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Scientific Econometric Analysis of Cultural Heritage Digitization in the Past Five Years: Based on CiteSpace, VOSviewer, and SciMAT

Wang Xiaoyu[1,2], Di Ye[1] & Qian Jiang[1]

[1] Suzhou University of Science and Technology, China

[2] University of Canterbury, Christchurch, Canterbury, New Zealand

Correspondence: Qian Jiang, Suzhou University of Science and Technology, Jiangsu, Suzhou, China.

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Abstract

This article aims to systematically review and analyze the research laws, key technological elements, and cutting-edge development trends in the field of digitalization of cultural heritage, laying a theoretical foundation for future research plans and providing reference for promoting further development in this field. Using bibliometrics and CiteSpace, VOSviewer, and SciMAT software based on the Web of Science database, a qualitative and quantitative analysis was conducted on the digital literature knowledge graph of cultural heritage from 2020 to 2024. The results obtained econometric maps from macro to micro perspectives, combined with background information, current trends, and knowledge structure analysis of spatiotemporal, co word, clustering, theme evolution, and other charts, exploring the evolution of this field from various angles. The digitization of cultural heritage has gradually developed from the initial stage to a new stage of global cooperation and policy application. The characteristic of this transitional process is that the research focus gradually shifts from the attention to culture itself to the application of technological means, and ultimately expands to the display and dissemination of cultural heritage. This article also summarizes several development trends in this field, including integration, proceduralization, technologicalization, standardization, intelligence, etc., while also exploring the current limiting factors.

Keywords: cultural heritage, digitization, scientometric analysis, deep learning, user experience

1. Introduction

Culture is closely intertwined with the destiny of a nation. Cultural prosperity leads to national strength, and cultural vitality fosters the flourishing of a people. Since the 18th National Congress of the Communist Party of China, the country has attached great importance to the protection and inheritance of cultural relics and artifacts. General Secretary Xi has repeatedly emphasized the need to fully realize the value embedded in cultural heritage, invigorate its presentation, and promote active engagement with the public. Under his guidance, significant progress has been made in the protection and transmission of cultural heritage.

Amid the rapid development of emerging technologies such as big data, blockchain, and artificial intelligence, the arrival of the "digital era" has been significantly accelerated. Against this backdrop, the display and dissemination of content have undergone profound changes. Therefore, this study systematically reviews English-language literature published over the past five years, summarizing popular themes and research characteristics. It identifies current research issues and trends and envisions future research directions, aiming to facilitate deeper investigations and practical applications in the field of cultural heritage digitization.

2. Research and Methods

2.1 Data Sources

2.1.1 Macroscopic Data

The first step in this study was to select journal articles from the Web of Science (WoS) database to create a unified analysis database. WoS is widely recognized as a major source of authoritative and representative citation data and enables more comprehensive citation analysis. To enhance the scientific rigor of this study, search strings were constructed to refine the search criteria.

In the second stage, database records were retrieved. Specific criteria were used to select papers from academic journals relevant to the research theme across multiple databases. Data were collected by inputting search terms into the "Topic" (TS) field in WoS. Since the accuracy of macroscopic data is closely related to the topic field, it was necessary not only to identify synonyms of "digital" and "cultural heritage" but also to include concrete forms of digitalization. Based on the classification proposed by Chen Xiaojiu and others, and incorporating recent digitalization methods such as "Game," the full search query was constructed as follows:(TS=("cultural heritage" OR "cultural resources" OR "cultural legacy" OR "tangible heritage" OR "intangible heritage" OR "heritage protection"), AND TS=("digital" OR "data processing" OR "protection and inheritance" OR "photogrammetry" OR "3D scanning" OR 3S technologies including "GPS," "RS," "GS" OR "digital library" OR "digital archives" OR "digital museums" OR "VR," "AR," "MR" OR "APP" OR "digital cartoon" OR "digital interact" OR "virtual repair" OR "panoramic photography" OR "game")), AND DT=("article"), AND LA=("English"). The search date was August 1, 2024. After excluding retracted articles, 4,998 articles were obtained. These articles were subjected to macroscopic annual analysis (see Fig. 1).

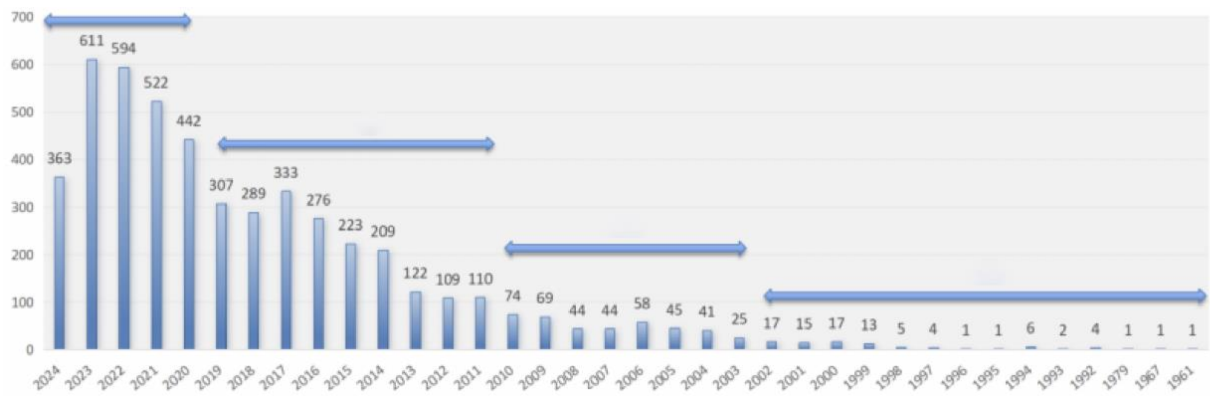


Figure 1. Annual output of papers

The initial stage (1961–1999) experienced slow and fluctuating growth, with the annual number of publications not exceeding 20. During this period, the concept and importance of digitalization of cultural heritage gradually gained recognition and understanding.

The second stage (2000–2010) showed a significant growth trend.

The advent of the 21st century and the emergence of commercial information providers such as Google and Microsoft further accelerated the digitalization of cultural heritage, aided by the development of computing infrastructure such as 3D modeling and Web 2.0, which enabled user searches in massive digital content libraries.

The third stage (2011–2019) was characterized by a digital technology boom and the global initiation of digital heritage projects. During this period, technologies such as Internet 3.0, 3S, and panoramic photography matured, and the widespread use of mobile devices further accelerated the spread of digital culture.

The fourth stage (2020–2024) marked the phase of promotion and innovation. Since 2019, there has been a rapid expansion in cultural heritage digitization research, with annual publications exceeding 400. Publication data showed that in 2023, the number peaked at over 600 articles. This indicates that the integration of cultural heritage into digital protection and dissemination is a pressing priority, exhibiting a stable growth trend. Research and applications in cultural heritage digitization have continuously expanded and innovated during this phase.

2.1.2 Data Refinement

Following the analysis of publication volume, it was found that the number of papers published in the past five years was considerable, but bibliometric analysis was relatively insufficient. Therefore, the study scope was preliminarily set to focus on literature from the most recent five years.

Initially, among the 2,510 articles obtained for 2020–2024, titles and abstracts were screened to verify compliance with inclusion criteria (see Table 1). Subsequently, the full content of each article was carefully read and analyzed to determine its relevance to the theme of cultural heritage digitization. Two types of literature were excluded: (1) studies where cultural heritage digitization was merely supplementary information, such as climate impact assessments on heritage; and (2) studies focused solely on chemical analysis of heritage materials, such as microbial activity on mural surfaces.

After this step, 1,036 articles remained. Finally, after deduplication, 1,033 articles were selected for subsequent bibliometric analysis.

Table 1. Article screening

Year	Initial number	After screening
2020	422	222
2021	522	195
2022	594	230
2023	611	270
2024	361	119

2.2 Research Methods

Bibliometric analysis is a quantitative method for evaluating academic literature through retrieved bibliographic information, aiming to describe, evaluate, and monitor research outputs. Bibliometric analysis answers various research questions through the study of publications, citations, information sources, and scientific mapping. This type of analysis can detect the evolutionary trends of specific research fields and identify emerging topics shaping thematic evolution.

CiteSpace and VOSviewer are widely used software applications for bibliometric analysis and visualization. They assist researchers in constructing knowledge networks and identifying major achievements in respective fields. VOSviewer, in particular, utilizes advanced algorithms and computational logic, making it highly suitable for processing and visualizing large datasets to ensure high-quality visual outputs.

In addition, SciMAT, an open-source scientific mapping software, was used to describe the thematic and conceptual evolution of research fields and to generate thematic evolution cluster maps based on time series data.

This study integrates the use of CiteSpace, VOSviewer, and SciMAT to collect, organize, and visualize research data related to cultural heritage digitization. Through these analyses, researchers can objectively summarize and evaluate the research background, important topics, and the evolution of knowledge structures. This process facilitates a comprehensive understanding of the research foundations, frontiers, and hotspots in this field and helps predict potential future research trends.

