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Mapping Artificial Intelligence and Digital Transformation in Museums

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Abstract:

This study examines the development of research on artificial intelligence and digital transformation in museums, with particular attention to immersive experiences, visual analytics, and the digitization of museum exhibits. A bibliometric analysis combined with qualitative thematic analysis was conducted on publications indexed in the Web of Science Core Collection for the period 2016-2026. The results show that the literature has evolved from isolated digital initiatives toward integrated systems that combine augmented reality, machine learning, and semantic data infrastructures to enhance visitor experience and support documentation and collection management. The analysis identifies three main thematic clusters: (1) immersive experiences and human-computer interaction in museums; (2) artificial intelligence and visual analytics for collections and visitors; and (3) gamification, sustainability, and the digital transformation of museum offerings. The findings indicate increasing scholarly interest in personalized systems, visitor behavior tracking, and data-driven museum services, while also highlighting persistent challenges related to organizational implementation and governance. The study contributes to a better understanding of the current research structure in this field and outlines future directions concerning the implementation of artificial intelligence and ethical museum governance.

Keywords: artificial intelligence (AI), cultural heritage, visitor engagement, augmented reality, virtual reality, immersive experience, museums

JEL: O33, Z11, C38, D83, L86, M15

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INTRODUCTION

The implementation of artificial intelligence (AI) systems in museums and cultural heritage organizations represents the most important cultural sector development during the past ten years (Giannini & Bowen, 2019; Hyvonen, 2020). Artificial intelligence brings new automation capabilities that enable users to interact with museum systems through customized experiences which change the way people connect with museums and the way museums define their cultural educational social and economic functions according (Ioannakis et al., 2020; Meng et al., 2022). The art museums,

natural history museums, science museums, history museums and industrial heritage museums all research conversational agents, recommendation systems, behavioral analytics, virtual reality, augmented reality environments and machine learning system infrastructures to transform their operations from traditional observation spaces into interactive environments which focus on building experiences and creating knowledge together with their users (Duguleana et al., 2020; Pruulmann-Vengerfeldt, 2022).

In this context, the specialist literature has diversified, addressing themes such as the personalization of visitor experience, digital and virtual museums, the use of AI in conservation and documentation, as well as the ethical implications of the datafication of audiences (Giannini & Bowen, 2019; Pruulmann-Vengerfeldt, 2022; Avlonitou et al., 2025). Existing studies propose conceptual frameworks for the hybrid physical-digital museum, describe applications developed for extended reality and intelligent agents, and investigate professionals' attitudes towards emerging technologies (Derda & Predescu, 2025; Kiourexidou & Stamou, 2025). However, these contributions remain scattered across several fields – museum studies, digital heritage, human-computer interaction, tourism studies, and education – which makes it difficult to obtain a coherent overall picture of this domain.

The article investigates the research problem that requires a systematic quantitative mapping of the existing literature on the use of artificial intelligence in museums and cultural heritage organizations in the recent period. Studies examine the use of different technologies in various types of museum organizations, but fail to provide bibliometric information on the chronological development and collaborative networks, thematic clusters and relationships between key concepts in this field. Without an overview, researchers find it difficult to identify research areas that have been over- or under-investigated.

The main objective of this article is to conduct a bibliometric analysis of how artificial intelligence is used in museums and cultural heritage organizations, and to identify the linkages between the key terms employed in this field. First, the theoretical background will be evaluated, the details of the methodology will be defined, and data will be collected from the Web of Science database; afterwards, the findings will be presented and discussed.

The article presents three main academic contributions to the field. First, it presents an updated bibliometric map of research on artificial intelligence in museums during the period 2016–2026. Second, using co-word and thematic cluster analyses, it identifies the main directions of development and how they are interconnected. Third, it correlates the bibliometric results with theoretical discussions on digital and hybrid museums and offers research recommendations for the development of professional practices focused on artificial intelligence.

Based on these objectives, the research is guided by the following research questions:

1. What are the main temporal, geographical and disciplinary developments in the literature on the use of artificial intelligence in museums and cultural heritage organizations in the period 2016–2026?
2. What key themes and technologies can be identified through co-word analysis and how are these structured into thematic clusters?
3. What are the emerging thematic areas that particularly reflect current and future directions of research on digital technologies in museums?

1. LITERATURE REVIEW

The existing literature published between 2016 and 2026 demonstrates that this research area has reached an advanced development stage (Avlonitou et al., 2025; Derda & Predescu, 2025; Kiourexidou & Stamou, 2025). Research studies from 2016 demonstrated that researchers investigated virtual and augmented environments which functioned as tools for cultural mediation and informal educational activities (Tavcar et al., 2016; Hu et al., 2017). The museum infrastructure of invisible artificial intelligence systems consists of a recommendation engine which generates personalized route suggestions, a visitor flow analysis tool, an emotional analysis instrument, a digital twin reconstruction support system, and a partner system for designing narrative experience (Torres-Ruiz et al., 2020; Rahimi et al., 2025; Vasiljevic et al., 2025).

Many research projects demonstrate virtual guide prototypes which include chatbots, intelligent AR applications, and VR systems that use non-player character technology models (Duguleana et al., 2020; Nielsen et al., 2025; Trichopoulos et al., 2023). Other research establishes theoretical frameworks which develop research agendas that study visitor datafication processes, museum artificial intelligence ethical considerations, and the digital cultural ecosystem which museums support (Hyvonen, 2023; Prulmann-Vengerfeldt, 2022; Ratten, 2024).

The primary conceptual framework of this research builds upon recent studies by Castellano and Vessio (2022) and Rinaldi et al. (2022), which analyse artificial intelligence techniques used in the visual domain of cultural heritage, particularly machine learning and deep learning methods for image-based identification, classification and clustering of cultural artefacts.

Sriporn et al. (2022) have studied tourist behaviour in virtual museums using intelligent, feature-selection-based models, showing how AI can support the analysis of visitor patterns and experience design, while Tian et al. (2025) have applied deep learning-based predictive models to forecast art museum visitor numbers, illustrating how AI can also inform capacity planning and visitor flow management.

Duguleana et al. (2020), Noh and Hong (2021) and Trichopoulos et al. (2023) have developed and evaluated different types of conversational agents for museums, ranging from rule-based virtual assistants and reenacted chatbots to large language model-based guides integrated into digital museum experiences.

Research by Dal Falco and Vassos (2017) and Rennie (2016) shows how technological systems can be integrated into free-choice learning environments, multisensory experiences and participatory social spaces that combine physical objects with digital content, highlighting the role of these configurations in deepening visitor engagement and learning.

