

Article

Extended Reality Research for Cultural Heritage in the European Union: Insights from a Bibliometric Analysis

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Highlights

Please indicate how your work links to systems science via your contributions to systems practice, theory, and/or methodology.

- It treats extended reality research on cultural heritage in the European Union as a complex socio-technical system and maps its structure and evolution with a science-mapping methodology combining co-authorship, co-word, burst, and thematic evolution analyses.
- It proposes a systems-level knowledge structure framework in which value-oriented, technological, and digital implementation dimensions interact as interdependent subsystems that shape research and practice.

What are the main findings and/or the implications of the main findings?

- European Union research output (1368 publications, 1989–2025) grew by 11.35% per year, it is concentrated in Italy, Spain, and Greece (59.5%), and it is strongly associated with national heritage endowment, while smaller member states act as collaboration brokers.
- The field is shifting from technology-driven experimentation towards value-oriented integration (extended reality, digital twins, and HBIM), which calls for integrated documentation-to-experience workflows and targeted European Union capacity building in under-represented member states.

Abstract

This study conducts a bibliometric analysis of research on extended reality (XR) technologies in cultural heritage research in the European Union (EU). It maps the overall research landscape and offers insights to inform the future development of XR in this field. Despite the growing interest in XR within the heritage sector, existing reviews tend to focus on specific technologies or application areas rather than providing a comprehensive overview, particularly in the European context. Europe remains a leading region in cultural heritage practice and research. To address this, the study analyses 1368 publications indexed in the Web of Science Core Collection between 1989 and 2025, affiliated with the 27 EU member states. The analysis uses Bibliometrix, VOSviewer and CiteSpace to examine publication trends, geographical distribution, collaboration networks, keyword patterns and thematic evolution. The results reveal that the annual output increased by an average of 11.35%, accelerating after 2012 and peaking at 174 publications in 2022. Italy, Spain, and Greece account for almost 60% of publications, with Italy contributing 36.2% alone, whereas smaller countries such as Denmark, Belgium, and the Netherlands demonstrate the highest rates of international co-authorship. Research hotspots have shifted from technology-driven 3D



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documentation and single-technology experiments towards integrated XR, digital twins, HBIM, and user-centred immersive experiences. These findings synthesise a structural framework comprising three interconnected dimensions that shape the field's knowledge landscape. The first is a value-oriented dimension addressing key heritage aims, including education, virtual archaeology, museum engagement, and architectural heritage conservation. The second is a technological dimension covering core foundations such as virtual reality, augmented reality, mixed reality, 3D modelling, and photogrammetry. The third is a digital implementation dimension focusing on practical approaches such as immersive experiences, storytelling, gamification, and interactivity. The study also identifies three priorities for future research: developing comprehensive technical guidelines, investigating broader socio-technical influences, and strengthening cross-cultural comparative studies.

Keywords: cultural heritage; digital technology; extended reality; XR; virtual reality; VR; augmented reality; AR; mixed reality; MR; bibliometric analysis

1. Introduction

1.1. Research Background

The world's cultural heritage has withstood the test of time. Yet, threats such as urban sprawl, pollution, neglect, conflict, looting, and even tourism are endangering these landmarks of our past at an ever-increasing pace [1]. In this context, digital technology has opened new avenues for the protection and dissemination of cultural heritage. Among these is extended reality (XR), here referring jointly to virtual reality (VR), augmented reality (AR), and mixed reality (MR) [2]. As an innovative means of integrating the virtual and real worlds, XR assists cultural heritage institutions and museums in preserving and presenting their heritage assets in novel and original ways [3].

XR is an umbrella term that encompasses various technologies. These are commonly described using the reality–virtuality continuum proposed by Milgram and Kishino [4], which provides a conceptual distinction between them. This continuum places VR, AR and MR on a spectrum according to the degree of interaction between real and virtual environments. The concept of XR can be traced back to the mid-20th century and the early exploration of immersive display systems. However, the real breakthrough came at the turn of the 21st century. Private organisations began developing wearable vision systems, and XR devices became commercially available [5]. At the same time, integrating XR into game engines such as Unity and Unreal Engine significantly lowered the barriers to content development [6]. The onset of the global pandemic prompted major technology firms, including Meta, Google, Microsoft and Apple, to accelerate metaverse development, with the aim of delivering immersive human–computer interaction experiences [7]. In an academic context, there is a growing body of quantitative evidence demonstrating the diverse value of XR applications across different fields. For instance, a meta-analysis of 36 studies showed that AR had a moderate positive effect on students' innovative abilities, with an effect size of 0.702 [8]. Beyond education, an analysis of 13 studies found that AR significantly improved navigation performance compared with traditional navigation tools, with an overall effect size of 0.554 [9]. In healthcare, a systematic review and exploratory meta-analysis of 13 randomised controlled trials involving 881 participants found that VR, AR, and exergaming interventions improved pain and function in adults [10]. In the context of museum learning, Zhou et al. [11] reported significant positive effects of AR and VR on academic achievement and learners' perceptions, with respective effect sizes of 0.45 and 0.59.

XR technology has also experienced rapid development in the field of cultural heritage research over the past decade, transitioning from proof of concept to widespread application. AR technology enhances the memorability of visitors' experiences at heritage sites by overlaying virtual information onto the real environment [12]. VR technology creates fully immersive virtual environments, allowing participants to experience a sense of presence in the virtual world [13]. MR technology further integrates physical and digital elements to create more complex immersive experiences [14]. From a technical perspective, XR tools represent a crossroads where multidisciplinary research in computer vision, artificial intelligence, computer graphics, and natural interaction converge. These tools offer unique potential to revolutionise cultural heritage experiences in terms of interpretation, visualisation, and interaction [15]. Beyond the technical dimension, the potential of XR-related technologies has also been demonstrated in cultural heritage from both economic and social perspectives [16].

As one of the regions with the highest concentration of cultural heritage, Europe has accumulated extensive project-based research experience in cultural heritage digitisation. Many European countries have committed to regulating and directing this process in order to achieve optimal results [17]. In particular, the European Union (EU) has played a central role in shaping this agenda, with substantial funding being invested in cultural informatics and cultural heritage [18]. Over the years, EU-funded projects and academic research have continuously driven the application and development of digital technologies in cultural heritage. Among these technologies, XR has emerged as a key area of development. This trend was further reinforced by the EU's 2016 Next Generation Internet initiative, which explicitly supported research and innovation in the European XR ecosystem [19]. For instance, the Mergin' Mode project [20] demonstrated the integration of MR with geoinformatics to merge real and virtual environments for monument presentation. Ramos Sánchez et al. [21] explored the use of AR and VR to enable global virtual access to the Columbarios site in Mérida. Boboc et al. [22] developed a mobile augmented reality application that guides users through multiple European locations related to the Roman poet Ovid, thereby enhancing public engagement. All three studies received EU funding, demonstrating the diversity of project content and technical strategies employed to advance the deep integration of digital technology and cultural heritage through XR in Europe.

1.2. Research Gaps in Existing Reviews

With the increasing focus on XR technologies such as AR, VR, and MR in cultural heritage digitalisation, a growing number of high-quality review studies have emerged. These reviews employ various research methods, including bibliometric analysis, systematic reviews, case studies and thematic analysis, to examine XR applications in cultural heritage from multiple perspectives.

To position the present study more precisely, it should be compared with recent representative reviews. Three observations emerge. Firstly, in terms of research content, existing studies have primarily focused on a single technology or application domain. Examples include AR [16,23], VR [24,25], museums [26], tourism [27,28], education [29] and HBIM [30]. Secondly, from a regional perspective, Europe has been at the forefront of funding and promoting digital heritage initiatives. Several reviews have examined the European context across diverse research areas [31–33], and cultural heritage research has even been characterised as Eurocentric [34]. Yet, none of these studies treat the EU as an explicit unit of analysis or relate publication patterns to the European heritage and policy context. Thirdly, bibliometric analysis, which uses quantitative methods to examine patterns of publication, collaboration, and intellectual structure [35], is well suited to

addressing these gaps. However, even the most recent large-scale bibliometric studies remain largely descriptive in nature [26,36,37].

Accordingly, the research gap addressed in this study comprises three parts. A content gap: existing studies often examine different directions separately, making the overall thematic structure of XR research in cultural heritage difficult to understand as a whole. A regional gap: the EU, despite accounting for a large share of research in this area and pursuing a distinctive policy agenda for heritage digitisation, has not yet been examined as a coherent unit of analysis. And a synthesis gap: existing mappings mainly describe publication patterns but seldom bring these findings together into a structured knowledge framework that can guide future research. The present study addresses these three gaps simultaneously.

1.3. Research Questions and Structure

In response to the above research gaps, it becomes clear that in the field of XR and cultural heritage, particularly in the EU context which shapes the specificity of XR applications, the overall academic landscape and evolutionary trends remain insufficiently examined through systematic quantitative analysis. This study therefore employs bibliometric analysis to address the following research questions, developed deductively from the three gaps identified in Section 1.2 and from the established two-part structure of bibliometric analysis. This structure distinguishes between performance analysis, concerned with the contributions of research constituents, and science mapping, concerned with the relationships among these constituents [38]. RQ1 to RQ3 operationalise performance analysis at the levels of time, country and actor. This addresses the regional gap by making the EU's internal distribution of output and collaboration visible. RQ4 and RQ5 operationalise science mapping. This addresses the content gap by examining the field's integrated thematic structure over its full timespan. RQ6 addresses the synthesis gap. It does this by integrating the answers to RQ1 to RQ5 into a knowledge structure framework.