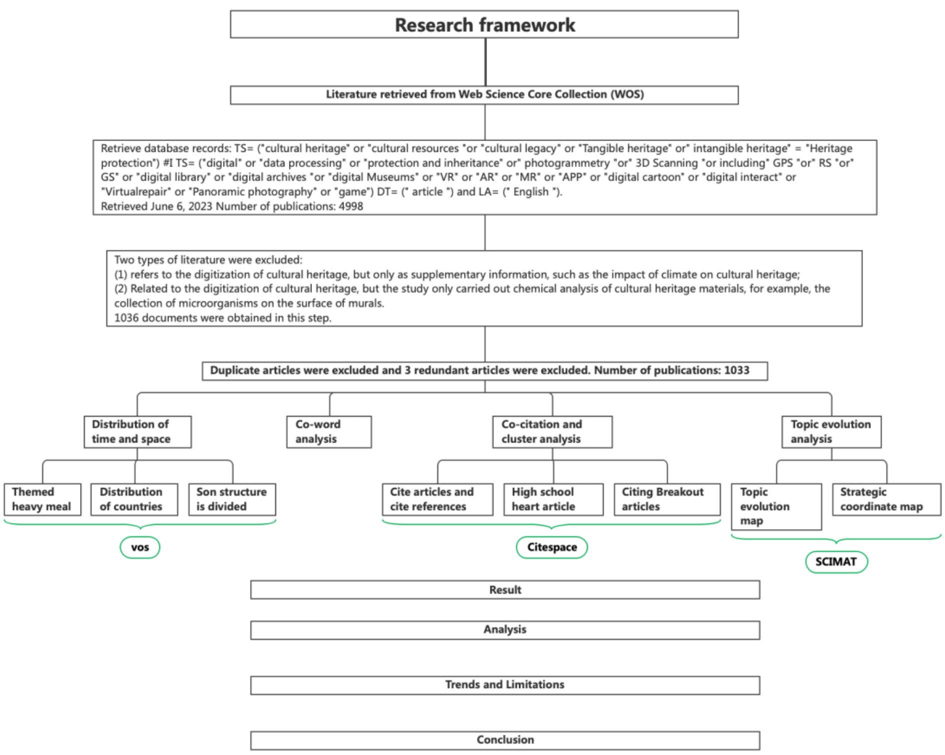


Figure 2. Overall Framework of Research

3. Results

3.1 Spatiotemporal Distribution

3.1.1 Topic Overlap

2020: During this period, there were 66 themes, of which 28% persisted into subsequent periods.

2021: A total of 72 themes appeared, with 28 new themes emerging, 30 themes lost, and 55% of the original themes retained.

2022: The number of themes increased to 55, including 13 new themes and 19 lost themes.

2023: Approximately 20.45% of the themes were retained during this period.

2024: Currently, there are 40 themes, with 13 new themes.

These data reveal the evolutionary trends of cultural heritage research themes, including the emergence of new topics and the disappearance of old ones at different stages. This analysis contributes to understanding the knowledge structure and provides valuable insights into the changing research trends within the field.

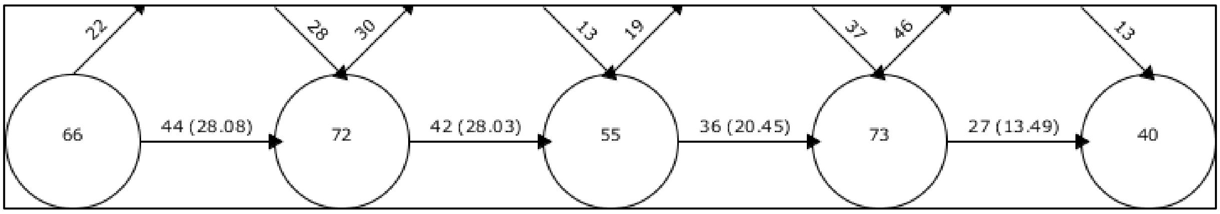


Figure 3. Digital Theme Overlapping Map of Cultural Heritage

3.1.2 National Distribution

Figure 4 illustrates the collaboration among countries on the theme of cultural heritage digitization. In the figure, the size of the circles corresponds to the number of publications related to cultural heritage digitization by each country, while the thickness of the lines represents the degree of collaboration between countries. China is the most active country in the field of cultural heritage digitization, making significant contributions, particularly through close cooperation with the United Kingdom, Thailand, and Malaysia. Italy closely follows China in publication volume. Spain, the United Kingdom, and the United States have also made notable contributions to research in this area. Although some countries have relatively fewer publications, they are actively engaged in international collaborations. This study primarily focuses on developed countries, highlighting their dominant role in cultural heritage digitization research and collaboration. Such collaborative efforts promote knowledge exchange and advance the study and application of cultural heritage digitization.

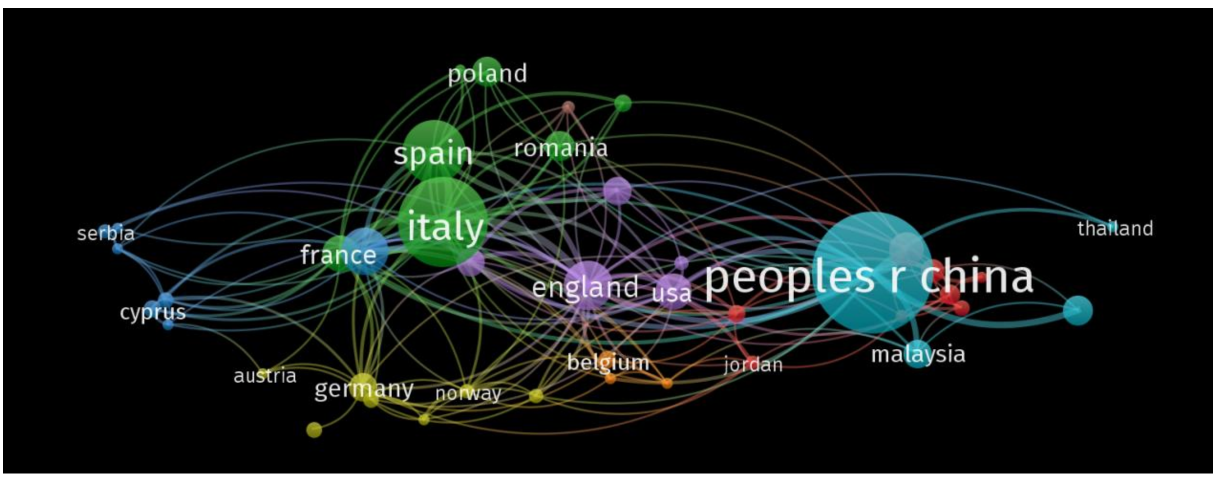


Figure 4. Digital National Distribution Map of Cultural Heritage

3.1.3 Institutional Distribution

Table 2. Top 10 institutions with the high number of citations and Total link strength

No.	organization	Citations	organization	Total Link Strength
1	politecn torino	420	politecn torino	12
2	univ seville	261	univ west attica	9
3	univ politecn marche	246	politecn milan	6
4	politecn milan	229	chinese acad sci	6
5	cnrs	189	babes bolyai univ	6
6	univ sarajevo	144	univ aegean	6
7	cyprus univ techno	137	athena res ctr	6
8	bruno kessler fdn fbk	134	univ seville	5
9	politecn bari	125	univ politecn marche	5
10	univ florence	123	politecn bari	5

Table 2 lists the top 10 institutions with the highest number of citations. Total link strength reflects the level of institutional collaboration—the higher the number, the stronger the partnership network. Politecnico di Torino received the most citations (420), far surpassing other institutions. The University of Seville, Università Politecnica delle Marche, and Politecnico di Milano followed closely, with 261, 246, and 229 citations respectively. However, the number of citations an institution receives does not always correlate directly with its degree of collaboration. Among the top-ranking institutions, Politecnico di Torino stands out for its high citation count and relatively active collaboration frequency. The University of West Attica ranks second in total link strength, with a score of 9.

3.2 Co-word Analysis

Based on the co-occurrence keyword network, the research keywords in this field can be categorized into eight clusters (Table 3, Figures 4 and 5), with the following results: Total number of items: 90. Total number of links: 2,611. Total link strength: 4,251. Each cluster is closely related to specific research themes. This study mainly analyzes the top three clusters: Firstly, the red cluster is closely associated with virtual reality (VR) and augmented reality (AR) in the context of digital entertainment for cultural heritage. It includes aspects such as presentation (protection and preservation), user experience (education and engagement), virtual heritage, and reconstruction (research and rebuilding) (Figure 5-1). Secondly, the green cluster focuses on cultural heritage, involving technologies such as artificial intelligence (AI), Historic Building Information Modeling (HBIM), machine learning, and data fusion (Figure 5-2). Thirdly, in the Digital Humanities cluster, the main keywords include Semantic Web and Art. These keyword classifications enhance the understanding of the major themes and research directions in this field while providing valuable insights into the knowledge structure and evolving research trends. Figure 6 illustrates the distribution and interrelationships of these keywords, highlighting their significance within different thematic areas.