The audience visiting museums has different experiences because mobile phone applications have evolved significantly from their initial function of helping people navigate the museum. Currently, these applications can manage visitors' needs and preferences in real time. Virtual guides and chatbots operate in physical exhibitions (temporary or permanent) and virtual tours, providing useful information by answering questions from people visiting the museum. Moreover, they adapt very well to the characteristics of the visitors to offer them the most pleasant experience possible (Duguleana et al., 2020; Noh & Hong, 2021; Popescu, Corboș & Bunea, 2023).

Systems that recommend personalized routes for the public are very advanced. They use information about how visitors have interacted with the museum in the past, along with data from social networks and sensors, to create a natural and pleasant experience. These systems allow the public to choose from the different routes they have created through intelligent algorithms (Tavcar et al., 2016; Torres-Ruiz et al., 2020).

Recently, a new trend in the museum field has been the systematic collection of data about visitors. This process, known as the datafication of visitors, enables museum organizations to better understand visitors' behaviour and preferences. Moreover, it allows them to track the speed at which visitors move through the museum and how they respond emotionally to different exhibitions. All this information helps organizations improve their permanent and temporary exhibitions, create personalised experiences for different target groups, and adapt their strategies in real time (Pruulmann-Vengerfeldt, 2022; Ragusa et al., 2020; Ivanov, 2024).

The use of artificial intelligence in museums has moved beyond the stage of a simple guidance tool and has become an essential component in the analysis and evaluation of visitor behaviour. This analytical dimension is transforming how cultural organizations understand the interaction between visitors and exhibits, shifting from manual observation to the examination of complex datasets. Measurement technologies and methodologies employ eye-tracking and facial expression recognition, physiological sensors, sentiment analysis techniques in order to assess visitors' attention, emotional engagement and satisfaction. Artificial intelligence makes it possible to identify visitor behaviour both in virtual reality environments and in physical exhibitions enhanced with digital features, by tracking visitors' movements and analysing how long they view particular exhibits as well as how they respond to specific visual and narrative stimuli (Ai et al., 2021; Fathy et al., 2023; Mavridou et al., 2025; Tian et al., 2026). This information is used to improve exhibition design, to adjust lighting, information density, or modes of presentation, suggesting a shift from design based primarily on curatorial intuition to design supported by predictive models and behavioural analytics (Fominska et al., 2024; Jiang et al., 2025).

Another area of research focuses on interactive virtual museums and immersive environments that use augmented, virtual or mixed reality together with artificial intelligence as core technologies to enable user engagement, system adaptation and virtual presence. Virtual museums have evolved from being 3D replicas of physical art galleries into adaptable spaces that allow the dynamic reorganisation of content, while virtual characters, intelligent agents and adaptive scenarios orchestrate visitor interactions (Hu et al., 2017; Meinecke et al., 2022; Meng et al., 2022). In many projects, artificial intelligence intervenes both in production activities—through automatic 3D reconstruction and model generation, as well as object recognition—and at runtime, by deciding which content the system displays, how users navigate the environment, and how the difficulty of educational tasks is adjusted (Khan et al., 2021; Ipalakova et al., 2025; Pan et al., 2024).

Experiments with the metaverse and XR technologies use museums and heritage sites to create multi-user environments that enable social presence through non-player characters and AI-controlled avatars, while human visitors and artificial agents interact with one another (Anwar et al., 2025; Nielsen et al., 2025; Nisiotis et al., 2024; Sanchez-Amboage et al., 2023).

Museums use artificial intelligence technologies in various areas, such as management, conservation, and digital infrastructure. Machine learning algorithms are employed for classifying and indexing collections, for automatically recognising, describing heritage objects, for detecting deterioration, and for assigning rich metadata on the basis of large visual and textual datasets (Castellano et al., 2021; Rinaldi et al., 2022). Photogrammetry, 3D reconstruction supported by neural networks, semantic segmentation models, and NeRF techniques generate highly accurate digital representations of objects and spaces, enabling the creation of digital twins for monuments, archaeological sites, and exhibition halls (Rahimi et al., 2025; Tytarenko et al., 2025; Vasiljevic et al., 2025).

At the same time, knowledge graphs, semantic web-based infrastructures, and combinations of symbolic and sub-symbolic AI are proposed as solutions for organising collections and enabling serendipitous exploration. Their main purpose is to establish connections between different organizations and fields of study (Bernasconi et al., 2023; Hyvonen, 2023; Maree, 2025).

This technological infrastructure makes it necessary to address questions of governance and ethics, together with issues of cultural justice. The process of datafying visitors generates debates at the intersection of surveillance practices and the requirements of informed consent, as well as concerns about equity in cultural access, including questions about who owns the data, how they are used, and how predictive modelling techniques represent different audience segments (Pruulmann-Vengerfeldt, 2022; Ragusa et al., 2020).

Deploying artificial intelligence for the selection, presentation and interpretation of cultural heritage requires a re-examination of the role of the museum curator and of the museum's institutional authority as an epistemic power: the extent of responsibility that professional standards allow to be delegated to automated systems, what is meant by an "AI-generated narrative" in museum spaces, and how the balance between human creativity and algorithmic generativity is negotiated (Baradaran, 2024; Ratten, 2024; Avlonitou et al., 2025). The literature also indicates that using limited, strongly context-dependent training data increases the risk that machine learning models will reproduce and amplify historical and cultural biases present in those datasets (Khilko & Gorelova, 2024; Liu et al., 2023).

Museum organizations, together with their professional staff, are experimenting with working models that combine human collaboration with artificial intelligence and with human-centric AI systems, which serve as tools for co-creating value rather than replacing human expertise (Avlonitou et al., 2025; Derda & Predescu, 2025; Sabie, Purdescu & Niță, 2025). Recent studies offer conceptual frameworks that guide museums in the sustainable implementation of AI, while also examining staff attitudes towards social robots and proposing ways to measure the impact of AI on accessibility, inclusion, and audience engagement (Modlinski et al., 2024; Materazzini et al., 2024). Research agendas that investigate museums in the age of artificial intelligence call on institutions to develop their own standards frameworks, including ethical design principles, interoperability requirements, and specialised training protocols for museum staff (Hyvonen, 2023; Pruulmann-Vengerfeldt, 2022).