RQ1: *What are the temporal evolution trends in this field?*

RQ2: *What are the geographical distribution and collaborative patterns in this field?*

RQ3: *Who are the core knowledge contributors in this field?*

RQ4: *What are the major research hotspots in this field?*

RQ5: *How has the thematic structure of the field evolved over time?*

RQ6: *What key dimensions define the knowledge structure of this field, and can they be integrated into a domain framework to inform future research directions?*

To address these research questions, this paper is structured as follows: Section 1 outlines the research context, identifies existing gaps, and articulates the study objectives and questions. Section 2 details the bibliometric analysis methodology, including data sources, retrieval strategies, analytical tools, and the overall analysis workflow. Section 3 presents the results and answers RQ1 to RQ5 in turn: publication and citation trends (Section 3.1, RQ1), geographical distribution and collaboration networks (Section 3.2, RQ2), author and institutional influence (Section 3.3, RQ3), keyword analysis (Section 3.4, RQ4), and thematic structure and evolution (Section 3.5, RQ5). Section 4 provides an explicit answer to each research question and addresses RQ6 by synthesising the findings into a knowledge structure framework comprising value-oriented, technological, and digital implementation dimensions. Section 5 highlights contributions, identifies research limitations, and proposes future directions.

2. Materials and Methods

2.1. Search Sources and Strategies

This study selected the Web of Science (WoS) database as the primary data source. WoS is one of the world's oldest, most widely used, and most authoritative databases of research publications and citations, featuring complete citation linkages and enhanced metadata that support a wide range of bibliometric analyses [39]. While other databases (such as Scopus) offer broader journal coverage, WoS is valued for its rigorous indexing standards, comprehensive citation tracking, and strong representation of high-impact journals across multiple disciplines. These features make WoS particularly suitable for the literature search and bibliometric analysis conducted in this study. To ensure the comprehensiveness of the search, this study adopted a related synonym expansion strategy by incorporating synonyms related to “cultural heritage” with synonyms related to “XR technology” into the search query. A Boolean search string was constructed and applied to the Web of Science Core Collection, targeting the Topic (TS) field, which includes title, abstract, keyword plus, and author keywords. The final topic search string was determined as follows:

TS = ((“Virtual Reality” OR “Augmented Reality” OR “Mixed Reality” OR “Extended Reality” OR “VR” OR “AR” OR “MR” OR “XR”) AND (“Cultural Heritage” OR “Heritage”))

It should be noted that no WoS subject category restrictions were applied because XR-based heritage research is published across a wide range of categories, including computer science, engineering, archaeology, the humanities and tourism. A category filter would have excluded relevant work.

2.2. Data Collection and Selection

Based on the search strategy outlined in Section 2.1, the database search was finalised on 1 June 2025 across all available databases, resulting in a total of 2823 articles. To align with the European research context of this study, and given the EU's shared policy framework for digital humanities and cultural heritage digitisation [40], the EU is treated as an analytically coherent unit. Accordingly, this study focuses on the 27 EU member states rather than Europe in a broader sense, excluding the United Kingdom and non-EU European countries such as Norway, Switzerland, and Iceland. The geographical scope was defined using the Web of Science Country/Region (CU) field, which is based on author affiliations. Therefore, records were included when at least one author was affiliated with an EU institution. Although numerous studies have identified the use of English in academia as a source of inequality and segregation in science, the convenience of a common language in science must be recognised [41]. Therefore, to ensure the accuracy of content understanding and adhere to the dominant language of scientific communication, this study still limits its analysis scope to English-language literature. Finally, the literature type is restricted to Articles and Proceedings Papers, excluding Reviews, Book Chapters, and other types of literature. After applying the collection and selection criteria, the screening process yielded a total of 1368 articles for bibliometric analysis.

2.3. Analysis Tools

Bibliometrix and VOSviewer are both suitable for visualising bibliometric research in a specific domain, and each offers distinct features and usage requirements [42]. Bibliometrix, an open-source R package, provides functionality for calculating a variety of bibliometric indicators [43]. In this study, it was primarily employed to extract and visualise data related to publication trends, journal distribution analysis, and thematic structures. VOSviewer is a freely available computer program for constructing and viewing bibliometric maps [44]. In this study, it was used to analyse author collaboration networks, institutional collaboration

networks, and keyword co-occurrence networks. CiteSpace is a system designed to detect and to visualise emerging trends and radical changes in scientific disciplines over time [45]. In this study, CiteSpace was used as a supplementary tool to complement keyword burst analysis. Bibliometrix (version 4.1.4), VOSviewer (version 1.6.20), and CiteSpace (version 6.1.R6) were used in combination. The 1368 publications identified in Section 2.2 were exported with their full records and cited references in plain-text format. The overall research process for this bibliometric analysis is shown in Table 1.

Table 1. Bibliometric Analysis Research Flow.

Parameter	Description
Database & Indexes	Web of Science Core Collection (last accessed 1 June 2025)
Search Field	“TOPIC” (title, abstract, keyword plus, and author keywords)
Search Terms	TS=((“Virtual Reality” OR “Augmented Reality” OR “Mixed Reality” OR “Extended Reality” OR “VR” OR “AR” OR “MR” OR “XR”) AND (“Cultural Heritage” OR “Heritage”)) (resulting in 2823 records)
Countries/Regions	Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden (resulting in 1480 records)
Language	English only (resulting in 1427 records)
Type of Article	Articles and Proceedings Papers (resulting in 1368 records)
Analysis Tools	Bibliometrix, VOSviewer, CiteSpace
Bibliometric Methods	Bibliometrix: Publication and citation statistics, keyword frequency analysis, thematic mapping, thematic evolution VOSviewer: National collaboration analysis, Institutional collaboration network, keyword co-occurrence network CiteSpace: Citation burst detection

3. Results

The main bibliometric information about the dataset (Table 2) indicates consistent growth in XR-related cultural heritage research in EU countries since 1989, with an average annual growth rate of 11.35%. Research in this field is highly collaborative, with an average of 4.09 authors per paper and 21.56% of papers involving international collaboration. Although the literature is relatively recent, with an average age of 5.87 years, the average number of citations per paper is 9.77, reflecting both the active nature of research in this field and its growing academic influence. To further illustrate these data, the following sections present the publication and citation trends over time (Section 3.1), the geographical distribution and collaborative network (Section 3.2), the leading contributors and institutional dynamics (Section 3.3), a keyword analysis (Section 3.4), and the thematic structure and strategic mapping (Section 3.5).

Table 2. Main Information of the Bibliometric Data.

Description	Results
Timespan	1989:2025
Sources (Journals, Books, etc.)	664
Documents	1368
Annual Growth Rate %	11.35
Document Average Age	5.87
Average Citations per Doc	9.777
References	36,294
Authors	3807
Single-authored Docs	111
Co-Authors per Doc	4.09
International Co-authorships %	21.56

3.1. Publication and Citation Trends over Time

Figure 1 presents the publication trends between 1989 and 2025. The trajectory indicates a clear progression of the field, which can be divided into three major developmental stages. Figure 2 presents the publication trends between 1989 and 2025, showing a clear progression that can be divided into three major developmental stages. From 1989 to 2012, the annual number of publications was extremely low, mostly in the single digits, with minimal fluctuation. During this period, XR technologies were still at an early stage of development, and their applications in cultural heritage remained limited. From 2013 to 2018, publication output increased markedly, with a notable step change in 2013 when the annual output more than doubled compared with 2012, followed by an increase from 39 publications in 2013 to 107 in 2018. This growth was driven by both technological developments and major EU digital cultural policy initiatives. For instance, technological developments include the commercialisation of consumer-level VR headsets such as the Oculus Rift [46] and the adoption of mobile AR platforms such as ARKit, ARCore, or Vuforia [47]. Likewise, major EU digital cultural policy initiatives include the Europeana programme [48] and the Horizon 2020 framework [49]. From 2019 onwards, publication output increased more rapidly, reaching a peak of 174 articles in 2022. A temporary decline in 2020 may be partly related to the disruption of conferences during the COVID-19 pandemic, particularly as conference proceedings form a substantial part of the corpus. The subsequent increase towards the 2022 peak may reflect growing interest in immersive and remote access to cultural heritage during and after the pandemic [50]. Publication numbers then declined slightly in 2023 and 2024. This may partly reflect indexing delays for recent conference proceedings in WoS, so the most recent figures should be interpreted with caution. As of June 2025, 48 papers had been published, and the annual total may remain below previous years due to the incomplete publication and indexing period.

A further examination of citation dynamics (Figure 2) reveals that although publication volumes were very low in the early phase (1989–2012), the average citations per article were relatively high, so this limited body of work had notable scholarly influence. As interest in the field grew and the number of publications increased, citation performance tended to fluctuate downward across the subsequent two stages. The year 2020 marked one of the citation peaks, with an average of 3.34 citations per article. After 2022, the field showed high research output but lower average citation rates, which should be interpreted with

caution, as recent publications had shorter citation windows and their citations were still accumulating at the time of data retrieval in June 2025.

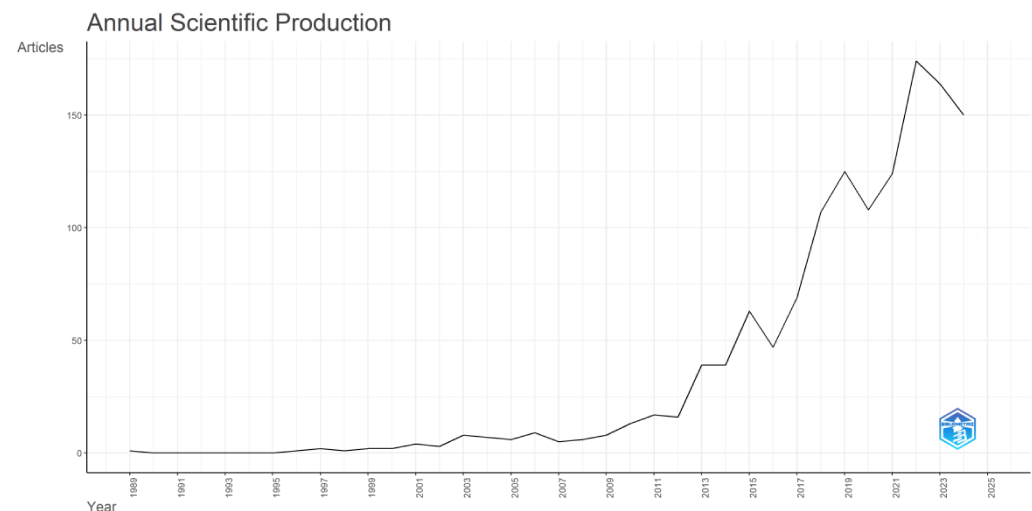


Figure 1. Annual Trends in Publications (Generated by Bibliometrix).