Table 3. Digitization of 8 co-occurrence words data for cultural heritage

cluster	Item	Links	Total link strength	Occurrences
1	virtual reality	88	256	75
2	cultural heritage	169	711	277
3	digital humanities	28	51	26
4	hbim	56	113	27
5	reconstruction	61	118	34
6	3d printing	31	50	21
7	gis	41	64	23
8	game engine	11	14	5

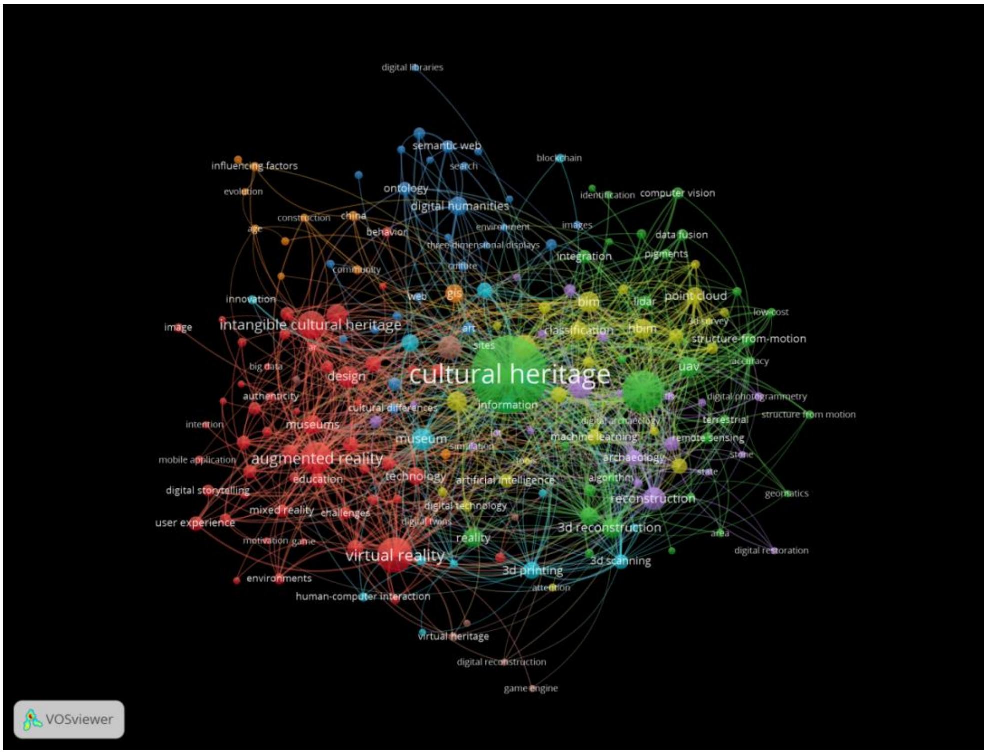
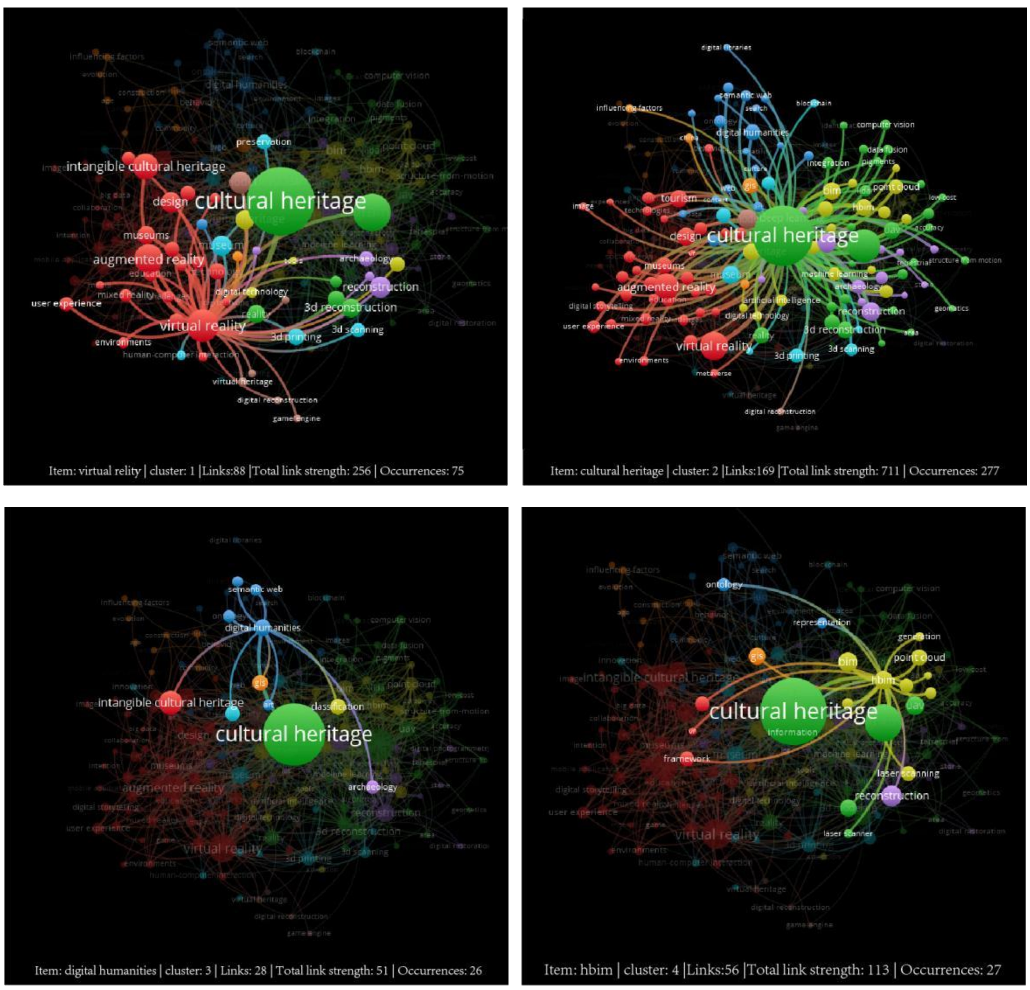


Figure 5. Co-word map of Digitalization of cultural heritage



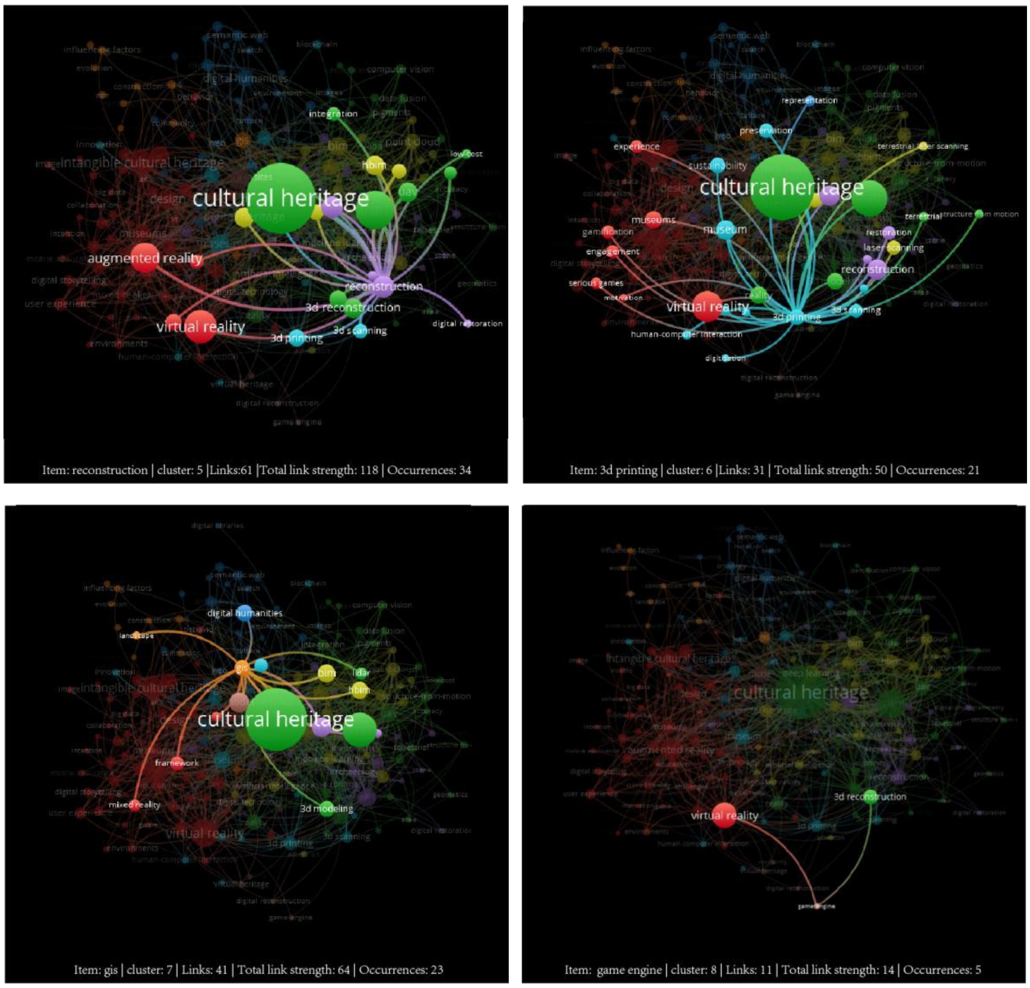


Figure 6. 8 co-occurrence word maps of cultural heritage digitization

3.3 Co-citation and Clustering Analysis

3.3.1 Co-citation Cluster Analysis

Using CiteSpace for clustering analysis, a total of 11 clusters were generated. The modularity (Q) value of the cluster network was 0.7155, indicating significant network associations within each cluster (Q > 0.3). The overall silhouette (S) value was 0.7979, suggesting reasonable intra-cluster similarity (0.5 < S < 1). A total of 11 major clusters were identified. These clusters were labeled with their respective index terms, including: "HBIM (Historic Building Information Modeling)" "Deep Learning" "User Experience" "Digital Twin" "Modified Camera" "Classification" "Cultural Heritage Conservation" "3D Printing" "Digital Humanities" "Silk Fabrics" "Unmanned Aerial Vehicle Photogrammetry" "Traditional Crafts." Except for Cluster #0, all clusters demonstrated improved structure and more reasonable cluster similarity. Cluster #0 (HBIM - Historic Building Information Modeling), Cluster #1 (Deep Learning), Cluster #2 (User Experience), and Cluster #3 (Digital Twin) are identified as the most significant clusters, among which Cluster #0 is the largest. According to the mean formation time, the most recently formed clusters include: Cluster #2 (User Experience), Cluster #3 (Digital Twin), Cluster #4 (Modified Camera), Cluster #12 (Greco-Roman Archaeology). In contrast, Cluster #1 (Deep Learning), Cluster #9 (Silk Fabrics), and Cluster #14 (Materials) were formed at an earlier stage (see Table 4 and Figure 7).