2. METHODOLOGY

Data Source and Search Strategy

The bibliometric analysis was conducted using records retrieved from the Web of Science Core Collection (WoSCC) on 19 February 2026. A topic-based query was designed to capture literature at the intersection of (1) artificial intelligence, (2) museum/cultural heritage contexts, and (3) visitor/experience/engagement outcomes. The search string was: ("artificial intelligence" OR "AI" OR "machine learning" OR "deep learning" OR "intelligent system" OR "expert system" OR "generative AI" OR "chatbot") AND ("museum" OR "cultural heritage" OR "heritage institution" OR "art gallery" OR "exhibition" OR "gallery visitor") AND ("visitor experience" OR "museum experience" OR "visitor engagement" OR "digital curation" OR "digital engagement" OR "audience interaction" OR "educational program" OR "knowledge discovery" OR "content personalization" OR "interactive display" OR "interactive exhibits" OR "immersive technology" OR "augmented reality" OR "virtual reality").

Inclusion Criteria and Dataset Construction

The initial query yielded 572 records and was refined in WoSCC by language (English), timespan (1999–2026), document type and period (English-language articles, 2016–2026 - to reflect the most active phase of the topic's development; $n = 229$), and research areas ($n = 202$). Three items labelled as retracted publications were removed prior to mapping and interpretive analyses, resulting in a final analytical corpus of 199 documents.

The procedures for inclusion and exclusion have decreased the initial database of 572 records to a final analytical collection of 199 documents which the PRISMA flow diagram shows in Figure 1.

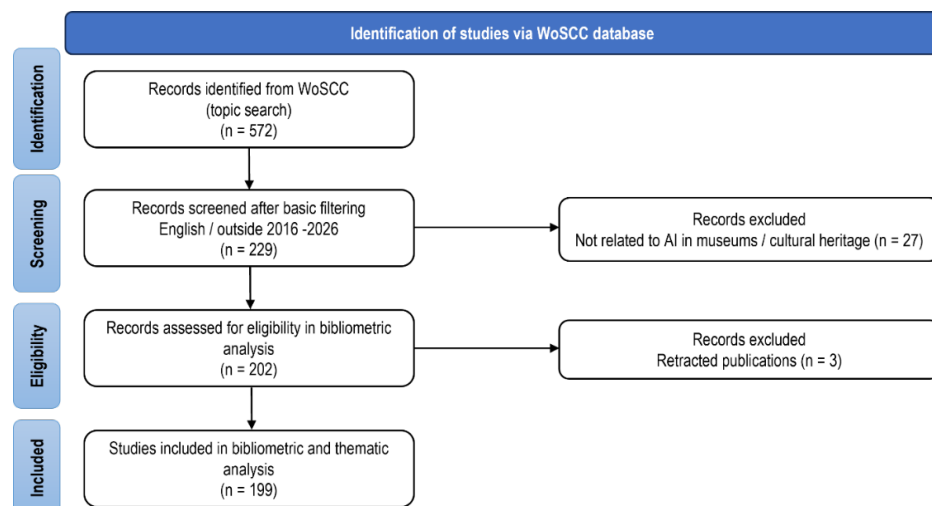


Figure 1. PRISMA flow diagram of the literature selection process

Source: Authors

Data Export and Preprocessing

Full records were exported from WoSCC in a format compatible with bibliometrix (plain-text WoS export, including cited references). The exported file was imported into R version 4.4.0 (2024-04-24 ucrt) “Puppy Cup” (Aria & Cuccurullo, 2017) and analyzed using bibliometrix via the Biblioshiny interface. After import, the dataset was screened to exclude retracted items. No additional manual cleaning of authors, sources, or keywords was performed beyond standard bibliometrix parsing, and all indicators and networks were computed on the resulting analytical corpus.

Bibliometric Analysis and Visualization

Similar with other bibliometric research (Ștefan, Popa & Breazu, 2025) the analyses were performed using the bibliometrix package through Biblioshiny, including:

- Descriptive performance analysis (annual scientific production, leading sources, leading authors, geographic production, and citation impact by country).
- Conceptual structure analysis based on keyword co-occurrence (co-word network) and thematic mapping (centrality–density positioning of themes).
- Intellectual structure analysis using source co-citation networks to identify clusters of frequently co-cited outlets.
- Thematic evolution analysis to trace the flow of dominant themes across successive time slices.

Network clustering in Biblioshiny relied on the Louvain community-detection algorithm.

3. RESULTS

The exported dataset contains 202 documents published across 127 sources, authored by 720 authors, and citing 10,304 references. The corpus includes 752 Author Keywords (DE) and 285 Keywords Plus (ID). Collaboration is relatively high (3.74 co-authors per document) and 28.22% of publications involve international co-authorship. The average citation impact is 14.36 citations per document, and the average document age is 2.82 years (Table 1).

Table 1. Main descriptive indicators of the dataset (WoS, 2016-2026)

Indicator	Value
<i>Timespan</i>	2016–2026
<i>Sources</i>	127
<i>Documents (exported)</i>	202
<i>Retracted publications excluded</i>	3
<i>Documents (final analytical corpus)</i>	199
<i>Annual growth rate (%)</i>	10.31
<i>Average document age (years)</i>	2.82
<i>Average citations per document</i>	14.36
<i>References</i>	10,304
<i>Author Keywords (DE)</i>	752
<i>Keywords Plus (ID)</i>	285
<i>Authors</i>	720
<i>Single-authored documents</i>	24
<i>Co-authors per document</i>	3.74
<i>International co-authorships (%)</i>	28.22

Source: Authors' analysis based on Web of Science Core Collection data (retrieved 19 Feb 2026) using bibliometrix/Biblioshiny (R)

Figure 2 shows the annual scientific production on artificial intelligence applications in museums/cultural heritage/visitor-related contexts. Overall, publication activity remained low and relatively stable between 2016 and 2020 (2–8 papers per year), followed by a clear growth phase starting in 2021. Output doubled from 17 papers in 2021 to 37 papers in 2024 and peaked in 2025 (73 papers), indicating a rapid acceleration of scholarly interest in the topic. The most recent year (2026) is not interpreted because it is only partially covered at the time of data extraction.