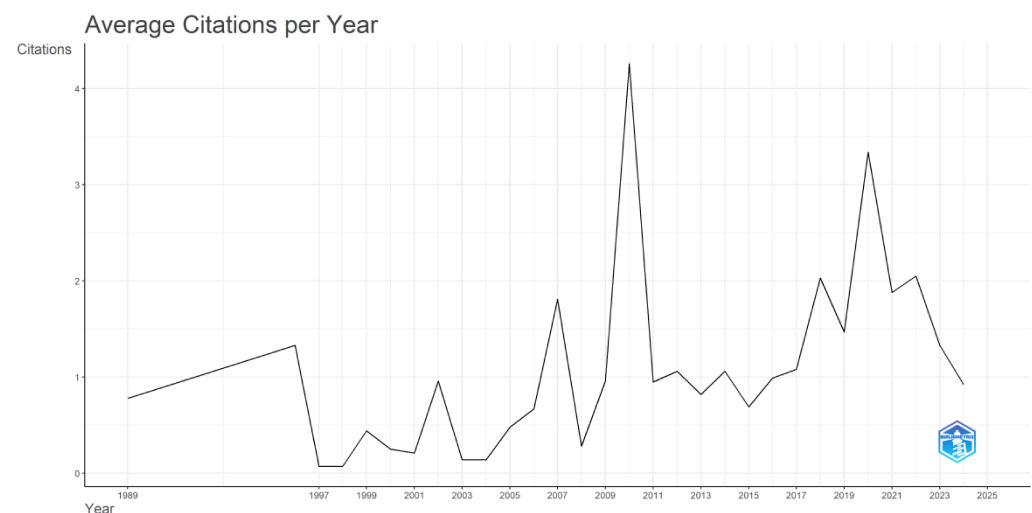


Figure 2. Trends in Average Annual Citation Rate (Generated by Bibliometrix).

3.2. Geographical Distribution and Collaborative Networks

3.2.1. National Research Contribution

The fifteen EU countries with the highest number of corresponding author publications are shown in Figure 3 and Table 3, with colours distinguishing single-country publications (SCPs) from multi-country publications (MCPs). In Bibliometrix, publications are attributed to the country of the corresponding author, while SCPs and MCPs are classified based on the affiliations of the full authorship team. The data indicate that research output is highly concentrated in the three Southern European countries of Italy, Spain, and Greece, which together account for nearly 60% of all publications. Italy leads the field with 36.2% of the total output, demonstrating its academic dominance in this field. Spain and Greece also rank highly because of their rich cultural heritage and active participation in EU digitisation initiatives. In contrast, while Northern and Western European countries such as Denmark, Belgium and the Netherlands produce fewer publications, they exhibit notably higher levels of international collaboration. Denmark and Belgium, for example, record MCP shares of 61.9% and 42.9% respectively, compared with only 12.5% for Italy. This suggests

that countries leading by volume are not necessarily the most internationally connected (see Table 3).

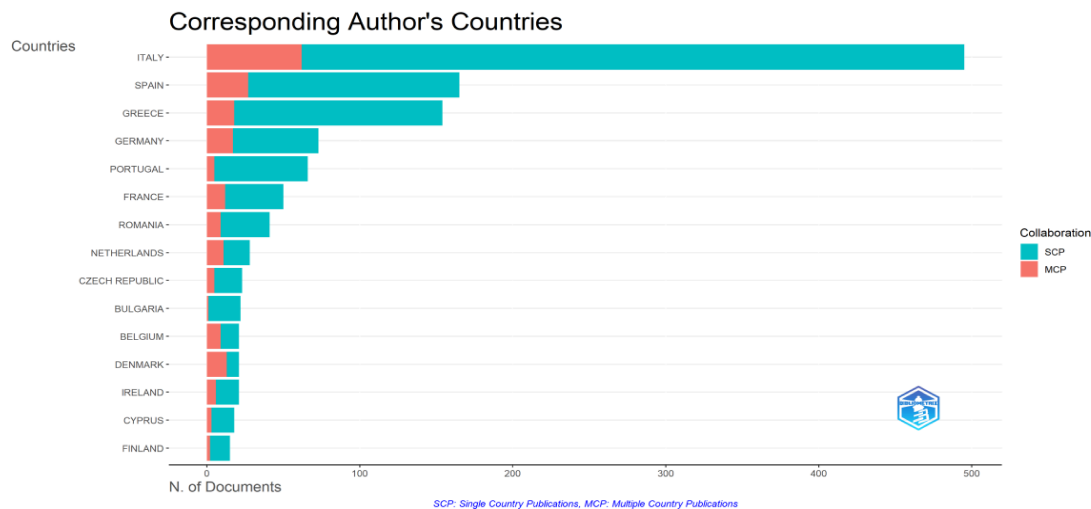


Figure 3. Number of Publications by Country (Generated by Bibliometrix).

Table 3. Top 15 Countries by Number of Publications.

Country	Articles	Articles %	SCP	MCP	MCP %
ITALY	495	36.2	433	62	12.5
SPAIN	165	12.1	138	27	16.4
GREECE	154	11.3	136	18	11.7
GERMANY	73	5.3	56	17	23.3
PORTUGAL	66	4.8	61	5	7.6
FRANCE	50	3.7	38	12	24
ROMANIA	41	3	32	9	22
NETHERLANDS	28	2	17	11	39.3
CZECH REPUBLIC	23	1.7	18	5	21.7
BULGARIA	22	1.6	21	1	4.5
BELGIUM	21	1.5	12	9	42.9
DENMARK	21	1.5	8	13	61.9
IRELAND	21	1.5	15	6	28.6
CYPRUS	18	1.3	15	3	16.7
FINLAND	15	1.1	13	2	13.3

3.2.2. National Collaboration Network

Co-authorship network analysis provides a focused way to examine international collaboration patterns of a research topic through authors' country affiliations [51]. Based on this approach, a country-level co-authorship network was generated using VOSviewer (Figure 4). The national collaboration analysis shows that Italy, Spain, Greece, Germany, and France are not only the highest-output countries in this field: these countries also serve as central hubs in the collaboration network. Italy leads with a total link strength of 118, underscoring its core role. Consistent with the multi-country publication patterns, nations such as the Netherlands, Sweden, and Denmark play notable intermediary roles in the collaboration network despite their relatively lower publication volumes. They effectively

connect multiple EU nations alongside non-European partners including the United States, China, South Korea, and Canada, reflecting active participation in cross-border projects and knowledge exchange. By contrast, countries such as Bulgaria and Romania exhibit weaker collaborative ties and remain on the periphery of the network. Strengthening international cooperation will be essential for these nations to enhance their future research visibility and impact.

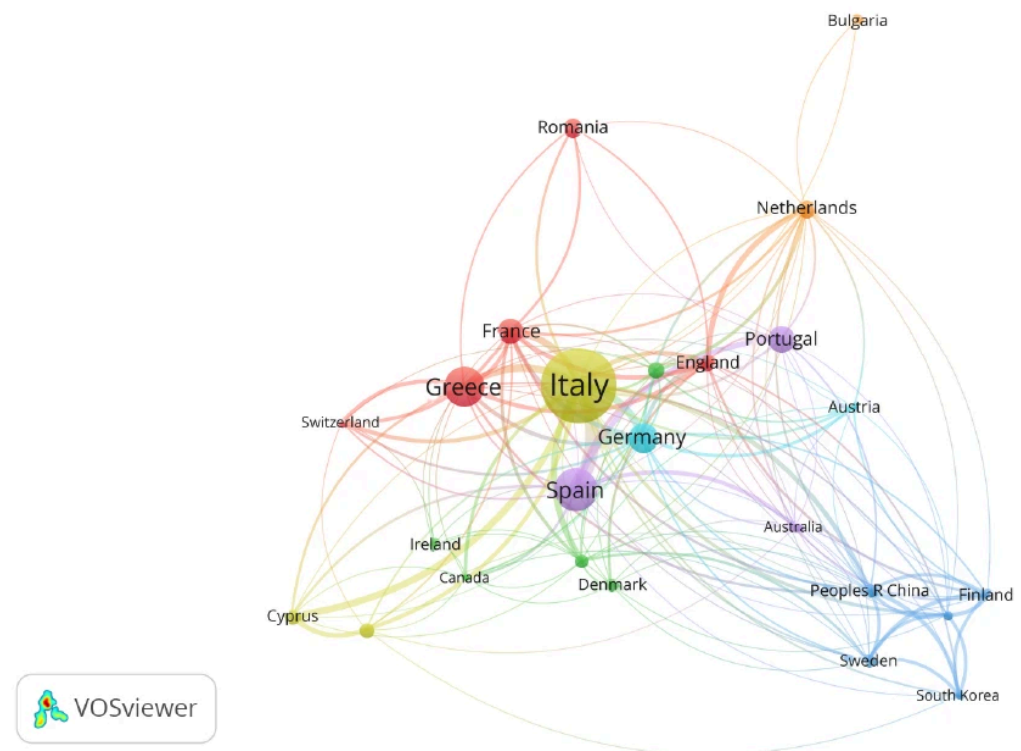


Figure 4. National Collaboration Network (Generated by VOSviewer).