Table 4. Clustering of literature co-citation

lusterID	Size	Silhouette	mean(Year)	Label (LLR)
0	40	0.825	2018	Hbim
1	38	0.941	2017	deep learning
2	34	0.87	2020	user experience
3	33	0.859	2020	digital twin
4	30	0.847	2020	modified camera
5	26	0.922	2018	Classification
6	22	0.933	2018	cultural heritage conservation
7	21	0.997	2019	3d printing 3d
8	15	0.932	2019	digital humanities
9	14	0.895	2017	silk fabrics
10	14	0.902	2018	unmanned aerial vehicle photogrammetry
11	13	0.974	2018	traditional crafts
12	12	0.973	2020	greco-roman archaeology
14	4	0.988	2017	materials

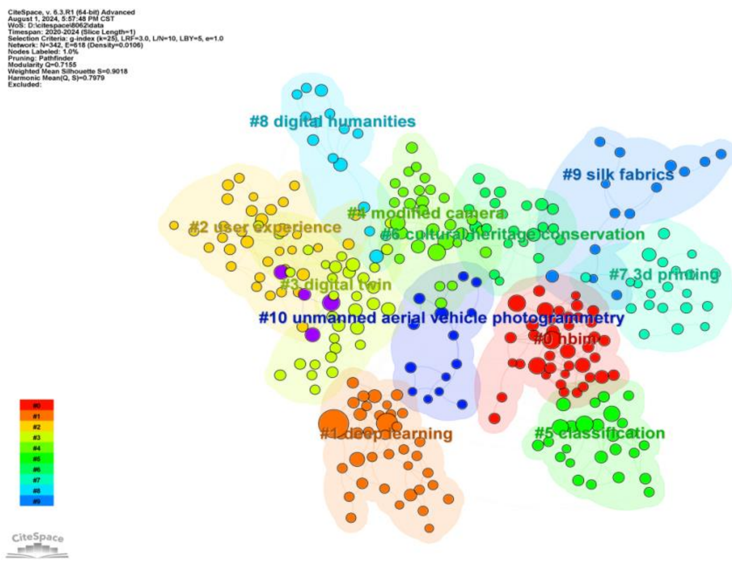


Figure 7. Digitalization of cultural heritage Clustering of literature co-citation map

The evolution of citation clusters can be observed through the timeline visualization (Figure 8). In this diagram, the size of each node corresponds to its citation count, and the connecting lines illustrate citation relationships. Initially, Clusters #2, #3, and #8 exhibited a prolonged lack of related publications, indicating a decrease in activity or a cessation of new research within these clusters during that period. In contrast, Cluster #0 showed the longest duration and maintained the most extensive connections with other clusters, suggesting its sustained activity throughout the entire research period. This cluster likely represents an important research direction or a highly focused area of scholarly interest. Clusters #0, #1, and #3 have maintained research activity for more than a decade, highlighting their significance as representative themes of enduring academic attention. Moreover, Clusters #0, #2, #3, #4, and #6 are characterized by a high level of continuity, indicating that they are persistent research hotspots that have attracted sustained interest and frequent citations over time. These observations help researchers understand the dynamic evolution within different clusters and identify which themes have retained long-term research activity.

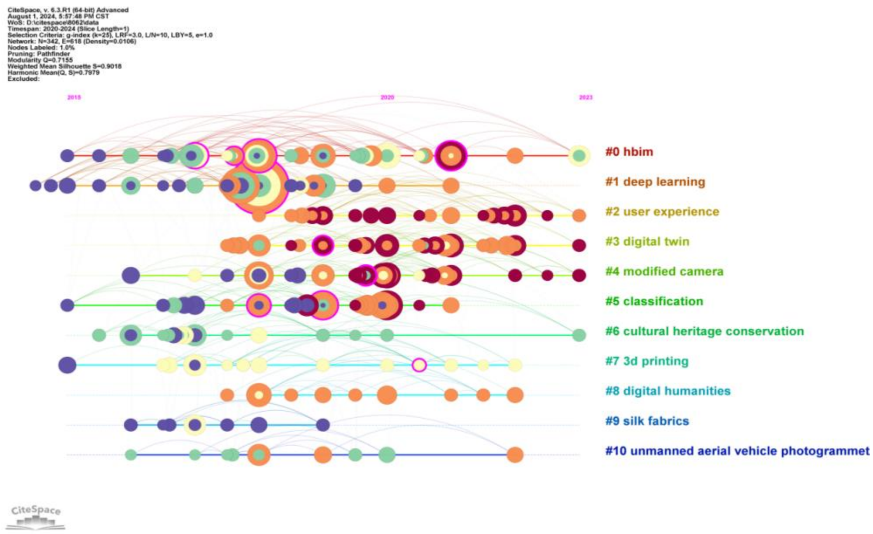


Figure 8. Timeline of co-citation clusters

The top five most-cited articles are mainly concentrated within four major clusters (Cluster #0, Cluster #1, Cluster #2, and Cluster #3), which are described in detail as follows:

Cluster #0: Historic Building Information Modeling (HBIM) refers to a specialized form of Building Information Modeling (BIM) in which the modeled objects are specifically limited to historical entities, such as historic districts, heritage buildings, and other culturally significant structures[1]. The most frequently cited authors within this cluster are listed in Table 5.

Table 5. Citation and cited literature for Cluster #0

Freq	Author	Year	Source	ClusterID
16	Lpez F	2018	MULTIMODAL TECHNOLOGIES AND INTERACTION	0
15	Pocobelli DP	2018	HERIT SCI	0
14	Pepe M	2021	J CULT HERIT	0
12	Pepe M	2020	APPL SCI-BASEL	0
10	Rodriguez-Gonzálvez P	2017	INT ARCH PHOTOGRAMM	0

Cluster #1: Deep Learning enables the extraction of complex patterns and features from cultural heritage data, thereby facilitating the preservation and restoration of artifacts, monuments, and historical sites in a more precise and automated manner. The most frequently cited authors within Cluster #1 are listed in Table 6.

Table 6. Citation and cited literature for Cluster #1

Freq	Author	Year	Source	ClusterID
51	Bekele MK	2018	ACM J COMPUT CULT HE	1
23	Aicardi I	2018	J CULT HERIT	1
10	Jo YH	2019	ISPRS INT J GEO-INF	1
8	Yang XC	2019	ISPRS INT J GEO-INF	1
7	Sanz-Ablanedo E	2018	REMOTE SENS-BASEL	1

Cluster #2: User Experience (UX) in cultural heritage digitization can be defined as the overall perception and interaction experienced by users when engaging with the digital representations of cultural heritage sites, artifacts, or narratives. The most frequently cited authors within Cluster #2 are listed in Table 7.

Table 7. Citation and cited literature for Cluster #2

Freq	Author	Year	Source	ClusterID
8	Boboc RG	2022	APPL SCI-BASEL	2
6	Hou YM	2022	ACM J COMPUT CULT HE	2
6	Bekele MK	2019	FRONT ROBOT AI	2
6	Bozzelli Guido	2019	DIGITAL APPLICATIONS IN ARCHAEOLOGY AND CULTURAL HERITAGE	2
5	Balletti C	2019	ISPRS INT GEO-INF	2

Cluster #3: Digital Twin in cultural heritage digitization research refers to a highly detailed and dynamic virtual replica of physical cultural heritage assets, such as buildings, monuments, or artifacts. These digital twins are created by integrating real-time data from sensors, 3D models, historical records, and other data sources, enabling continuous monitoring and management. The most frequently cited references within Cluster #3 are listed in Table 8.

Table 8. Citation and cited literature for Cluster #3

Freq	Author	Year	Source	ClusterID
9	Marra A	2021	SENSORS-BASEL	3
9	Jouan P	2020	ISPRS INT J GEO-INF	3
8	Liang HL	2018	J CULT HERIT	3
8	Funari MF	2021	SUSTAINABILITY-BASEL	3
7	Trunfio M	2022	J HERIT TOUR	3

2.3.2 High Centrality Articles

High-centrality articles refer to those that are frequently cited or co-cited across different disciplines. These publications are crucial to the development of the research field, serving as key nodes in multidisciplinary or evolving knowledge networks. The analysis identified the top five articles with the highest centrality (as shown in Table 9 and Figure 9). These works can be regarded as milestones in the field of cultural heritage digitization. The article with the highest centrality is authored by Alshawabkeh Y, located within Cluster #4, with a centrality score of 0.32, while the centrality scores of the other articles are all below 0.15.

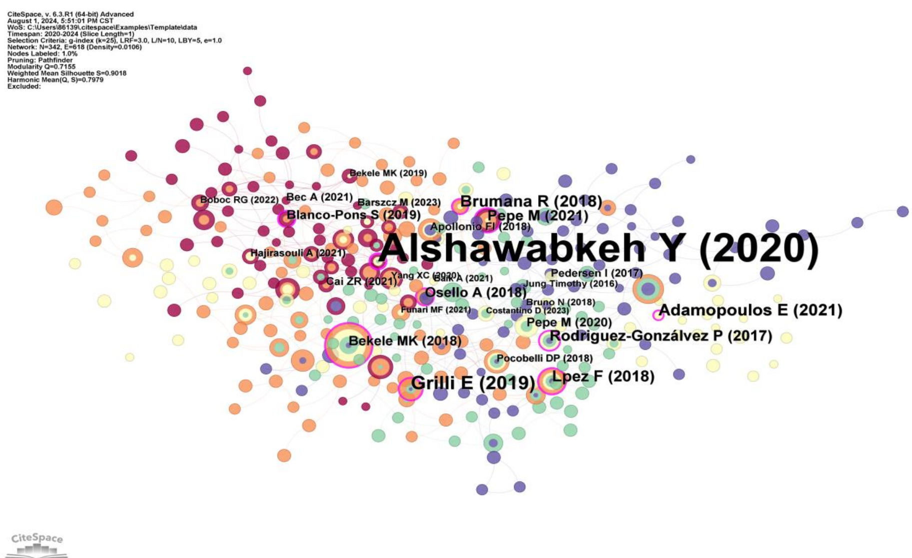


Figure 9. Betweenness centrality map

2.4 Thematic Evolution Analysis

Thematic evolution analysis is used to construct a co-occurrence matrix, conduct theme clustering analysis, and generate strategic coordinate maps based on density and centrality. This analytical method helps identify research hotspots across different periods and predict potential future research topics. Additionally, by assessing the relationships among thematic groups, an evolution map can be created to illustrate the temporal progression of research issues. For this analysis, SciMAT v1.1.04 was employed with the following configuration parameters: Frequency reduction thresholds were set to 1,1,1,1,1. Network reduction thresholds were set to 1,1,1,1,1. Association strength was used as the similarity normalization measure within the network. The simple centers algorithm was applied for clustering. These analytical tools and configurations assist researchers in gaining a comprehensive understanding of the evolutionary dynamics and trends within their respective research fields.