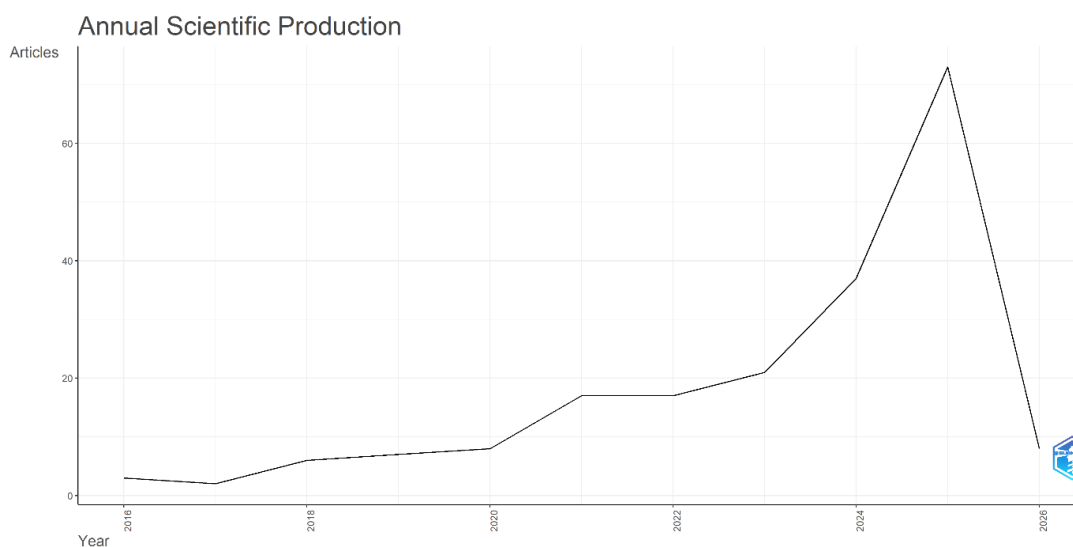


Figure 2. Annual scientific production

Source: Authors' analysis based on Web of Science Core Collection data (retrieved 19 Feb 2026) using bibliometrix/Biblioshiny (R)

Table 2 lists the most productive publication outlets in the dataset. The leading sources are predominantly multidisciplinary, technology and computing-oriented journals, alongside domain-specific venues focused on cultural heritage and computing in heritage contexts. Applied Sciences–Basel (9 articles) and Electronics (7) are the top outlets by volume, followed by ACM Journal on Computing and Cultural Heritage and Sustainability (6 each). A second tier of sources (5 articles each)

includes *Frontiers in Robotics and AI*, *Heritage*, *Journal of Cultural Heritage*, and *Scientific Reports*, confirming the topic's positioning at the intersection of AI methods, immersive/digital technologies, and applied heritage/museum research.

Table 2. Most relevant sources (top 10 by number of documents)

Source	Documents
<i>Applied Sciences–Basel</i>	9
<i>Electronics</i>	7
<i>ACM Journal on Computing and Cultural Heritage</i>	6
<i>Sustainability</i>	6
<i>Frontiers in Robotics and AI</i>	5
<i>Heritage</i>	5
<i>Journal of Cultural Heritage</i>	5
<i>Scientific Reports</i>	5
<i>PLOS ONE</i>	4
<i>AI & Society</i>	3

Source: Authors' analysis based on Web of Science Core Collection data (retrieved 19 Feb 2026) using bibliometrix/Biblioshiny (R)

Authorship in this domain is highly dispersed, with no single scholar dominating output. In the current dataset, the most prolific author (Tavcar, A.) contributed three documents, while the remaining leading authors each contributed two documents, as shown in Figure 3. This distribution indicates that research on AI-enabled museum and cultural heritage experiences is produced by a broad set of teams rather than a small core of repeatedly publishing authors.

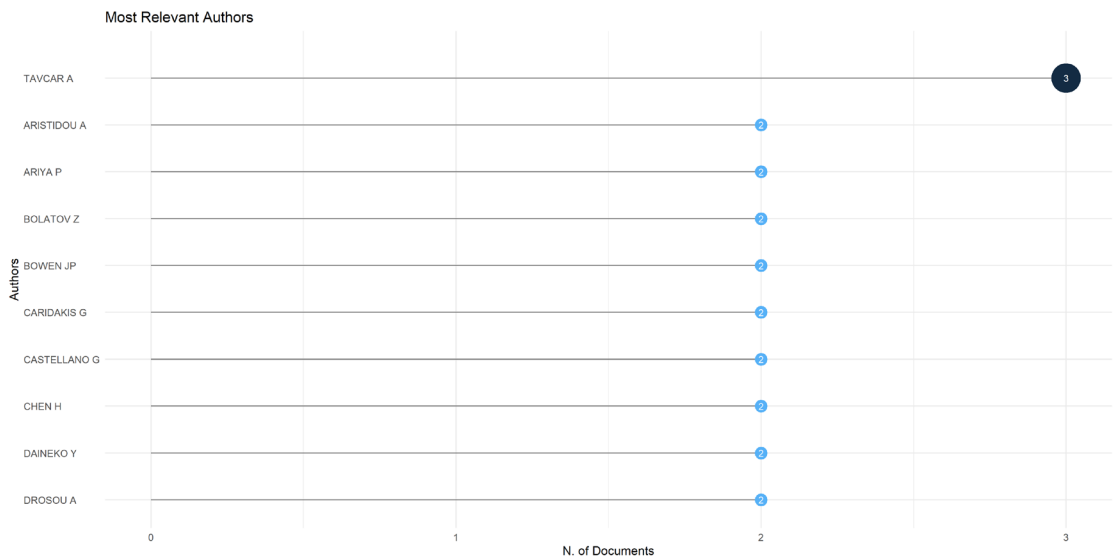


Figure 3. Most relevant authors (top 10 by number of documents)

Source: Authors' analysis based on Web of Science Core Collection data (retrieved 19 Feb 2026) using bibliometrix/Biblioshiny (R)

The geographic distribution of publications indicates broad international participation in research on artificial intelligence applications in museums/cultural heritage and visitor-related contexts. As shown in Figure 4, scientific production is unevenly distributed, with a clear concentration in Asia and Europe. At the country level, China dominates output (127 documents), followed by Italy (60) and Greece (29). A second group of contributors includes South Korea (27), the USA (27), the United Kingdom (25), Spain (24), and Germany (22), while Malaysia (9) and Thailand (9) appear as smaller but visible contributors. This distribution is consistent with the overall collaboration profile of the dataset, in which

28.22% of publications involve international co-authorship, indicating that the field develops through both national research programs and cross-border teams. International collaboration patterns further show that co-authorship is structured around a small number of recurrent links. The most frequent collaborations are China–South Korea (8) and China–USA (5), followed by China–United Kingdom (4) and USA–United Kingdom (4); additional notable links include Italy–Poland (3) and Italy–USA (3).

