominent red cluster featuring researchers like Wang Y., Kim J., Park J., and Choi J.; a blue cluster with Zhang Z., Zhang Y., Li X., and Zhang R. as key contributors; a green cluster including Lampropoulos G., Page M.J., Rauschabel P.A., and Davis F.D.; and a smaller yellow cluster with Li Y. at its center. Moreover, the visualization reveals several patterns of collaboration. For example, dense interconnections within clusters indicate strong research communities, while cross-cluster connections (particularly between the red and blue groups) suggest interdisciplinary collaboration. Additionally, the size of the nodes represents the publication volume or citation impact, with researchers such as Wang Y., Zhang X., and Li Y. appearing as influential authors. Notably, the network demonstrates a significant East Asian presence (particularly Chinese, Korean, and Japanese researchers) in XR heritage preservation research, alongside Western contributors (Lampropoulos, Davis, Rauschabel). This pattern aligns with the bibliometric analysis, which demonstrates China and the United States as leading countries in publication output, with the visualization revealing the specific researcher networks driving their productivity. The co occurrence network demonstrates conceptual linkages across research themes, suggesting that future studies should integrate technological, cultural and experiential dimensions more explicitly.

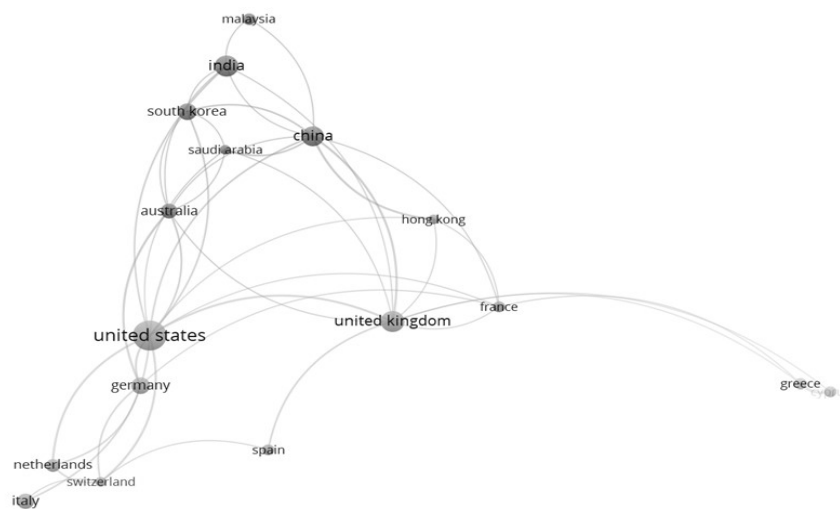


Figure 9: Countries' collaboration
 Source: VOSviewer

This network diagram illustrates international collaboration patterns among countries, represented as nodes connected by lines. The map reveals two main clusters: an Asian group centered around China (connected to India, Malaysia, South Korea, and Saudi Arabia), and a Western cluster with the United

States and United Kingdom as major hubs connecting to European nations (Germany, France, Italy, Netherlands, Switzerland, Spain) and Australia. Furthermore, the thickness and color of lines likely represent the strength and type of collaborations, with the United Kingdom appearing as a bridge between Asian countries (particularly connections to Hong Kong) and Western nations. Additionally, the United States demonstrates strong connections to both European countries and Australia, while Greece appears relatively isolated with minimal connections. Thus, this visualization likely represents academic, economic, or diplomatic partnerships between these nations. The country collaboration map indicates that international partnerships play an important role in knowledge exchange and may be especially valuable for strengthening XR related heritage research in Malaysia.

LIMITATIONS AND FUTURE RESEARCH

While this bibliometric analysis offers valuable insights, several limitations must be acknowledged. First, the study exclusively used data from the Scopus database, excluding grey literature, book chapters, and non-indexed journals, which may contain relevant information. Second, bibliometric techniques measure the quantity of publications and citations. However, it does not assess the quality or practical impact of individual studies. Ultimately, the analysis primarily focused on international trends. Hence, future studies should consider conducting empirical case studies of XR implementation in Malaysian heritage sites such as George Town or Melaka. Moreover, future research could also explore qualitative approaches to evaluate user experiences and effectiveness of XR in preserving urban heritage.

CONCLUSION

This bibliometric analysis provides a structured overview of research developments on XR technology in urban heritage preservation and demonstrates that the field is expanding rapidly across temporal, geographic, and thematic dimensions. The findings show that XR scholarship has evolved from an emphasis on technical feasibility toward broader concerns involving education, public engagement, interpretation, and interdisciplinary application. At the same time, the global distribution of research remains uneven, with strong dominance by a relatively limited number of countries, institutions, and scholars.

For Malaysia, these findings highlight both opportunity and challenge. XR offers significant potential to strengthen urban heritage documentation, interpretation, conservation planning, and public awareness, particularly in historically significant settings such as George Town and Melaka. However, the effective adoption of XR in heritage preservation depends on more than technological availability alone. It also requires sustained funding, stronger

digital infrastructure, interdisciplinary expertise, institutional collaboration, and context sensitive implementation strategies that respect cultural authenticity and local conservation priorities.

More broadly, the study suggests that developing countries should not simply replicate international XR models without adaptation. Instead, successful implementation requires alignment with local capacities, governance structures, and heritage values. Future research should therefore move beyond bibliometric mapping and examine empirical applications of XR in specific heritage contexts, including user experience, conservation outcomes, and policy relevance. In this way, XR can be positioned not only as an innovative technological tool, but also as a meaningful instrument for sustainable urban heritage safeguarding.

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