Table 9. Top 5 high betweenness centrality articles

Number	Centrality	Node	Source	Clustering
1	0.32	Alshawabkeh Y, 2020	DIGITAL APPL ARCHAE	4
2	0.15	Grilli E, 2019	REMOTE SENS-BASEL	5
3	0.13	Lpez F, 2018	MULTIMODAL TECHNOLOGIES AND INTERACTION	0
4	0.13	Adamopoulos E, 2021	ISPRS INT J GEO-INF	7
5	0.13	Brumana R, 2018,	APPL GEOMAT	0

2.4.1 Thematic Evolution Map

Figure 11 presents the evolution paths of research themes in the field of cultural heritage digitization, revealing the relationships among different issues and highlighting the key evolutionary trajectories. This analysis contributes to a better understanding of the knowledge structure and research trends within the field. Each node represents a thematic cluster, with the size of the node proportional to the number of related articles. The lines represent the evolutionary relationships between themes:Solid lines indicate that adjacent themes share major keywords, typically representing mainstream evolution.Dashed lines indicate that themes share secondary keywords, representing branch evolution. The color and thickness of the lines are proportional to the similarity between themes — the deeper and thicker the line, the stronger the association strength. The map shows that new research issues emerge in each time interval, reflecting the continuous development and evolution of research in the field of cultural heritage digitization. Among them, the themes "MUSEUM" and "POINT-CLOUD" are highly correlated with other topics, indicating strong evolutionary relationships. A clear evolutionary path (highlighted by the yellow line) is observed from "MUSEUM" → "MUSEUM" → "MUSEUM" → "DESIGN", illustrating that this theme has maintained sustained attention throughout the entire period. Another key evolutionary path (highlighted by the purple line) evolves from "DESIGN" → "ONTOLOGY" → "GIS" → "UAV" → "DIGITAL TWIN", showing the progressive relationship among themes related to digital twin technologies. Finally, several branching paths are also evident, such as the red path from "3D MODEL" → "POINT-CLOUD" → "GIS" → "DIGITAL HUMANITIES" → "TRADITIONAL CHINESE PAINTING", suggesting that research on China's cultural heritage digitization has gradually gained international recognition.

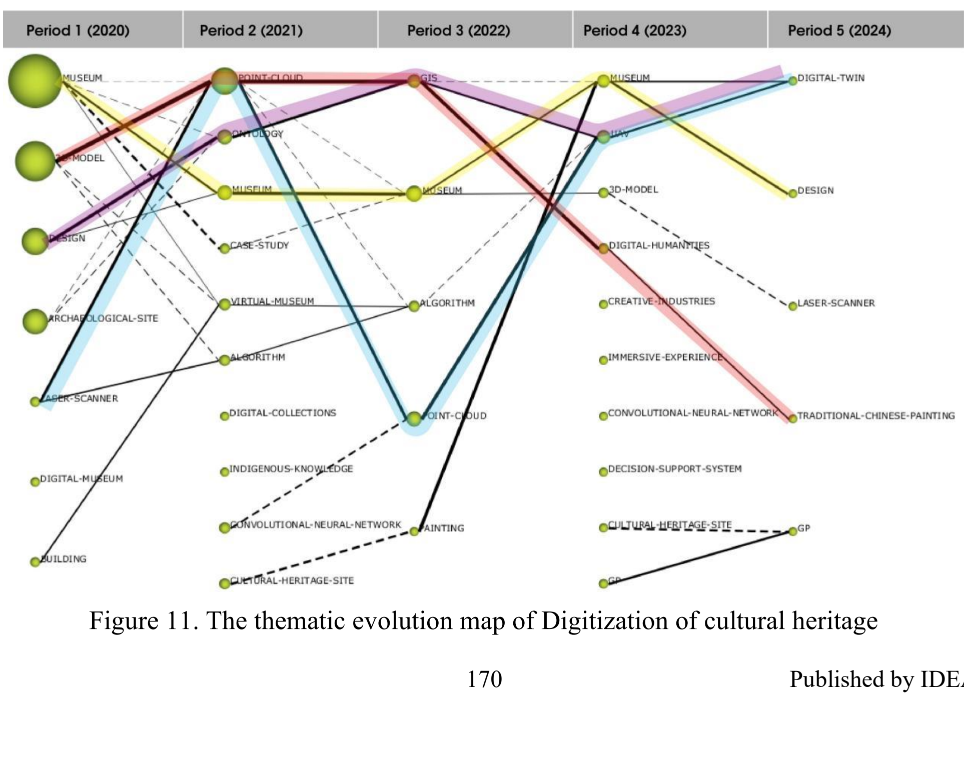


Figure 11. The thematic evolution map of Digitization of cultural heritage

2.4.2 Strategic Coordinate Maps

The strategic coordinate maps generated using SciMAT visually display the evolutionary status of research themes across four time intervals.

In these maps, each node represents a thematic cluster, and the number within the node indicates the number of articles associated with that theme — larger numbers represent more popular themes. The horizontal axis represents centrality, indicating the strength of a theme's connection with other themes. A higher centrality value suggests that the theme plays a more important role in the research field and is more closely related to various issues. The vertical axis represents density, reflecting the degree of association among keywords within the theme. A higher density indicates tighter internal connections, suggesting a more mature stage of development. The plane is divided into four quadrants, each representing different types of thematic evolution: The top-left quadrant contains mature but isolated themes. The bottom-left quadrant contains emerging or declining themes. The top-right quadrant represents well-developed and highly connected driving themes. The bottom-right quadrant contains important but underexplored themes that have the potential to become future research hotspots.

Based on the observations from Figure 12, there are differences in the driving themes and themes with development potential across different periods. From 2020 to 2023, "MUSEUM" consistently appeared as a theme with development potential, which aligns with the results shown in the thematic evolution map. This trend is driven by the development of associated themes such as 3D MODEL, GIS, and ALGORITHM, along with the growing emphasis on INDIGENOUS KNOWLEDGE (ranked based on centrality). Finally, from 2024 onward, the primary driving theme is GP (Geoprocessing), while the themes with development potential include "DIGITAL TWIN" and "TRADITIONAL CHINESE PRINTING". These observations help to understand the evolution of research themes and the shifting research priorities across different periods, while also providing valuable clues for researchers to predict potential future research hotspots.

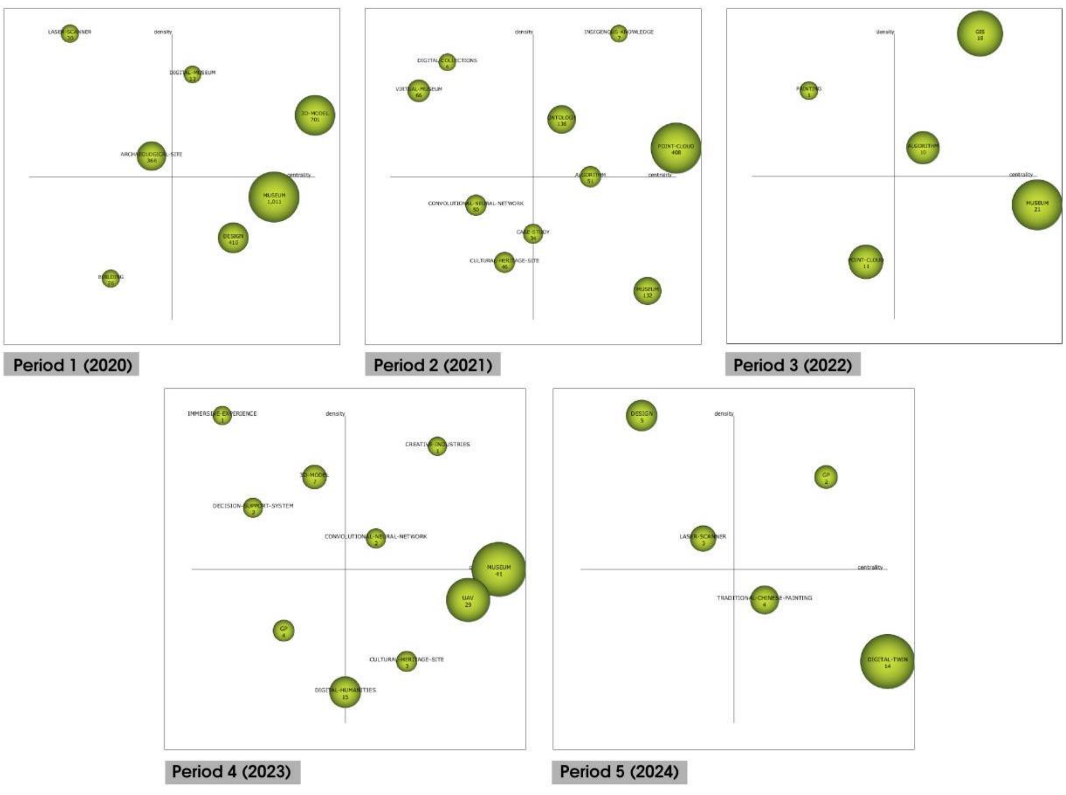


Figure 12. Strategic coordinate diagrams of Digitization of cultural heritage from 2020-2024