Country Scientific Production

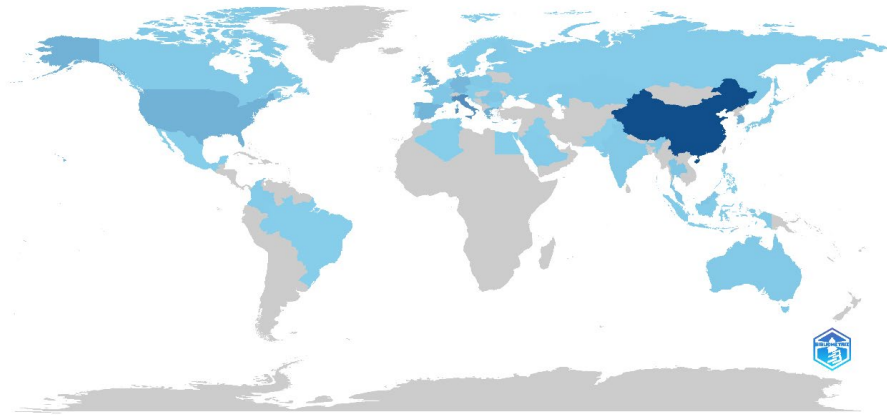


Figure 4. Country scientific production (number of documents by country)

Source: Authors' analysis based on Web of Science Core Collection data (retrieved 19 Feb 2026) using bibliometrix/Biblioshiny (R)

Citation impact by country shows a different pattern from publication volume (Figure 5). While China leads in the number of documents, the United Kingdom emerges as the most influential contributor in terms of citations (1,126 citations), far ahead of the next countries. China ranks second (376 citations), followed by Italy (283) and Greece (260). The next tier includes the USA (115), Finland (97), Portugal (82), Romania (76), Germany (68), and Pakistan (46). Overall, these results suggest that the knowledge base is internationally distributed, but high-impact contributions are more concentrated, with the UK functioning as a major citation hub in this corpus despite not being the top producer by volume.

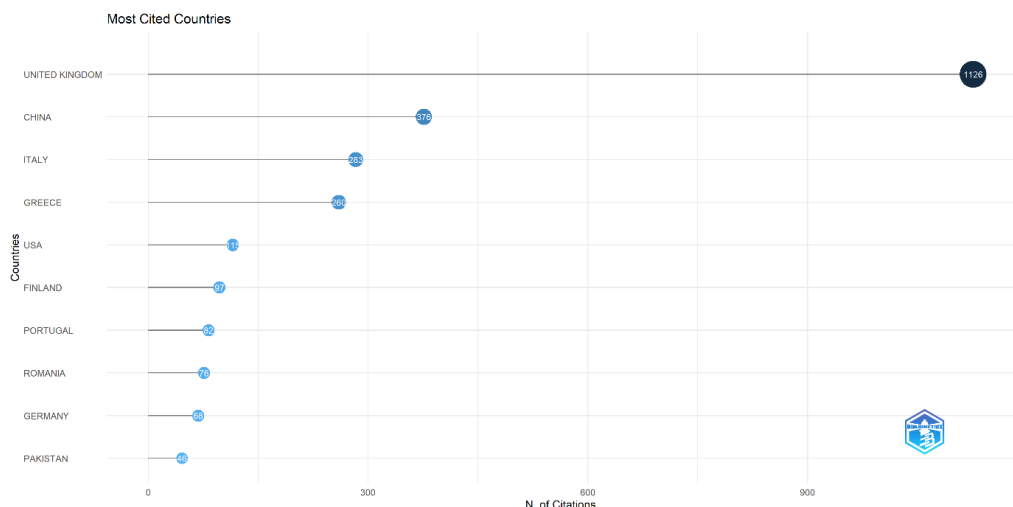


Figure 5. Most cited countries (total citations by corresponding author country)

Source: Authors' analysis based on Web of Science Core Collection data (retrieved 19 Feb 2026) using bibliometrix/Biblioshiny (R)

Figure 6 presents the thematic map (centrality \times density), which shows how topics are positioned in terms of their relevance to the field (centrality) and their internal development (density). The most prominent motor theme is the cluster centred on augmented reality–cultural heritage–virtual reality, indicating that immersive technologies represent the core and most developed research stream in this corpus. In contrast, several clusters appear as basic themes, including those related to education/experience/impact and students/experiences/framework, suggesting widely connected lines of work that support the field but remain less internally consolidated. The map also identifies niche themes, such as hospitality/management/information technology and image retrieval, which are well-developed but more peripheral to the main conceptual backbone. Finally, social media/big data appears in the emerging/declining space, indicating either a nascent direction in this dataset or a topic losing momentum relative to immersive and AI-driven approaches.