3.3. Leading Contributors and Institutional Dynamics

3.3.1. Author Productivity and Impact

The analysis of the most productive authors and their academic influence is based on publication counts (Figure 5) and local citation data (Figure 6). It should be noted that, in highly collaborative research fields such as this, both publication and citation metrics may be influenced by co-authorship patterns. As a result, some authors or institutions may rank higher in analyses based on publication or citation counts than their individual contributions warrant. In terms of publication output, Pierdicca R ranks first with 24 publications, with research mainly focusing on AR applications for cultural heritage and photogrammetry-based survey methods [52]; De Paolis L. T., with 21 publications, concentrates on VR and human–computer interaction [53]; and Banfi F, who has published 19 papers, focuses on HBIM (Heritage Building Information Modelling), 3D modelling, and virtual museums [54]. Citation impact analysis reveals a distinction between research productivity and academic influence. Among these authors, Pierdicca R demonstrates both high publication output and strong citation performance, positioning this author as a core contributor to the field. In addition, authors including Frontoni E, Malinverni E. S., and Bekele M. K. have achieved high citation impact through key collaborative work, notably a widely cited survey synthesising augmented, virtual, and mixed reality applications in cultural heritage [55].

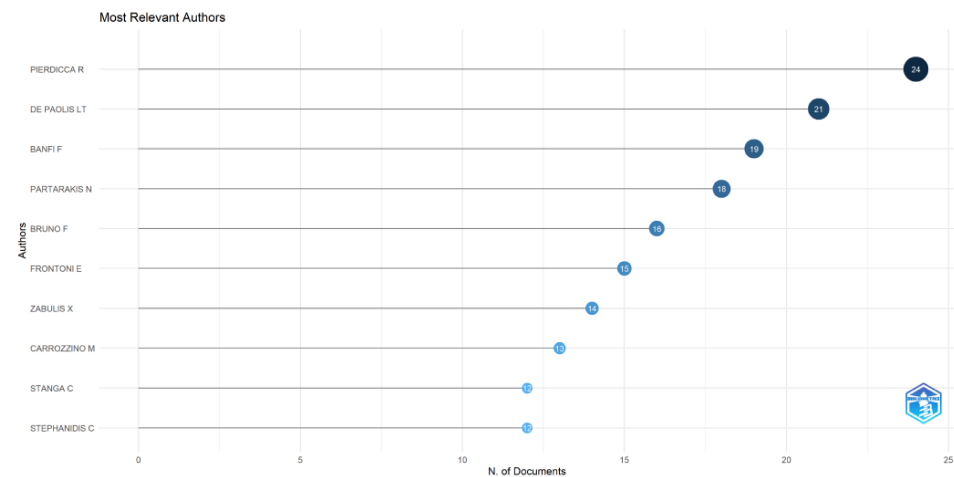


Figure 5. Number of Publications by Author (Generated by Bibliometrix).

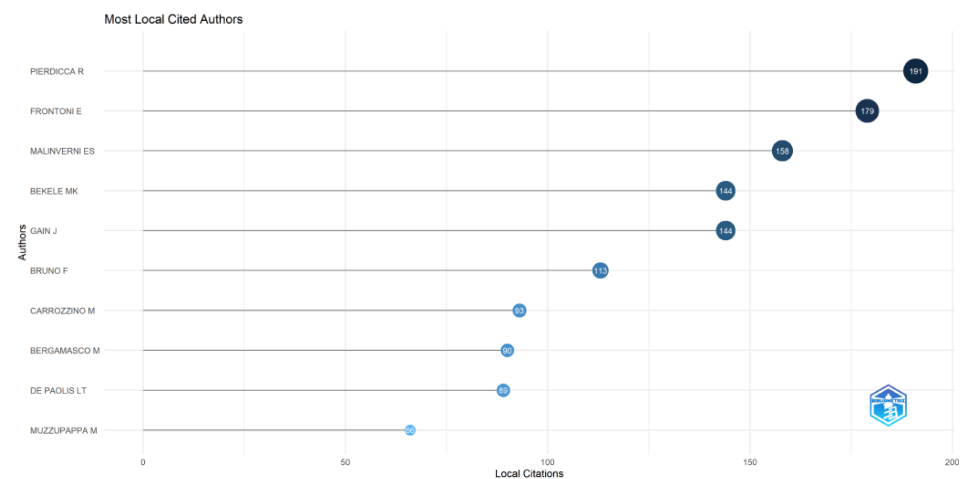


Figure 6. Citation Impact by Author (Generated by Bibliometrix).

3.3.2. Institutional Productivity and Impact

Figure 7 shows the publication volume of research institutions and indicates that Italy once again demonstrates clear dominance in this field. The top three leading universities and research institutions are all from Italy: the Consiglio Nazionale delle Ricerche (CNR), the Polytechnic University of Milan, and the Marche Polytechnic University. This dense academic cluster reflects Italy's long-term accumulation and leadership in digital heritage research. Additionally, academic institutions in countries such as Greece, Spain, Portugal and France also make important contributions.

Figure 8's citation data analysed with VOSviewer show that Italian institutions, in addition to their consistently high publication counts, also maintain strong citation performance. Beyond Italy, some institutions with relatively fewer publications, such as the univ calabria (University of Calabria), cyprus univ technol (Cyprus University of Technology), and univ salamanca (University of Salamanca), achieve outstanding citation results. Several national and regional universities across different parts of the EU have also established themselves as stable research hubs, offering diverse academic resources and research directions that support the broader development of digital cultural heritage research in Europe.

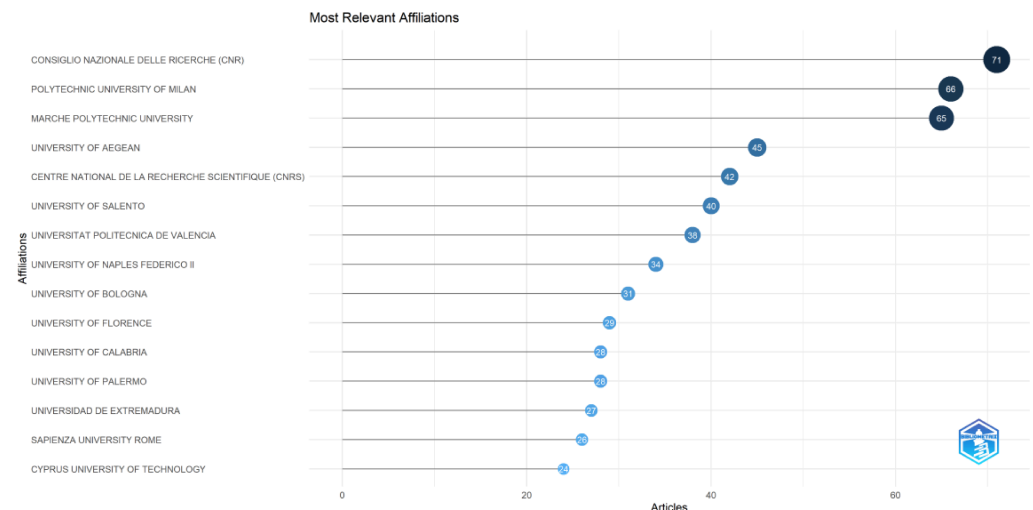


Figure 7. Number of Publications by Institution (Generated by Bibliometrix).

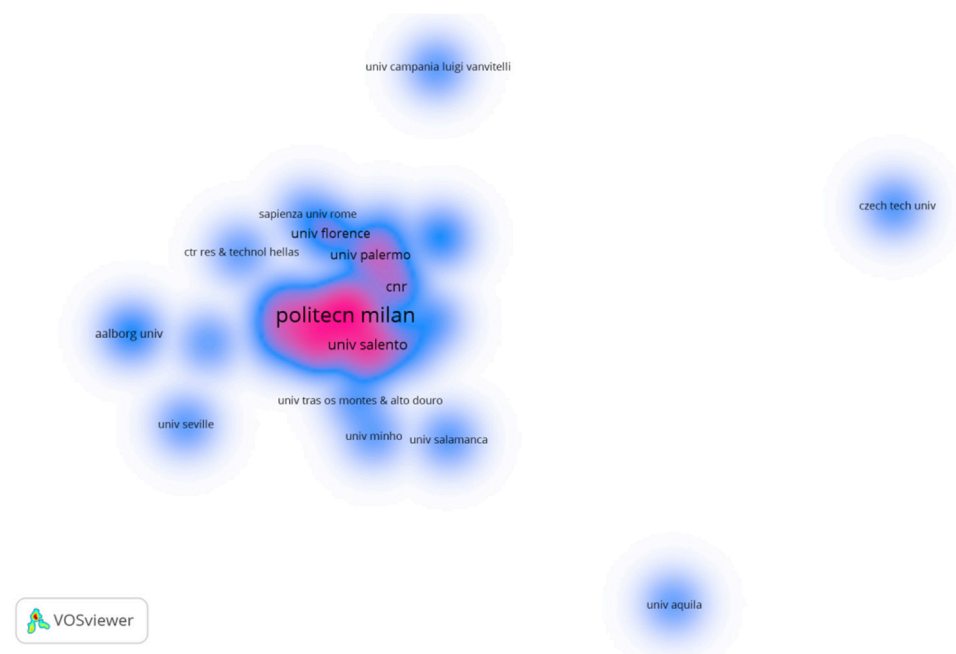


Figure 8. Citation Impact by Institution (Generated by VOSviewer).