3. Results Analysis

3.1 Spatiotemporal Distribution

From 1961 to 2024, the number of publications in the field of cultural heritage digitization fluctuated but exhibited an overall upward trend, reaching a peak in 2023. This indicates that research activity in the field has been gradually increasing and expanding over time. The overlapping thematic map (Figure 3) shows that the number of new keywords consistently exceeds that of lost keywords, suggesting continuous development and advancement within the research field. The growth in the total number of keywords and the retention rate of keywords also reflects the increasing maturity of research directions and the establishment of substantive disciplinary inheritance. Based on the overall number of publications and the trends in keyword evolution, research in the field of cultural heritage digitization demonstrates great potential and offers ample space for future development. Regarding active countries, China and Italy are the major contributors in the field of cultural heritage digitization. They have published a large number of papers and established close collaborative relationships with other countries at both the author and institutional levels. This trend may be attributed to their abundant heritage resources, strong research capabilities, and shared concerns about heritage preservation. Active international collaboration facilitates the sharing of digital technologies and the dissemination of cultural knowledge. At the institutional level, Politecnico di Torino ranks first in both citation counts and collaboration network strength. However, the number of publications or the extent of collaboration networks among other institutions does not match their citation performance; for example, the University of Seville and the Università Politecnica delle Marche have high citation counts but relatively limited collaboration networks, lacking prominent research connectivity.

3.2 Co-word Analysis

This study clarifies the meaning and formation of the top three co-word clusters.

Cluster 1: Virtual Reality: Presentation (protection and preservation), User Experience (education and engagement), Virtual Heritage, and Reconstruction (research and rebuilding) (Figure 5-1).

Since 2020, virtual reality (VR) and augmented reality (AR) have attracted widespread attention.Their applications in cultural heritage digitization are highly rational and manifest in several aspects:Presentation (Protection and Preservation): VR and AR technologies enable the creation of digital copies of cultural heritage, reducing direct contact and physical wear on artifacts.This is particularly important for fragile or already damaged artifacts.For example, virtual models created through 3D scanning can be used for research and exhibition without physically touching the artifacts, thus protecting them from further damage.User Experience (Education and Engagement): VR and AR provide immersive experiences that allow users to "step into" historical scenes or buildings, offering firsthand experiences of past cultures and histories.Such experiences significantly enhance understanding and interest in cultural heritage.For instance, users can explore the full structure of the Roman Colosseum through VR or view reconstructions of ancient buildings via AR in modern environments.Virtual Heritage Accessibility:VR/AR technologies allow people who cannot physically visit heritage sites to experience them virtually.This provides equal access for individuals with disabilities and expands cultural heritage education to a global audience.Reconstruction (Research and Rebuilding): VR and AR can assist archaeologists and historians in simulating and reconstructing historical sites, testing hypotheses, and sharing findings.Virtual reconstruction, based on archaeological data, enables researchers to better understand and present historical contexts.With the growing emphasis on experiential aspects of digitization, the frequent appearance of related keywords is well justified.

Cluster 2: Cultural Heritage: AI (Artificial Intelligence), HBIM (Historic Building Information Modeling), Machine Learning, and Data Fusion (Figure 5-2).

Technologies such as AI, HBIM, machine learning, and data fusion provide powerful tools and methods that help researchers, conservation experts, and policymakers more effectively preserve and transmit cultural heritage. Cultural heritage is generally described as entities possessing historical, cultural, or scientific value, representing the collective memory and identity of a specific society or culture. In the article "Universality and Diversity: 50 Years of the UNESCO World Heritage Convention," the definition of cultural heritage emphasizes both its universality and diversity, discussing how the World Heritage Convention promotes the preservation of global cultural and natural diversity through the protection of such heritage.[2] Artificial Intelligence (AI) plays a crucial role in cultural heritage preservation, particularly in the areas of image recognition and data analysis. For example, AI can automatically identify and classify artifact images and analyze historical texts, thereby accelerating the organization and research processes related to cultural heritage. These technologies not only improve operational efficiency but also enhance the accuracy and depth of data processing. Historic Building Information Modeling (HBIM) is an important tool for cultural heritage preservation, especially in the digital reconstruction of historic buildings. HBIM integrates the physical attributes of architecture with historical information to create three-dimensional models that can be used for restoration, education, and exhibition purposes. For instance, damaged historical structures can be accurately reconstructed and virtually displayed through HBIM technologies. Machine Learning also plays a critical role in the protection and analysis of cultural heritage. By learning patterns from large datasets, machine learning can automate artifact classification, predict the environmental impacts on heritage sites, and simulate historical scenarios. For example, machine learning algorithms can analyze archaeological data to uncover previously unnoticed patterns in the distribution of historical sites. Additionally, it can support the creation of virtual cultural heritage displays, enhancing public understanding and interest in cultural heritage[3]. Data Fusion integrates data from different sources—such as remote sensing data, archaeological records, and environmental data—to provide a more comprehensive and precise analysis for cultural heritage research. This technology can be used to monitor the condition of cultural heritage sites, predict potential risks, and formulate corresponding conservation measures. For example, by combining Geographic Information Systems (GIS) with satellite remote sensing data, data fusion enables real-time monitoring of environmental changes affecting cultural heritage, allowing timely protective actions to be implemented.[4]

Cluster 3: Digital Humanities: Semantic Web and Art (Figure 5-3).

The primary goal of cultural heritage digitization is to address challenges related to preservation and dissemination within the humanities context, particularly in the realm of art, which is one of the most intuitive and engaging forms of digital representation. First, Digital Humanities refers to an interdisciplinary research approach that combines humanities disciplines with digital technologies. It is widely applied in the protection, research, and exhibition of cultural heritage. Through digital humanities methods, researchers can utilize a variety of digital tools and technologies—such as text analysis, data visualization, and 3D modeling—to process and analyze cultural heritage data. This approach not only improves research efficiency but also enhances the accessibility of cultural heritage and public engagement. For example, historical documents and artworks can be digitized and made available online, enabling global access for researchers and the public. Second, the application of Semantic Web technologies in cultural heritage digitization is primarily reflected in the organization and interconnection of data. The Semantic Web, through the use of standardized metadata and ontologies, allows cultural heritage data from different sources to be interoperable and linked, forming a rich, interconnected knowledge network. This technology not only enhances data discoverability and usability but also promotes interdisciplinary research and collaboration. For instance, by applying Semantic Web technologies, various types of digitized cultural heritage data can be organized and integrated into a unified knowledge graph, supporting complex queries and in-depth analysis by researchers. [5] Finally, Art plays a vital role in the digitization of cultural heritage, particularly in the areas of preservation, exhibition, and education. Through digital technologies such as 3D scanning, virtual reality (VR), and augmented reality (AR), historical artworks and heritage sites can be digitized and presented in virtual formats. This not only provides a means of protecting damaged or fragile artworks but also offers the public an entirely new interactive experience. For example, with VR and AR technologies, visitors can "enter" virtual museums or historical sites, experiencing cultural heritage that may no longer exist or is difficult to access in reality. The integrated application of these technologies has significantly advanced the digital preservation and dissemination of cultural heritage, enabling it to be better protected and more widely shared and studied on a global scale. This explains why "Digital Humanities" and "Art" are among the primary keywords emphasized in this study.

3.3 Co-citation and Clustering Analysis

3.3.1 Cluster Analysis

CiteSpace identified the references and cited articles associated with the four most significant clusters (#0, #1, #2, and #3).

By reviewing influential articles with high co-citation or citation rates, we identified the research foundations and frontiers for each cluster and organized their corresponding knowledge structures.

Cluster #0: HBIM (Historic Building Information Modeling)

Research Foundations

First, Data Acquisition and Processing: The research foundation of HBIM begins with high-precision data acquisition, typically achieved through technologies such as laser scanning and photogrammetry. The 3D point cloud data generated by laser scanning are used to accurately capture the geometric features of buildings. These data are subsequently processed to create detailed building information models. This process involves complex point cloud processing and geometric modeling techniques, often utilizing software such as Rhinoceros and MeshLab. Second, Geometric Modeling and Information Integration: An HBIM model is not merely a geometric representation of a building; it also integrates metadata related to building materials, historical context, and maintenance records. By embedding this metadata into the BIM environment, HBIM models become powerful tools for the protection, management, and exhibition of historic buildings. Third, Multidisciplinary Collaboration and Data Interoperability: HBIM research emphasizes the importance of multidisciplinary collaboration, particularly in achieving data interoperability. By integrating BIM models with other systems such as GIS, HBIM can support interdisciplinary research and applications. This data integration not only enhances the efficiency of cultural heritage management but also provides a rich information foundation for scholarly research. Finally, Practical Applications and Case Studies are crucial components of the current research foundation. HBIM has been successfully applied in numerous cultural heritage conservation projects, such as the rock-cut churches project in Grottaglie, Italy. These case studies demonstrate the effectiveness of HBIM in real-world applications, particularly in the areas of precise modeling, data integration, and digital management of heritage sites[6].

Research Frontiers

Based on five key articles, the research frontiers of HBIM (Historic Building Information Modeling) are primarily concentrated in the following areas:First, Automated Modeling and Data Processing:

Current research focuses on enhancing the degree of automation in the process from point cloud data to BIM models.

This includes the development of more intelligent algorithms capable of automatically recognizing and processing complex architectural forms, thereby reducing the need for manual intervention.