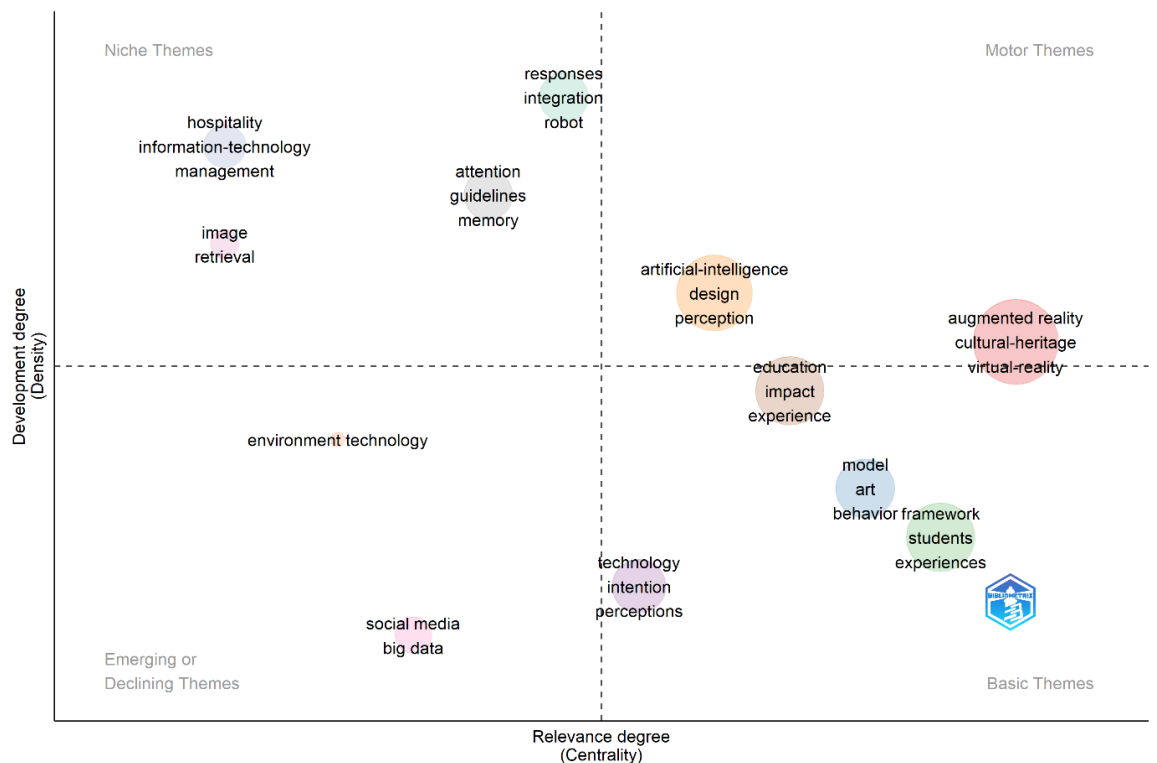


Figure 6. Thematic map (centrality \times density) of the research field

Source: Authors' analysis based on Web of Science Core Collection data (retrieved 19 Feb 2026) using bibliometrix/Biblioshiny (R)

To refine the thematic interpretation, the keyword network in Figure 7 visualizes co-occurrence relationships among the most frequent terms and highlights the conceptual hubs of the field. The network is structured around a small set of highly central terms.

The first cluster (Cluster 1), “Cultural heritage”, represents the strongest connector of the network (betweenness 215.974; PageRank 0.208), which shows that most studies investigate artificial intelligence from the perspective of its application to heritage. This core is closely linked to “virtual reality”, which in turn occupies a central position (betweenness 89.010; PageRank 0.144), suggesting that VR environments for heritage exploration (virtual museums, 3D reconstructions and immersive experiences) constitute the dominant research direction in the analyzed period.

The second cluster (Cluster 2) is centered on the term “artificial intelligence” (betweenness 93.334; PageRank 0.122) and connected to concepts such as “museum/museums”, “image recognition” or “human–computer interaction”. This thematic core is focused on artificial intelligence as a transversal infrastructure of museum organizations, which supports both the recognition and management of

heritage (tangible and intangible), as well as new forms of human-computer interaction and cultural mediation.

The third cluster (Cluster 3) revolves around the term “augmented reality” (betweenness 27,681; PageRank 0.071) and is connected to “mixed reality” and “machine learning”. This group defines the area dedicated to XR technologies that combine augmented reality with mixed reality and machine learning algorithms. The focus is on superimposing digital layers on real spaces and objects and on how artificial intelligence supports content adaptation and contextual interactions in hybrid physical-digital environments.

The fourth cluster (Cluster 4) is centered on the term “deep learning” (betweenness 26,000; PageRank 0.039) and connects the area of VR/AR applications with that of technological dimensions (3D reconstruction, computer vision or large language models). This thematic core indicates that there is a specialized literature oriented towards methods, which develops and tests neural network architectures for recognition, classification or prediction in museum and heritage contexts.

Overall, the network confirms that research in this area is anchored in immersive heritage applications (VR/AR) while increasingly integrating AI/ML methods (deep learning, machine learning) to support recognition, interpretation, and interaction in museum and heritage settings.

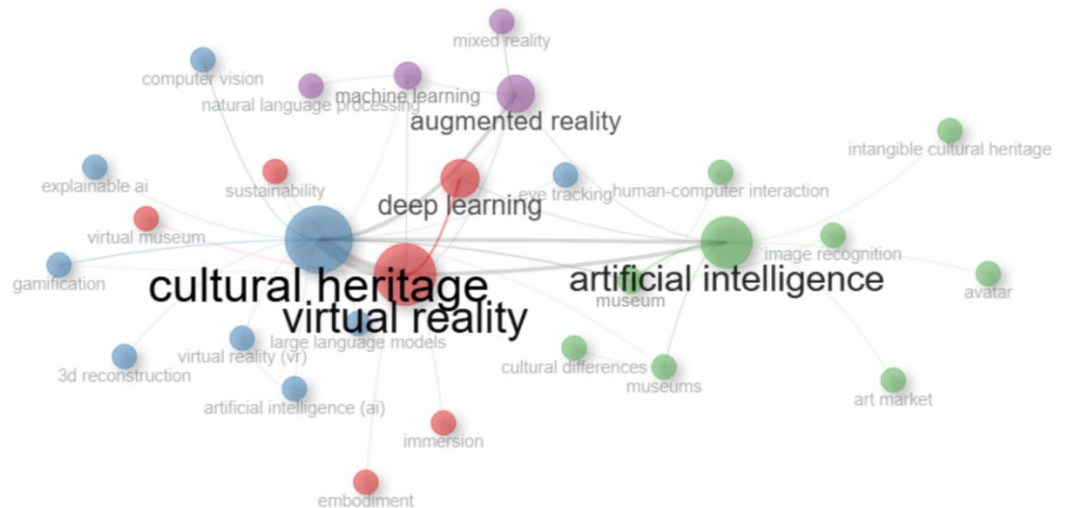


Figure 7. Keyword co-occurrence network (co-word analysis). Node size reflects prominence; links represent keyword co-occurrence; colors indicate clusters

Source: Authors' analysis based on Web of Science Core Collection data (retrieved 19 Feb 2026) using bibliometrix/Biblioshiny (R)

Figure 8 depicts the source co-citation network, which captures the intellectual foundations of the field by showing which publication outlets are most frequently cited together. The network reveals a clearly interdisciplinary knowledge base that combines computer-science methods outlets with heritage- and experience-oriented journals.

A first cluster is anchored in computer-science and engineering venues (Cluster 1), with Lecture Notes in Computer Science acting as the most prominent bridging source in the network (betweenness 107.041; PageRank 0.038), alongside arXiv (betweenness 28.992; PageRank 0.030), IEEE Access (betweenness 52.363), and conference/proceedings sources such as Proc. CVPR (IEEE).

Finally, in the most recent slice (2026), deep learning (2023–2025) and virtual reality (2023–2025) both connect to artificial intelligence (2026), indicating that recent work is increasingly framed under broader AI terminology while retaining strong links to immersive and learning-based methods.