3.3.3. Institutional Collaboration Network

Similarly to the national collaboration network, the institutional co-authorship network generated using VOSviewer (Figure 9) reveals that certain institutions play key bridging and connecting roles in research collaboration. The univ tras os montes & alto douro (University of Trás-os-Montes and Alto Douro) is positioned at the core of the network, showing the highest collaboration intensity (15) despite having a moderate publication output (11 papers). Its frequent collaborative activities highlight its active involvement in cross-institutional and cross-national research. Institutions such as inesc tec (INESC Technology and Science), univ aegean (University of the Aegean), and fdn res & technol hellas (Foundation for Research and Technology-Hellas) also demonstrate robust collaborative vitality. Conversely, certain institutions with higher publication volumes or citation counts, such as univ salamanca (University of Salamanca), politecn milan (Polytechnic University of Milan), and univ calabria (University of Calabria), exhibit lower collaboration intensity. This indicates that their research activities remain more concentrated within their own institutions, with relatively limited expansion of their collaborative networks.

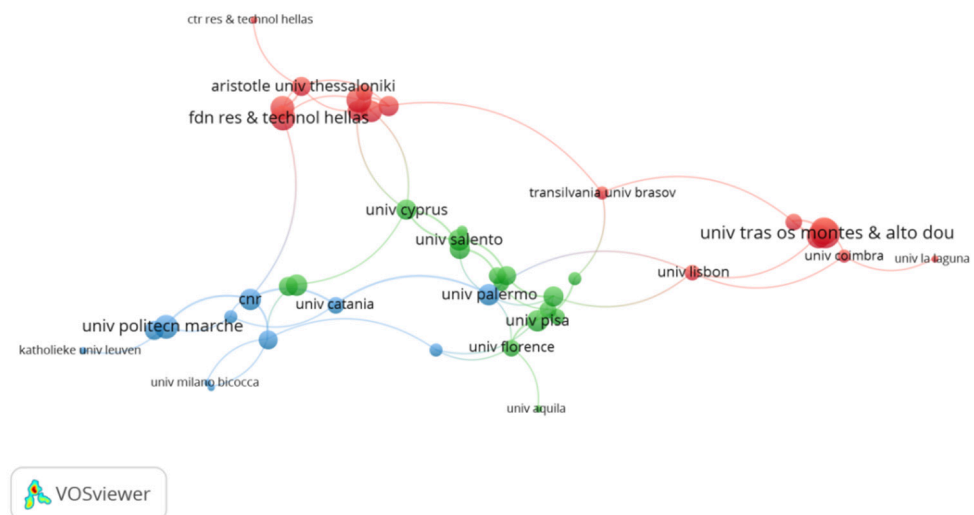


Figure 9. Institutional Collaboration Network (Generated by VOSviewer).

3.4. Keyword Analysis

3.4.1. Keyword Frequency and Trends

The word cloud provides a visual representation of high-frequency keywords, an analysis commonly used to identify research frontiers and hotspots [56]. The most frequently used keywords extracted from the analysed publications are presented in Figure 10 and Table 4. Before frequency ranking, the authors manually merged keyword variants following three rules. British and American spelling variants, singular and plural forms, and terms with equivalent ‘digital’-prefixed forms were combined. Related but distinct concepts, however, were kept separate. Merged terms are indicated with a slash in Table 4. Based on the frequency distribution, “cultural heritage” (405 occurrences), “virtual reality” (404 occurrences), and “augmented reality” (334 occurrences) are the most frequently used keywords, indicating that these three concepts occupy a central position in the research field. Other technology-related keywords, including “photogrammetry”, “3D modelling”/“3D modeling”, “mixed reality”, and “laser scanning”, also appear at relatively high frequencies. This reflects researchers’ strong interest in exploring specific technical approaches and methodologies. The frequent appearance of context-related keywords such as “museum”/“museums”, “education”, “3D reconstruction”, “archaeology”, and “intangible cultural heritage” highlights the interdisciplinary nature of the field, which integrates diverse cultural heritage contexts and research activities. At the same time, the recurrent use of keywords such as “storytelling”/“digital storytelling”, “user experience”, “gamification”, and “serious games” indicates that researchers primarily focus on enhancing audience engagement, strengthening user-centred approaches, and employing gamified educational strategies as concrete research methods for implementing XR-based digital heritage applications. Furthermore, several less frequently mentioned but forward-looking keywords, including “artificial intelligence”, “immersion”, and “accessibility”, point to emerging research directions and potential future developments in the field. Recent studies illustrate this trend, including research integrating AI-enhanced AR for heritage engagement [57], exploring immersive and gamified XR experiences in metaverse-based heritage applications [58], and evaluating accessibility and user experience in multiplatform virtual heritage museums [59].



Figure 10. Keyword Frequency Word Cloud (Generated by Bibliometrix).

Table 4. Top 25 Most Frequent Keywords.

N	Terms	Frequency
1	cultural heritage	405
2	virtual reality	404
3	augmented reality	334
4	photogrammetry	69
5	3D modelling/3D modeling	68
6	museums/museum	64
7	mixed reality	64
8	storytelling/digital storytelling	58
9	user experience	40
10	virtual museum	39
11	digital heritage/digital cultural heritage	66
12	extended reality	36
13	heritage	34
14	education	32
15	3D reconstruction	31
16	archaeology	28
17	virtual reconstruction	27
18	gamification	26
19	laser scanning	26
20	virtual heritage	26
21	serious games	23
22	intangible cultural heritage	22
23	accessibility	21
24	hbim	21
25	tourism	20

3.4.2. Keyword Co-Occurrence Network

Using VOSviewer, a keyword co-occurrence network was constructed by setting a minimum threshold of 20 occurrences per keyword. As shown in Figure 11, a total of 40 high-frequency keywords were identified. In the network, node size represents keyword frequency, while link thickness indicates co-occurrence strength [60]. Based on these recurrent keywords, five distinct clusters (red, green, blue, yellow, and purple) were further identified, revealing core research hotspots and interconnected pathways in the field.

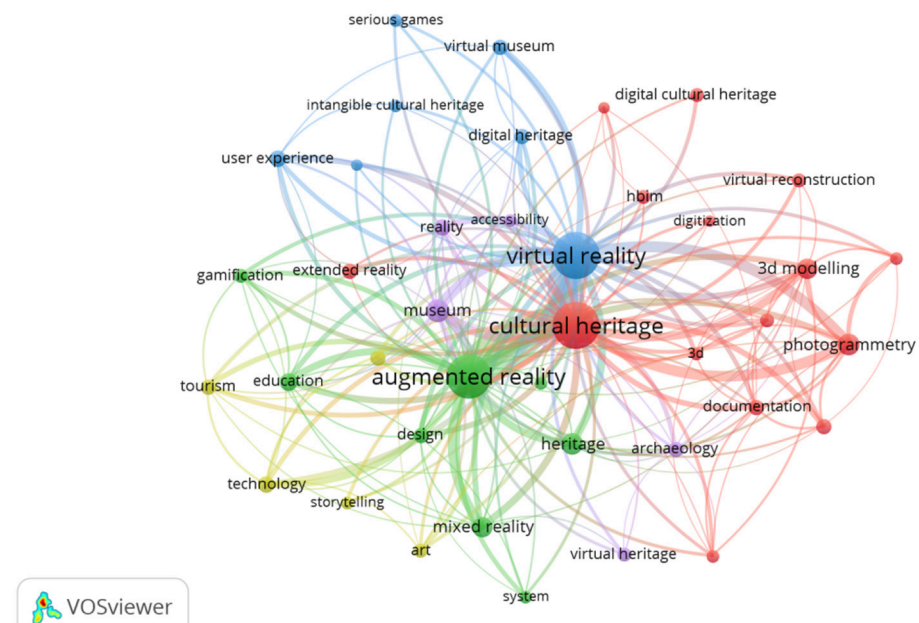


Figure 11. Keyword Co-occurrence Network (Generated by VOSviewer).

From the co-occurrence nodes, “virtual reality” (467 occurrences), “cultural heritage” (462 occurrences), and “augmented reality” (420 occurrences) emerged as the most central keywords in this domain, exhibiting the highest connection strengths of 875, 886, and 752 respectively. This indicates that these three keywords are highly correlated in research and constitute the primary research hotspots. Additionally, keywords such as “museum”, “photogrammetry”, “3D modelling”, and “mixed reality” also show high frequencies and strong connection strengths.

From the cluster distribution, Red Cluster 1 centres around “cultural heritage” and represents the most structurally dense part of the entire network, encompassing 15 keywords including “3D”, “photogrammetry”, “laser scanning”, “digitisation”, “virtual reconstruction”, and “visualisation”. This cluster primarily focuses on three-dimensional digital modelling and visualisation technologies for cultural heritage, emphasising the role of precise modelling and digital documentation in the application of XR technologies to cultural heritage contexts. This represents the most traditional and technology-driven research direction in this field, indicating that the digital transformation of cultural heritage still prioritises technological implementation as its fundamental starting point. The second category (Green Cluster 2) revolves around “augmented reality”, encompassing keywords such as “design”, “education”, “gamification”, “mixed reality”, and “system”. This highlights the close connection between AR technology and educational applications, gamified experiences, and systematic design methodologies. The third category (Blue Cluster 3) is dominated by “virtual reality”, including keywords such as “digital heritage”, “intangible cultural heritage”, “virtual museum”, “serious games”, and “user experience”. This cluster places greater emphasis on the immersive and narrative presentation of cultural

heritage, highlighting the critical role of user engagement and interactive experience in cultural dissemination. Yellow Cluster 4 consists of “art”, “technology”, “storytelling”, “management”, and “tourism”, forming a cluster that reflects the integration of digital cultural heritage research with broader social, cultural, and economic dimensions. Purple Cluster 5 includes keywords such as “accessibility”, “archaeology”, “museum”, and “virtual heritage”, focusing on issues of accessibility in heritage display and its intersecting relationships with archaeology and museum studies. This cluster features a relatively loose structure, emphasising the accessibility and openness of heritage knowledge, and serving as a foundation for digital cultural policies and public-oriented research.