Enhancing automation not only accelerates the model generation process but also improves the accuracy and consistency of the resulting models[7]. Second, Modeling of Complex Geometries: HBIM faces significant challenges when dealing with the complex and irregular geometries of historic buildings. Research frontiers are focused on developing advanced modeling technologies and tools capable of accurately handling such intricate forms. In particular, researchers are seeking more flexible and precise solutions for the parametric modeling and accurate representation of architectural forms[8]. Third, Integration of Multi-source Data and Interoperability: HBIM research is actively exploring how to integrate various types of data—such as laser scanning, photogrammetry, and historical documents—into a unified model. This integration involves not only geometric data but also material properties, historical information, and maintenance records. Moreover, cross-platform and interdisciplinary data interoperability has become a research hotspot, aiming to enhance the versatility of HBIM models across different systems and applications[9]. Another important research frontier in HBIM is promoting the sustainable conservation of cultural heritage through multidisciplinary collaboration. This involves cross-disciplinary cooperation among fields such as architecture, history, archaeology, and computer science to develop more comprehensive and efficient conservation strategies. By integrating knowledge and technologies from different disciplines, HBIM can better support the long-term protection and management of cultural heritage. Moreover, by combining HBIM with Virtual Reality (VR) and Augmented Reality (AR) technologies, HBIM is not only used for modeling and analysis but also for the digital presentation and educational dissemination of historic buildings. These technologies offer immersive experiences to the public, making the education and communication of cultural heritage more vivid and interactive, thereby enhancing public awareness of heritage conservation[10].

Cluster #1: Deep Learning

Research Foundations

The application of deep learning in cultural heritage preservation began with the integration and preprocessing of multi-source data. This includes the use of technologies such as Unmanned Aerial Vehicle (UAV) photogrammetry, Terrestrial Laser Scanning (TLS), and Structure-from-Motion (SfM) to acquire high-precision 3D point cloud and image data. These datasets provide rich training material for deep learning models. During the data preprocessing phase, procedures such as denoising, alignment, and segmentation are employed to ensure the quality and consistency of the input data for the models[11]. A core application of deep learning in cultural heritage is enhancing the geometric accuracy of 3D models. By leveraging multi-source data and optimized Ground Control Point (GCP) configurations, deep learning algorithms can significantly improve the precision and detail representation of digital models of cultural heritage. This technology is particularly important in constructing building models with complex geometries, ensuring greater realism and accuracy. Semantic segmentation is another key application of deep learning in cultural heritage. Using deep learning algorithms, researchers can automatically identify and classify different elements within 3D models, such as building materials and structural components. This automated process reduces the need for manual intervention, increases the efficiency and accuracy of Historic Building Information Modeling (HBIM), and enriches the semantic information of the models, making them more practical and valuable[12]. It is noteworthy that in the virtual presentation and preservation of cultural heritage, deep learning combined with Virtual Reality (VR) and Augmented Reality (AR) technologies provides immersive experiences. Deep learning can enhance the detail representation and interactive experience within virtual and mixed reality environments by automatically generating and optimizing 3D models. These technologies enable cultural heritage to be better displayed and disseminated in virtual environments[13].The widespread application of deep learning has significantly enhanced the level of automation in cultural heritage digitization. Compared to traditional manual modeling methods, deep learning algorithms can automatically perform various complex tasks, such as point cloud to model conversion, semantic annotation, and structural analysis. This automation not only improves work efficiency but also reduces the occurrence of human errors[14].

Research Frontiers

In the field of cultural heritage digital modeling, a primary research frontier of deep learning lies in enhancing the automation from data acquisition to model generation. Current studies are dedicated to developing more intelligent algorithms capable of automatically recognizing and classifying 3D point clouds derived from multi-source data (such as laser scanning, photogrammetry, and Structure-from-Motion (SfM)), thereby reducing human intervention. This level of automation not only improves the efficiency of model generation but also enhances the geometric accuracy and semantic richness of the models[15]. Another important research frontier is the semantic segmentation of complex geometries, especially within Historic Building Information Modeling (HBIM). Researchers are developing more advanced deep learning models capable of handling cultural heritage objects with intricate geometric structures. These models can automatically segment and label different architectural elements, supporting more detailed and accurate HBIM modeling, while also integrating historical knowledge to enhance the semantic expressiveness of the models. As Virtual Reality (VR) and Augmented Reality (AR) technologies become increasingly prevalent in cultural heritage applications, deep learning is being utilized to enhance the intelligent interactivity of these immersive technologies. Current research focuses on optimizing the detail representation within virtual environments through deep learning algorithms, thereby improving user interaction experiences, particularly in the virtual presentation and educational applications of cultural heritage. Additionally, deep learning is being applied to optimize geometric accuracy during the cultural heritage digitization process. Specifically, by improving the configuration and distribution of Ground Control Points (GCPs), deep learning algorithms can enhance the overall accuracy of models and effectively assess the impact of different configurations on model precision. Research frontiers in this area are dedicated to developing more cost-effective and efficient solutions for large-scale heritage digitization projects[16]. Another current research focus is how to achieve semantic integration of multi-source data through deep learning. By combining 3D data from different sources with historical documents, deep learning models can automatically generate HBIM models enriched with semantic information. These models not only record the geometric forms of buildings but also embed their historical context and material characteristics.

Cluster #2: User Experience

Research Foundations

The research foundation of user experience in cultural heritage lies in creating immersive cultural experiences through technologies such as Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). These technologies enable users to deeply experience and explore digitized historical scenes and cultural heritage sites. CHAMPION E emphasized the importance of these technologies in enhancing user experience and promoting cultural learning[17]. The same study also demonstrated that personalization and user-centered design are key foundations for user experience in cultural heritage. By analyzing user behaviors and preferences, cultural experiences can be tailored to meet the diverse needs and interests of different users. The study highlighted the role of personalized experiences in enhancing cultural heritage preservation and dissemination. Research on user experience also includes the application of multimodal interaction and gamification. Through these methods, users can interact with cultural content in more natural and diverse ways. This approach not only increases user engagement but also improves the effectiveness of cultural learning. In the ArkaeVision project, researchers explored how gamification mechanisms and personalized interactions can enhance user experience and memory retention[18].

Research Frontiers

The application of Mixed Reality (MR) technologies in cultural heritage is emerging as a major research frontier. MR technology seamlessly integrates virtual content with the real environment, allowing users to gain a deeper experience through interaction. The application of this technology offers new possibilities for the presentation and education of cultural heritage, enhancing users' sense of immersion and engagement. Researchers such as JONES A and others have demonstrated how MR can improve the overall user experience in cultural heritage by enabling multi-layered narrative approaches and real-time interactions. In virtual and augmented reality environments, collaboration and social interaction are also becoming important research directions. By enhancing multi-user collaborative platforms, users can jointly participate in cultural exploration and learning within virtual environm[19]. The study titled "A Comparison of Immersive Realities and Interaction Methods: Cultural Learning in Virtual Heritage" discusses how collaborative multimodal interaction can enhance user engagement and improve cultural learning outcomes. Another emerging research frontier is the use of Artificial Intelligence (AI) technologies to provide personalized cultural experience recommendations. AI can analyze users' interests and behavioral data to deliver tailored content within virtual cultural heritage environments[20]. BOBOC R G and other researchers have also explored how AI technologies can be utilized to enhance the personalization of cultural experiences and provide users with more engaging content[21]

Cluster #3: Digital Twin

Research Foundations

The research foundation of digital twin technology in cultural heritage first relies on high-precision data acquisition and modeling techniques, such as Terrestrial Laser Scanning (TLS), photogrammetry, and UAV-based surveying. These technologies enable the generation of detailed 3D point clouds and image data, providing the essential basis for creating digital twin models. Such data not only support the creation of accurate geometric models but are also used for further structural analysis and predictive modeling. For example, Chinese researcher Huilin Liang and colleagues demonstrated how multiple technological approaches can be utilized to collect and integrate data for the creation of detailed 3D models[22]. In digital twin research, parametric modeling and Finite Element Analysis (FEM) technologies are indispensable tools. Through these techniques, researchers can transform static 3D data into models capable of dynamic analysis, allowing them to simulate the behavior of historical buildings under different environmental conditions. This modeling approach is crucial for preventive conservation, as it helps predict potential structural issues and enables the formulation of proactive preservation strategies. Jouan P and colleagues further expanded the application of digital twin technology in preventive conservation by integrating multiple data sources and real-time monitoring to achieve dynamic management of cultural heritage assets[23]. The research foundation of digital twin technology also includes the application of Integrated Information Systems (IIS). These systems combine traditional cultural heritage management methods with modern information technologies, enabling more comprehensive management of cultural heritage by integrating data from multiple sources. For example, A. Marra and colleagues explored how the combination of IIS and digital twin technology can enhance the efficiency of cultural heritage conservation and management[24].

Research Frontiers

One of the research frontiers of digital twin technology in cultural heritage is the integration of real-time monitoring and dynamic analysis. Through Internet of Things (IoT) sensor networks, digital twin technology can capture environmental changes and structural conditions of cultural heritage sites in real time, enabling dynamic monitoring and analysis. This application not only helps identify potential risks but also allows for the simulation of different scenarios to test the effectiveness of conservation strategies. Such approaches hold significant promise for preventive conservation. Another frontier involves combining Artificial Intelligence (AI) and machine learning technologies with digital twin models to enhance the efficiency of data processing and analysis. For example, machine learning algorithms can automatically identify and classify large-scale point cloud data and update models in real time. This enables cultural heritage managers to respond more quickly to changes and optimize maintenance and conservation measures. The application of AI also includes predictive analysis, helping to forecast the impacts of future environmental changes on cultural heritage. Additionally, research frontiers include the integration of digital twin technology with Augmented Reality (AR) and Virtual Reality (VR) to provide users with immersive cultural heritage experiences. Through such integration, users can interact with cultural heritage in virtual environments, further enhancing public understanding and awareness of heritage preservation. This technology not only finds wide application in education and exhibition but can also be used to simulate the effects of different conservation measures, offering visualized decision support for cultural heritage management.