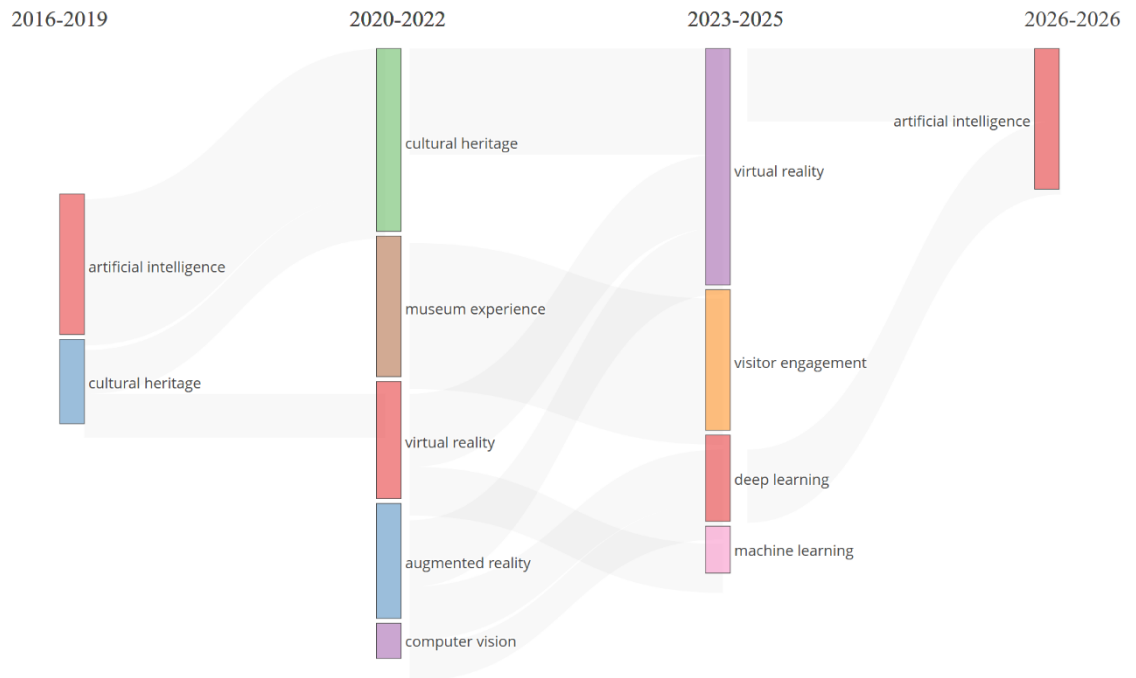


Figure 9. Thematic evolution across time slices (topic flows between periods)

Source: Authors' analysis based on Web of Science Core Collection data (retrieved 19 Feb 2026) using bibliometrix/Biblioshiny (R)

Emerging Thematic Areas

The results of the bibliometric analysis indicate that artificial intelligence and advanced digital technologies are fundamentally reconfiguring research areas in the museum sphere. From the analysis of publication trends, co-citation networks and thematic evolution, there is an increased interest in the use of these technologies in the design of immersive experiences, in visual analytics applied to scientific collections and visitors, as well as in the development of new models of presentation of the museum offer based on gamification and sustainability. This evolution is closely linked to the increasingly important role of machine learning and integrated digital infrastructures, which allow the involvement of visitors and the optimization of internal processes of museums.

The increasing frequency of terms such as "virtual reality", "visitor engagement", "deep learning", "machine learning", "computer vision", "digital twin", "gamification" and "sustainability" confirms the direction of the research paradigm towards solutions focused on the interaction between people and technology and on the strategic repositioning of museums in the cultural and tourism ecosystem.

At the same time, the analysis signals a gradual shift in research interests towards models based on large-scale data integration, continuous monitoring and personalization of the museum experience. The increasingly frequent references to virtual and augmented environments, computer vision and eye tracking techniques, knowledge graphs, 3D reconstruction and digital twins suggest that digital technologies are no longer viewed as isolated support tools, but are integrated into data ecosystems and institutional practices. These ecosystems allow the connection of information from digital collections, visitor behavior and external databases and their application in curatorial, educational and

decision-making processes, including the design of gamified experiences and programs oriented towards social and educational sustainability.

The persistence of the themes related to “cultural heritage”, “museum” and “museums” in all the analyzed intervals underlines the fact that digital transformation will not replace the mission of museums and will complement it with new forms of mediation and public involvement.

Based on the results obtained, three emerging thematic areas were identified that particularly reflect current and future directions of research on digital technologies in museums. The first area focuses on immersive experiences and human–computer interaction in museums, including virtual, augmented, mixed reality, virtual museums, the metaverse, interactive exhibition design, studies on visitor engagement and tourism experience. The second area focuses on artificial intelligence and visual analytics for collections and visitors, including applications of machine learning, deep learning, generative AI, computer vision, object detection, image recognition, knowledge graphs, 3D reconstruction, digital twins, natural language processing and eye tracking, used for documentation, knowledge discovery and information personalization. The third area addresses gamification, sustainability and digital transformation of the museum offer, comprising studies on gamification, sustainability, virtual museum and new models of public relations in which artificial intelligence is used to support long-term educational, social and tourism objectives. Table 3 summarizes these three thematic areas, which are discussed in detail below.

Table 3. Emerging thematic areas in research on artificial intelligence and digital transformation in museums

Emerging thematic area	Main focus	Core technologies / concepts	Main applications in museums	Broader implications
Immersive experiences and human–computer interaction	Explores how digital environments reshape museum experiences and visitor interaction	Virtual reality, augmented reality, mixed reality, virtual museums, metaverse, chatbots, virtual guides, recommender systems, multimodal interaction, eye tracking	Heritage reconstruction, interactive exhibition design, personalized guidance, adaptive content delivery, visitor engagement analysis, optimization of exhibition layout and narrative design	Museums evolve from static display spaces into interactive, participatory, and experience-oriented environments
Artificial intelligence and visual analytics for collections and visitors	Examines how AI supports the documentation, interpretation, management, and analysis of collections and visitor behaviour	Machine learning, deep learning, computer vision, object detection, image recognition, knowledge graphs, semantic web, 3D reconstruction, digital twins, natural language processing, generative AI, eye tracking, visitor path analysis	Classification of collections, conservation monitoring, data extraction, 3D modelling of heritage, integration of heterogeneous datasets, visitor profiling, behaviour prediction, recommendation systems, automated interpretation and summarization	Museums become data-rich institutions able to improve research, decision-making, personalization, and knowledge discovery
Gamification, sustainability, and digital transformation of museum offerings	Focuses on how museums use digital technologies to redesign public engagement, education, and tourism functions	Gamification, interactive storytelling, mobile apps, virtual museums, XR platforms, metaverse exhibitions, inclusive design, AI-supported accessibility tools, phygital experiences	Missions, challenges, and rewards for visitors; educational games; hybrid museum experiences; remote access; accessibility solutions; audience diversification; new tourism and monetisation models	Digital transformation expands the museum’s social, educational, and tourism role while raising governance, inclusion, and ethical questions

Source: Authors

Immersive Experiences and Human–Computer Interaction in Museums

This field of research studies how virtual reality, augmented reality, mixed reality technologies, along with human-computer interaction solutions, are reshaping museum operations into dynamic interactive environments. Research demonstrates how virtual reality and augmented reality technologies enable the reconstruction of heritage sites and artifacts, establishing complex narrative frameworks that present new perspectives on cultural artifacts in their native contexts (Hu et al., 2017; Zhong et al., 2021; Iacono et al., 2024; Wang & Ametefe, 2026).