3.4.3. Keyword Burst Analysis

Keyword burst detection was further applied, building on keyword frequency and the co-occurrence network to identify keywords with a sharp increase in occurrence frequency over specific periods [61]. This study applied CiteSpace’s Kleinberg algorithm [62], with the default parameters ($\gamma = 1.0$, minimum duration = 1 year) and one-year time slices, to visualise the temporal evolution of research keywords, as shown in Figure 12. The figure presents the 20 keywords with the strongest bursts, where “Year” indicates the first appearance of the keyword, “Strength” represents the intensity of the burst, and “Begin” and “End” indicate the burst period. The timeline covers the period from 1989 to 2025, with different colours distinguishing the period before the keyword appeared, the period without a burst and the detected burst period.

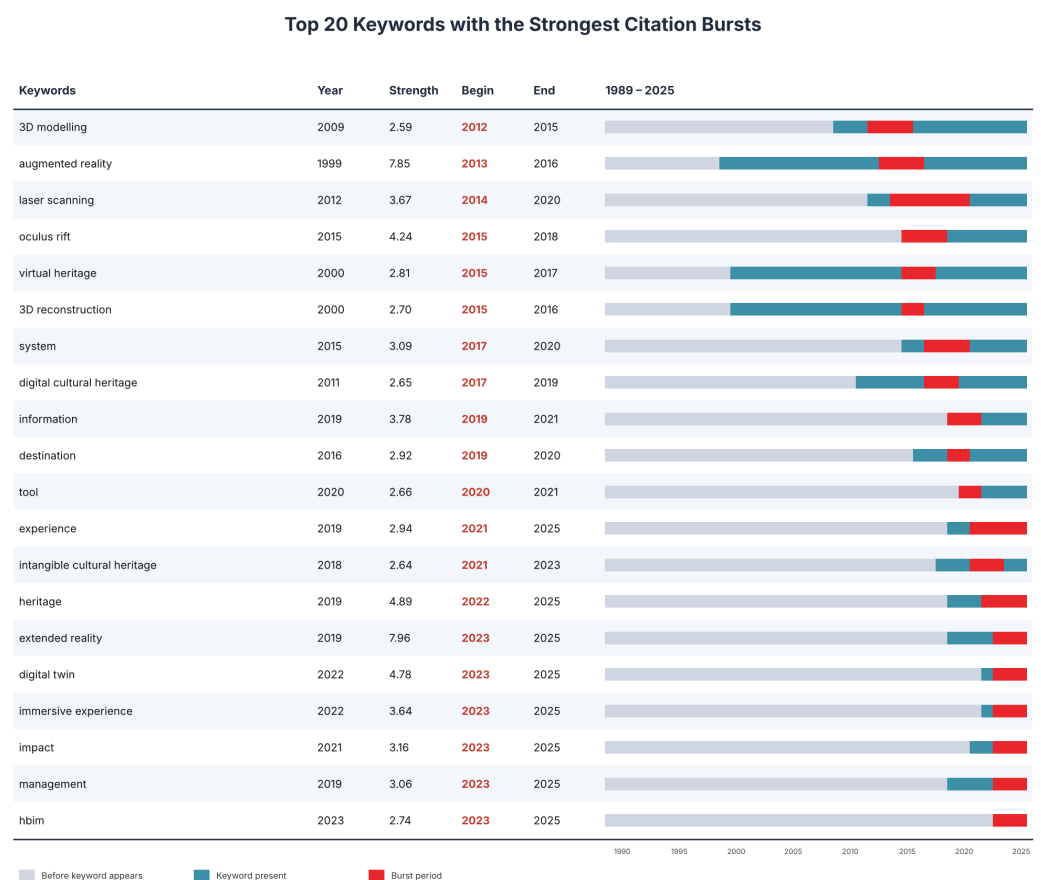


Figure 12. Keyword Burst Analysis (Generated by CiteSpace; redrawn by the author).

Early research shows a clear technology-driven orientation, with burst keywords mainly focused on specific technical implementation methods such as “3D modelling”, “augmented reality”, and “laser scanning”. During the same period, the emergence of

consumer-grade hardware such as “Oculus Rift” further facilitated immersive technology research. Heritage-related application concepts, including “virtual heritage” and “3D reconstruction”, were largely treated as direct applications of these emerging technologies, reflecting a research agenda strongly guided by technological feasibility. As technological tools matured, the research focus shifted from isolated technical experiments to the development of systematic solutions. The keyword “system” indicates a growing emphasis on digital heritage workflow standardisation, while “information” highlights a shift from geometric representation to data management. Notably, the appearance of “experience” as a burst keyword signifies a turning point, suggesting that the research value of heritage projects is moving from the heritage object toward the user experience, laying the groundwork for deeper exploration. From around 2022 to the present, research has entered a stage guided primarily by value-oriented objectives. The emergence of keywords such as “impact” and “management” reflects attention to evaluating digital heritage technologies and ensuring sustainable operations. Within this value-driven framework, technological advancement has demonstrated integration and enhancement: “extended reality” has become a unifying term replacing individual technologies, while “digital twin” and “immersive experience” serve as key pathways for achieving precise management and deep user engagement. In this context, “HBIM”, as an integrative paradigm combining the value of “management” with “digital twin” technology, has gained increasing attention for its capacity to support the structured documentation, monitoring, and long-term management of cultural heritage assets through comprehensive digital representations. Research at this stage has evolved into a closed loop, where complex value objectives guide technological advancement and the application of digital heritage methods and strategies.

3.5. Thematic Structure and Strategic Mapping

3.5.1. Strategic Thematic Mapping

The thematic map (Figure 13) was generated in Bibliometrix using co-word analysis of the 250 most frequent author keywords, with a minimum cluster frequency of 5 per thousand documents and association-strength normalisation. It divides research themes into four quadrants to assess their maturity and importance within the research network. Among the motor themes in the upper-right quadrant, cluster #1 “photogrammetry” is currently the most influential theme, encompassing key aspects such as archaeology, 3D reconstruction, 3D modelling, laser scanning, and digital twin. This cluster exhibits a high centrality value in the network, indicating its core role in this research field as it connects multiple sub-themes and demonstrates strong knowledge integration capabilities. Among the basic themes in the lower-right quadrant, cluster #2 “virtual reality” represents a typical foundational theme, including key aspects such as cultural heritage, augmented reality, mixed reality, museums, user experience, and education, reflecting its sustained impact potential in the knowledge network and its role as a critical foundation supporting the field’s development. Similarly, cluster #4 “extended reality” exhibits highly foundational characteristics, with key aspects including HBIM, virtual reality, augmented reality, and interactivity, representing exploratory directions for immersive integrated technologies. The upper-left quadrant contains niche themes, including cluster #3 “Oculus Rift”, cluster #5 “scan-to-BIM”, and cluster #6 “geoheritage”, which are internally mature but show weak connections to other themes. Additionally, “underwater cultural heritage” (cluster #7) is positioned in the lower-left quadrant, representing emerging or declining themes. This typically indicates areas that are still in early stages of development or have seen a decline in research interest, without close connections to other research areas or a high level of development in the field.

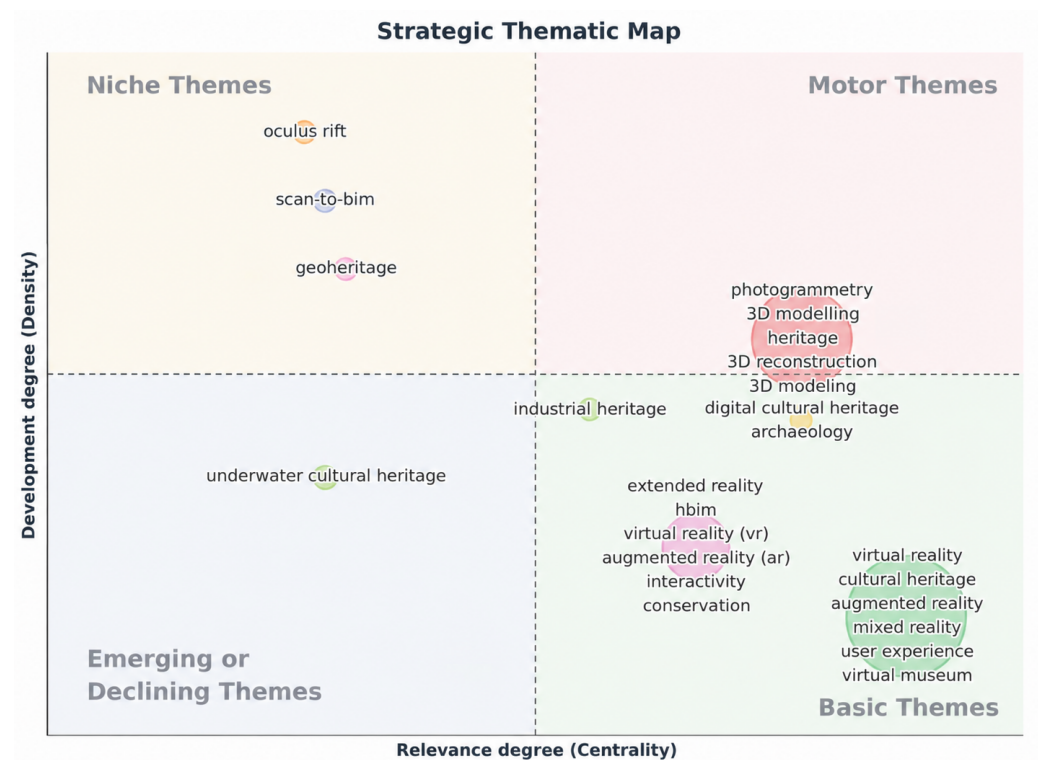


Figure 13. Strategic Thematic Mapping (Generated by Bibliometrix; redrawn by the author).