3.3.2 High Centrality Articles

According to data from CiteSpace, the article with the highest betweenness centrality is a study by Henry et al. (2012), with a centrality value of 0.14. Although this value is much lower compared to other fields, it still indicates the article's significant structural role within the network. The study aimed to elucidate the causes behind the decline in bee populations due to pesticide exposure (Henry et al., 2012). This article serves as a typical example demonstrating how, in the field of cultural heritage digitization, the integration of laser scanning and photogrammetry can optimize both geometric accuracy and visual quality. It emphasizes the importance of multi-source data integration and offers innovative methods for effectively documenting and conserving heritage sites, particularly suitable for detailed analysis and restoration decisions involving complex structures[25]. The remaining high-centrality articles collectively stress the necessity of generating high-precision 3D models through the integration of multi-source data, including laser scanning, photogrammetry, and UAV-based surveying. High-precision 3D models not only provide the foundation for cultural heritage recording and analysis but also support complex structural assessments and the development of conservation strategies. For example, H. Liang et al. explored how various technological methods can be employed for comprehensive documentation of complex Chinese classical gardens, representing a typical application of cultural heritage digitization[26]. Additionally, the application of automation and intelligent technologies, such as digital twin systems and machine learning, is emphasized to enhance the level of automation in data processing and analysis. For instance, the article "Classification of 3D Digital Heritage" discusses how machine learning techniques can be applied to automatically classify 3D heritage data, improving efficiency and reducing manual errors[27]. This intelligent application enables more precise and efficient management and conservation of cultural heritage. Moreover, a key feature emphasized across these articles is the need for interdisciplinary integration, combining technologies such as Historic Building Information Modeling (HBIM), Geographic Information Systems (GIS), Virtual Reality (VR), and Augmented Reality (AR). The article "A Review of Heritage Building Information Modeling (H-BIM)" summarizes the applications of HBIM in cultural heritage conservation, demonstrating how multiple technologies and disciplinary knowledge are integrated to better preserve and manage historic buildings[28]. Furthermore, these articles highlight not only technological innovations but also the application of digital technologies in cultural heritage education and exhibition. Through VR and AR technologies, the presentation of cultural heritage has become more vivid and interactive, attracting greater public attention and participation. Such innovations extend the scope of cultural heritage digitization beyond conservation into the fields of education and cultural dissemination. In conclusion, these articles are regarded as representative works in the field of cultural heritage digitization, as they illustrate the latest developments in multi-source data integration, application of intelligent technologies, interdisciplinary collaboration, preventive conservation, and educational and exhibition practices. These studies provide a solid theoretical foundation and practical technical pathways for the digital preservation of cultural heritage.

3.3.3 Citation Bursts

According to the citation burst analysis, the top five articles with the strongest citation bursts are identified in Figure 10. The article with the highest burst strength is by Pepe M et al. (2020), with a burst strength of 4.06. This study explores an efficient workflow for constructing Historic Building Information Modeling (HBIM) models and conducting structural analysis based on 3D point cloud data. The research focuses on utilizing modern surveying technologies, such as image-based modeling and laser scanning, to generate high-accuracy 3D models[29]. Another article with a high burst value is by Jo YH (2019), which was particularly influential during the 2020–2021 period. This study presents a method for three-dimensional digital documentation of the Magoksa Temple in Korea, combining terrestrial laser scanning and unmanned aerial vehicle (UAV) photogrammetry to generate detailed 3D models for comprehensive recording and analysis[30]. Dai A (2017) proposed a method that combines 3D Encoder-Predictor Networks (3D-EPN) and shape synthesis techniques to complete partially scanned 3D models. The article details how Convolutional Neural Networks (CNNs) are used to predict the shape of partially scanned 3D objects and correlate these predictions with 3D geometric data from a shape database to synthesize high-resolution models. This article was widely cited in 2020, reflecting its formalization within the field[31]. During the 2022 period, the article by Aicardi I (2018) exhibited a high burst value of 2.86. This study reviews recent trends in cultural heritage 3D surveying, especially advancements made through the photogrammetric computer vision approach. It analyzes the integration of traditional photogrammetry with modern computer vision techniques and demonstrates how image processing technologies can improve the accuracy and automation of 3D models[32]. For the 2023–2024 period, the article by Yang XC et al. (2020) shows a significant citation burst. This article emphasizes the role of Building Information Modeling (BIM) in cultural heritage documentation and management, and discusses the possibilities and challenges of expanding HBIM functionalities through integration with other technologies. The study ultimately proposes methods to enhance data interoperability and reduce information loss, aiming to better serve the digital preservation of cultural heritage[33].

3.4 Thematic Evolution Analysis

Based on the thematic evolution map (Figure 11) and the strategic coordinate map (Figure 12) generated by SciMAT, three major research focuses can be summarized for the field of cultural heritage digitization: museums, digital twins, and traditional Chinese painting. Firstly, research on museum digitization focuses on leveraging advanced technologies such as 3D scanning, Virtual Reality (VR), and Augmented Reality (AR) to enhance the preservation, accessibility, and educational value of cultural artifacts. Through the digitization of collections, museums can create virtual exhibitions that allow global audiences to explore and interact with cultural heritage in ways not possible through physical exhibitions alone. This approach not only aids in the protection of artifacts but also democratizes access to cultural education, enabling people around the world to remotely experience and learn about museum collections. Secondly, in cultural heritage, the concept of the digital twin refers to detailed, real-time virtual replicas of physical sites or artifacts. These digital models integrate data from various sources (e.g., sensors and 3D scanning) to continuously monitor and analyze the condition of heritage assets. The technology facilitates predictive maintenance and preservation by simulating different scenarios, assessing potential risks, and optimizing conservation strategies. Digital twins are becoming increasingly crucial for the proactive management of complex heritage sites. Lastly, the digitization of traditional Chinese painting involves the use of advanced technologies such as high-resolution imaging and Artificial Intelligence (AI) to preserve and study these culturally significant artworks. Digital efforts not only protect the physical integrity of these paintings by creating digital archives but also promote global understanding and appreciation of Chinese art. This digital preservation ensures that the intricate details and historical significance of traditional Chinese paintings are preserved for future generations.

4. Trends and Limitations

4.1 Research Trends

Based on the previous analysis, the research trends in cultural heritage digitization are moving towards diversification and technological integration. In recent years, with the rapid development of VR, AR, laser scanning, UAV photogrammetry, and machine learning technologies, methods of cultural heritage digitization have become more diverse and efficient. Future research trends can be summarized into five major directions: Multi-source Data Fusion: Research will increasingly focus on effectively integrating data from various sources, such as laser scanning, photogrammetry, UAVs, and sensor networks, to generate high-precision 3D models and digital twin systems. The integration of these technologies will enhance the detailed recording and dynamic monitoring of cultural heritage. Automation and Intelligence: With the introduction of AI and machine learning, the level of automation in cultural heritage digitization will continue to rise. Future research will explore how AI technologies can be used to automatically classify, analyze, and restore digital cultural heritage data, thereby reducing manual intervention and improving efficiency and precision. Real-time Monitoring and Preventive Conservation: The application of digital twin technology makes real-time monitoring and preventive conservation of cultural heritage possible. Future studies will focus on using real-time data analysis to identify potential risks in advance and develop corresponding conservation strategies to extend the lifespan of cultural assets. Immersive Experience and Education: With the advancement of VR and AR technologies, the display and educational methods for cultural heritage will become increasingly interactive and immersive. Research will examine how to better convey cultural information through these technologies and enhance public understanding and awareness of cultural heritage protection. Standardization and Open Data: As the application of these technologies becomes more widespread, there will be greater emphasis on standardizing cultural heritage digitization processes and promoting open data sharing. Establishing unified data formats and standards will improve data interoperability between projects and facilitate global collaboration in cultural heritage conservation.

4.2 Research Limitations

Despite the significant progress in cultural heritage digitization technologies, several limitations remain in practical application: High Costs and Technical Barriers: Advanced digitization technologies such as laser scanning, UAV photogrammetry, and 3D modeling often require expensive equipment and professional expertise, posing challenges for resource-limited heritage conservation projects. Complexity in Data Processing and Management: Large-scale 3D datasets and high-resolution image files demand substantial computational power and storage resources. Effectively managing and integrating multi-source data to ensure accuracy and consistency remains a major challenge. Incomplete Coverage of Heritage Features: The complexity of cultural heritage makes it difficult to fully capture all its characteristics, particularly intricate geometries, fine details, or dynamic changes. Current technologies may lack the precision and coverage necessary for comprehensive documentation. Long-term Data Preservation and Sharing Risks: Over time, digital formats and storage media may become obsolete, posing risks to long-term data accessibility and usability.Additionally, issues related to cultural sensitivity and privacy protection may limit the extent to which data can be openly shared. These limitations suggest that although digitization technologies offer enormous potential for cultural heritage preservation, significant challenges must still be overcome to achieve more effective and sustainable management practices.

5. Conclusion

This study employed bibliometric techniques, combining both qualitative and quantitative analysis, to evaluate the research focuses, frontier fields, and prospective trajectories of cultural heritage digitization over the past five years (2020–2024). The findings provide a conceptual foundation for future research in this field and offer insights that can assist managers and decision-makers in pursuing proficient management, informed decision-making, and effective conservation efforts. Ultimately, these efforts contribute to the promotion and sustainable development of human civilization.

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