3.5.2. Thematic Evolution Analysis

Using Bibliometrix with the same settings, the thematic evolution analysis maps the evolution of research themes across three principal periods, as shown in Figure 14. This analysis reveals the continuity, development, and transformation of research themes in XR-based digital cultural heritage across three stages: early (1989–2012), mid-term (2013–2018), and recent (2019–2025).

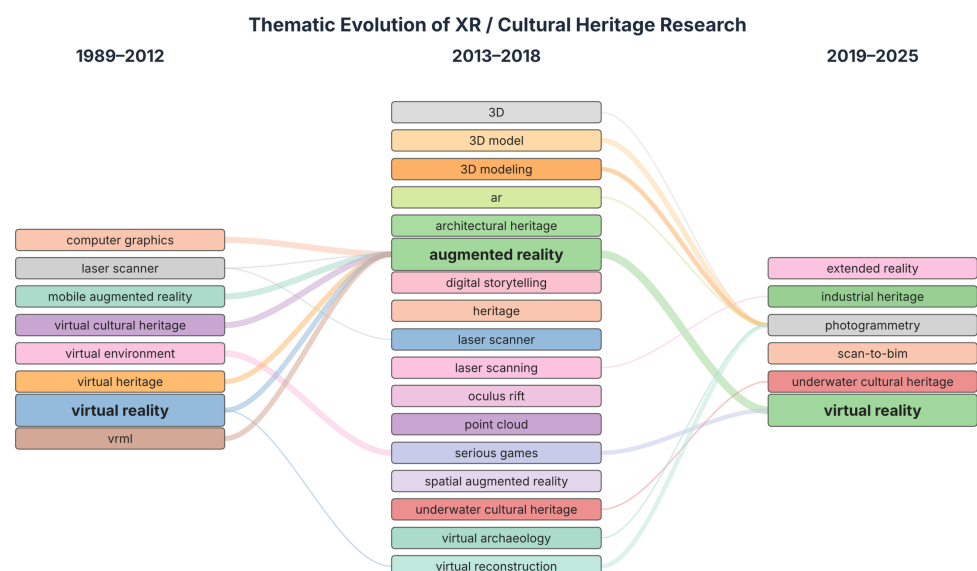


Figure 14. Thematic Evolution Diagram (Generated by Bibliometrix; redrawn by the author).

During the early stage, research themes were highly concentrated on foundational visualisation approaches and the feasibility exploration of XR technologies. This period was characterised by early technical concepts, with representative themes such as computer graphics, virtual environments, mobile augmented reality, and VRML (Virtual Reality

Modeling Language). Research during this stage remained relatively narrow, focusing primarily on technological implementation, as the themes reflected the experimental nature of the technological emergence phase and had not yet achieved deep integration across disciplinary or application contexts. During the mid-term period, research themes became increasingly diversified, with key terms such as augmented reality, 3D modelling, digital storytelling, virtual reconstruction, and serious games, indicating a horizontal expansion of research directions and project requirements. This phase was characterised by the close integration of technological tools with fields such as architecture, archaeology, and education, alongside a growing emphasis on immersive experiences. In the recent stage, thematic evolution is characterised by deep integration. Previously fragmented themes have increasingly converged and evolved into more inclusive and higher-level concepts. The emergence of the extended reality theme represents not merely a terminological shift, but a convergence of technological lineages and the unification of research paradigms. At the same time, industrial heritage has begun to emerge as a distinct theme, reflecting the expansion of heritage application contexts and value objectives. Scan-to-BIM, as a thematic direction, demonstrates how integrative technological strategies are being employed to develop more sustainable approaches to heritage conservation. Overall, thematic structures in this stage exhibit increased stability, indicating that the field is maturing into a research ecosystem characterised by deeply integrated technologies, diversified application scenarios, and increasingly complex strategic frameworks.

Notably, by extracting high-weight evolutionary relationships from the data, several clear evolutionary paths can be identified. The most prominent trajectory is the progression from virtual reality (1989–2012), to augmented reality (2013–2018), and further to extended reality (2019–2025), indicating a transition from single-technology approaches to integrated multi-technology frameworks encompassing AR, VR, and MR. The pathway from laser scanning (1989–2012) to photogrammetry and scan-to-BIM (2019–2025) reflects the evolution of data acquisition technologies from isolated tools to full-process digitalisation workflows. In addition, the transition from serious games (2013–2018) to virtual reality and extended reality (2019–2025) demonstrates how gamified design strategies have enhanced public engagement and facilitated more immersive modes of cultural heritage dissemination.

4. Discussion

This study employs systematic bibliometric analysis to explore the evolutionary trends, knowledge structure, and developmental trajectory of XR technology in European cultural heritage research. Drawing on 1368 publications published between 1989 and 2025, the analysis provides analytical answers to six central research questions, summarising each answer together with the evidence on which it is based.

RQ1: *What are the temporal evolution trends in this field?*

XR technology in European cultural heritage research shows a clear pattern of steady growth that gradually accelerates over time. The field expanded from sporadic publications in 1989 to a peak of 174 annual publications in 2022. The results highlight two key inflection points in 2013 and 2018, which mark transitions from an initial exploratory phase to a developmental stage, and subsequently from steady development to rapid expansion. Identifying these transition points helps clarify the field's developmental rhythm and the broader dynamics driving its evolution.

RQ2: *What are the geographical distribution and collaborative patterns in this field?*

The research reveals that XR and cultural heritage studies in the EU demonstrate a strong Southern European presence, alongside active and intensive collaboration patterns.

Southern European nations such as Italy, Spain, and Greece contribute nearly 60% of research outputs, with Italy holding absolute academic primacy. This pattern reflects the close correlation between national cultural heritage resource richness and digital technology research intensity, while also indicating these countries' active engagement in EU digital cultural activities. The study further identifies the Netherlands, Sweden, and Denmark as pivotal bridge-building nations in international collaborative networks. Despite lower publication volumes, these countries play crucial roles in connecting research networks both within and beyond the EU. Overall, these results demonstrate both the effectiveness of EU-level coordination mechanisms and the diversity of the research ecosystem across European countries.

RQ3: *Who are the core knowledge contributors in this field?*

A multi-tiered and networked knowledge contribution structure has emerged in this field. At the individual level, scholars such as Pierdicca, De Paolis, Banfi, Frontoni, Malinverni and Bekele form a core group of highly productive and influential researchers. At the institutional level, organisations such as the CNR and the Polytechnic University of Milan have developed dense academic clusters. Together with key institutions in Greece, Portugal, Spain and several other countries, they constitute the central research network of this domain. Knowledge innovation in this area relies on the academic leadership of core experts while also benefiting from broad and active collaborative networks. This structure provides a strong organisational foundation for the sustained development and dissemination of knowledge in the field.

RQ4: *What are the major research hotspots in this field?*

The keyword analysis highlights the major research hotspots in XR applications for cultural heritage. Across publications, “cultural heritage”, “virtual reality”, and “augmented reality” emerge as central concepts, while technology-related terms such as “3D modelling”, “photogrammetry”, “laser scanning”, and “mixed reality” reflect a strong focus on technical implementation. Keywords including “museum”, “education”, “3D reconstruction”, and “intangible cultural heritage” reflect the interdisciplinary and application-driven nature of the field. Terms like “digital storytelling”, “user experience”, and “serious games” highlight the diversity of research methods and strategies employed. In addition, several forward-looking keywords, including “artificial intelligence”, “immersion”, and “accessibility”, indicate emerging research directions in XR-based cultural heritage studies. Taken together, these findings suggest that major research hotspots are shaped by a set of closely connected research concerns. Scholarly attention commonly addresses heritage-related goals and values, with a focus on specific domains, including heritage sites, museums, education, and intangible cultural heritage. At the same time, substantial emphasis is placed on technological applications, such as scanning techniques, 3D modelling, and immersive technologies. Digital heritage methods and strategies are further developed in relation to specific heritage contexts, project objectives, and technological choices. Clustering analysis further reveals that research hotspots are not isolated; distinct clusters correspond to specific research directions. These range from technology-driven 3D modelling and visualisation to immersive educational and gamified experiences, to user-centred virtual reality emphasising engagement and storytelling, and finally, to societal and accessibility concerns. Temporal burst analysis adds a dynamic perspective, from early technology-driven experimentation to systematic solutions and workflow standardisation, and more recently to value-oriented research focusing on effective application, management, and sustainable operations.

RQ5: *How has the thematic structure of the field evolved over time?*

Thematic analysis indicates that research on XR-based digital cultural heritage in the EU has evolved significantly over time. In the early stage, research was primarily

technology-driven, focusing on the feasibility of individual technologies, representing an exploratory and experimental period. During the mid-term period, XR technologies became increasingly integrated with disciplines such as architecture, archaeology, and education, shifting the focus toward immersive experiences and diverse heritage application scenarios. In the most recent stage, research shows clear convergence and stabilisation, reflecting the integration of technological frameworks, value-driven applications, and the sustainability of work strategies. Overall, the thematic evolution follows a clear trajectory: from foundational experiments on isolated technologies to immersive applications across multiple contexts, and ultimately toward mature research guided by complex, sustainable digital strategies.

RQ6: *What key dimensions define the knowledge structure of this field, and can they be integrated into a domain framework to inform future research directions?*

Based on the findings of RQ1 to RQ5, this study constructs a knowledge structure framework (Figure 15) for XR-based digital cultural heritage research in Europe. The framework synthesises multiple insights from the bibliometric analysis and is organised around three interrelated core dimensions, together reflecting the field's theoretical foundations, practical applications, and future development directions.

First, the value-oriented dimension defines the key research priorities and intended impacts that drive XR deployment in the heritage sector. This value-oriented layer includes educational outcomes, museum engagement, virtual archaeology, architectural heritage conservation, intangible cultural heritage experiences, and cultural dissemination, emphasising that technological innovation in XR application is not pursued for its own sake but serves broader social, cultural, and educational objectives. Second, the technological dimension represents the technical foundation of digital heritage research and practice in this field, primarily including VR, AR, MR, 3D modelling, photogrammetry, and laser scanning. This technological layer provides the essential computational capabilities and immersive approaches that enable heritage sites and artefacts to be captured, reconstructed, and presented in digital form using XR technologies, thereby expanding possibilities for heritage documentation and public engagement. Third, the digital implementation dimension covers the practical methodologies and strategies through which XR technologies are applied to achieve specific project objectives. This implementation layer includes immersive experiences, digital storytelling, gamification approaches, interactivity, user experience, and HBIM-based workflows, demonstrating how technological capabilities are applied in practice and how XR tools can be configured, integrated, and deployed to deliver meaningful, engaging, and effective heritage experiences.

By integrating these three dimensions into a unified domain structure framework, the study provides a clear and systematic overview of the field, illustrating how research objectives, technologies, and implementation strategies interact. Beyond its layered structural representation, the framework also incorporates key insights derived from the research findings, including temporal evolution, geographical collaboration networks, and the contributions of leading scholars and institutions. Moreover, this integrated framework not only captures the current state of XR-based digital cultural heritage research in Europe by reflecting its multidimensional complexity, but also offers a conceptual foundation for future research by identifying scholarly trajectories, emerging trends, and promising directions for practical innovation.

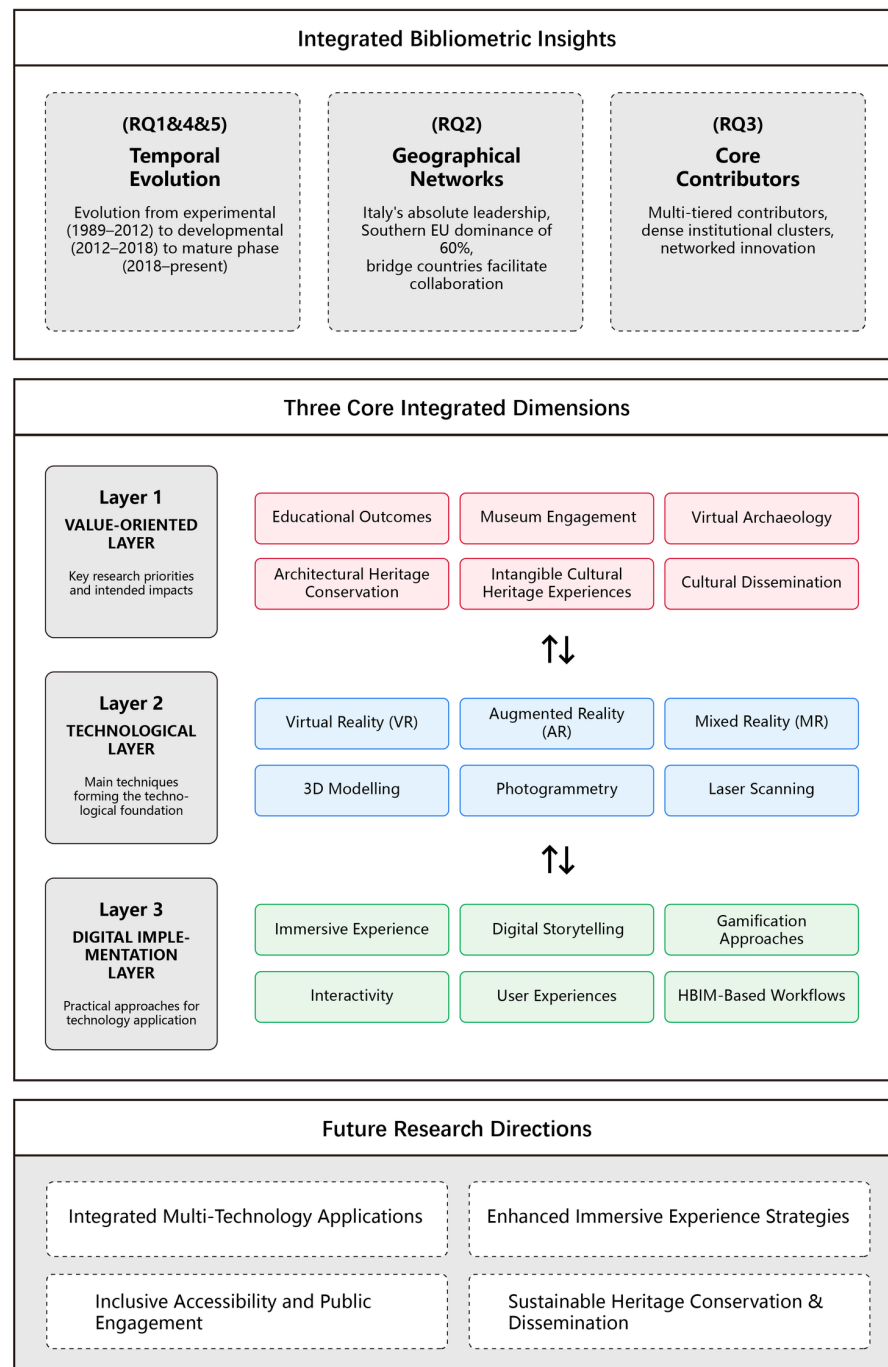


Figure 15. Knowledge Structure Framework for XR-Based Digital Cultural Heritage Research in the European Union (Source: the authors).

5. Conclusions

Research on the application of XR technology in the EU's cultural heritage sector has entered a new phase of development. From early technological explorations to current integrated innovations, the field shows strong momentum and broad application potential. Through a systematic bibliometric analysis of 1368 WoS publications from 1989 to 2025, this study maps the current state of research, knowledge structure and evolutionary trends. It shows that the field grew from sporadic early studies to a peak of 174 publications in 2022. It also shows that research output and collaboration are concentrated in Southern Europe, with Italy, Spain and Greece jointly accounting for nearly 60% of output. Furthermore, it shows that the field's knowledge structure can be organised into

three interrelated dimensions: value-oriented, technological and digital implementation. It provides insights that inform theoretical understanding of this emerging interdisciplinary field, while also identifying research limitations and highlighting promising directions for future investigation.

5.1. Research Contributions

By identifying the core research overview, major institutions and scholars, key hotspots and pathways, and thematic evolution over time, this study provides useful reference points for researchers entering the field of XR technology in cultural heritage, helping them understand development trends, establish collaborations, and select research directions. A further contribution lies in the study's focus on European research, offering an in-depth analysis of geographical distribution patterns across the EU. The collaborative model, in which Southern European countries take the lead and others serve as bridges, highlights the significant influence of cultural resources, policy support, and regional cooperation on the field's development. At the same time, the regional imbalances identified point to the need for targeted policy support and resource allocation to narrow disparities and promote more balanced growth. The most significant contribution of this study is the construction of a domain-specific research framework for XR technology applications in Europe's cultural heritage sector. By identifying three core dimensions, namely value objectives, technology, and digital implementation, along with their interrelated research evolution pathways, geographical distribution patterns, research contribution patterns, and mechanisms for future directions, this study provides a systematic analytical tool for understanding this complex interdisciplinary field. This framework not only supports a comprehensive understanding of the sector's current state and developmental trends, but also establishes a foundation for guiding future research.

5.2. Research Limitations

Although this study offers valuable findings, certain limitations remain. The research relies primarily on bibliometric analysis of the WoS database. Although WoS is recognised for its rigorous indexing standards and comprehensive citation tracking, other databases, such as Scopus, DOAJ, and EBSCO, provide additional coverage and may include relevant publications that are not indexed in WoS. The search string included the short abbreviations AR, MR, VR and XR. Without subject-category restrictions or systematic manual screening, the dataset may contain some unrelated records and introduce minor noise. In addition, analysing only English-language literature may exclude important studies published in other languages, particularly those in the native languages of European countries. This linguistic bias could affect a comprehensive assessment of research contributions from certain nations or regions. Furthermore, the dataset was retrieved on 1 June 2025, meaning that publications from the second half of 2025 and 2026 are not included in the quantitative analysis. Moreover, while bibliometric analysis objectively reflects the quantitative characteristics and network structures of research, a further in-depth review of the core literature and best practices is necessary to gain a deeper understanding of the practical applications of XR technologies in cultural heritage.

5.3. Future Research Directions

Despite these limitations, the findings of this study provide a foundation for future research. First, as XR technology applications in the cultural heritage sector continue to evolve, there is a clear need to establish comprehensive technical guidelines and a standards framework. Future research should prioritise technical standardisation, covering all stages of the process, including data acquisition, processing, storage, and presentation. By systematically collating lessons from successful case studies, best-practice guidelines

can be developed that are both replicable and scalable. This would ultimately contribute to a comprehensive technical framework for XR heritage applications, encompassing standardised workflows, user assessment frameworks, and specifications for cross-heritage project compatibility. Second, this study observes that the field is shifting from a technology-driven focus towards more complex, multidisciplinary applications that encompass broader social, cultural, and economic dimensions. However, current research remains limited in its examination of how broader socio-technical and cultural factors shape heritage digitisation technologies [63]. Future studies should therefore investigate in greater depth the influence of factors such as cultural adaptability, policy mechanisms, ethical concerns, and community engagement. Finally, as this study focuses primarily on the European context, future research should broaden its scope to include global-scale cross-cultural comparisons and knowledge transfer, thereby advancing the internationalisation of this field. In addition, future studies could update the present analysis with publications from 2025 onwards and combine several databases, such as WoS, Scopus, and regional databases, to test the robustness of the patterns identified here.

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