Studies by Anwar et al. (2025) and Sanchez-Amboage et al. (2023) show how these practices are now extending into metaverse environments and hybrid spaces, where museums become part of cultural tourism ecosystems. Researchers such as Paolanti et al. (2023), Ariya et al. (2025), and Liu et al. (2025), studies how virtual reality spaces simulate heritage sites, and digital avatars enhance experiential education and cultural learning through their design. Other research investigates how visitors to immersive museum exhibitions react to virtual reality environments and multisensory installations using emotion recognition technology and interactive narrative design (Fominska et al., 2024; Lucifora et al., 2024; Marasco et al., 2025; Niu et al., 2025).

Researchers Duguleana et al. (2020), Noh & Hong (2021), Chai-Arayalert et al. (2024) and Trichopoulos et al. (2023) study how conversational agents, chatbots and virtual guides assist visitors by providing personalized communication that meets their specific needs. Other studies investigate how contextual messaging and adaptive assistance functions work within virtual reality and augmented reality experiences, showing that recommender systems can function as effective solutions (Torres-Ruiz et al., 2020; Troussas et al., 2025; Tan & Ng, 2024). The human–computer dimension is complemented by studies on multimodal interaction (gestures, gaze, voice, body movement) that aim to create a natural relationship between visitors and digital environments (Raptis et al., 2021; Zidianakis et al., 2021; Yannier et al., 2022).

Other research analyzes the systematic evaluation of immersive experiences and their optimization through algorithmic methods. Studies by Fathy et al. (2023), Ai et al. (2021) and Li et al. (2021) use eye tracking, visual attention simulation models and deep learning to analyze how visitors perceive exhibition spaces and to optimize lighting, composition and placement of exhibits in VR and hybrid environments. Meng et al. (2022) propose user-centered evaluation models for exhibition narrative in digital museums, while Wen and Ma (2024) show how deep learning and interactive multimedia techniques can be used to adjust content in real time, based on visitors' reactions and preferences.

Artificial Intelligence and Visual Analytics for Collections and Visitors

This research direction aims to use artificial intelligence and visual analytics techniques to document, interpret and manage collections and to understand visitor behavior. Studies largely use machine learning and deep learning methods for image recognition and classification, object identification and data extraction from museum collections (Castellano et al., 2021; Castellano & Vessio, 2022; Khan et al., 2021). Studies on object detection and image recognition applied to heritage objects and archaeological sites show that these technologies accelerate the classification process, contribute to the detection of degradation and the monitoring of the state of conservation of the pieces (Athab & Karim, 2024; Rahimi et al., 2025; Pan et al., 2024). Research using 3D reconstruction, semantic point clouds and digital twins demonstrates the potential of artificial intelligence to create three-dimensional representations of built and mobile heritage, which can be used both for research and restoration, as well as for virtual experiences (Feng et al., 2025; Tytarenko et al., 2025; Vasiljevic et al., 2025).

The research by Hyvonen (2020), Bernasconi et al. (2023) and Maree (2025) demonstrates how knowledge graphs together with Semantic Web tools enable scientists to gather collection data from different sources and make complex inquiries which they can visualize in advanced ways. Other

research shows that, shows that integrating knowledge graphs with deep learning and content-based image retrieval and geospatial platforms enables systems to connect images, texts, analytical data, spatial information in a way that researchers and the general public can easily access (Rinaldi et al., 2022; Lee et al., 2025; Kyropoulou et al., 2025).

Researchers use eye tracking and visual attention modeling and visitor path visualization techniques to study visitor interactions with exhibition spaces and display objects while determining optimal exhibition path design and exhibition layout (Ai et al, 2021; Fathy et al., 2023; Li et al. 2021). The research studies apply machine learning and deep learning methods on telemetry data, egocentric images, unstructured data to predict visitor behavior patterns which helps with user profiling and segmentation and personalization tasks (Ragusa et al., 2020; Sriporn et al., 2022; Ivanov, 2024; Jiang et al., 2025; Tian et al., 2025). Recent studies examine the application of generative AI and large language models - based analytics for textual description extraction, textual feedback analysis, digital content evaluation which leads to advanced recommendation systems and automated summarization and interpretation tools (Hsueh & Hsu, 2026; Drissi et al., 2025; Carter et al., 2022).

Gamification, Sustainability and Digital Transformation of Museum Offerings

The latest research direction focuses on gamification, sustainability and digital transformation of museum offerings, focusing on how artificial intelligence and new digital technologies are enabling museums to perform their functions in both the cultural and tourism sectors.

The literature analyzes how interactive storytelling and reward gaming systems create greater visitor engagement, leading to longer visitor relationships with cultural organizations, according to several studies (Li et al., 2024; Sanfilippo et al., 2025; Tan & Ng, 2024; Kosti et al., 2025).

Studies dedicated to the gamification of virtual museums and city heritage experiences show that the integration of playful elements (missions, challenges, scores, collecting digital objects) can support both educational and cultural tourism development objectives, especially among young audiences and users familiar with gaming environments. Other research analyzes how museums can transform into hybrid platforms, in which the physical offer is complemented or extended by virtual museums, metaverse exhibitions and remote experiences.

Papers such as those by Sanchez-Amboage et al. (2023), Anwar et al. (2025), Shin et al. (2023) and Troussas et al. (2025) highlight how the metaverse, XR platforms and mobile gaming applications are transforming the way cultural content is produced, distributed and consumed. These contributions discuss both opportunities (expanded geographical access, new monetisation models, audience diversification) and risks, such as dependence on digital infrastructures, fragmentation of experience, potential tensions between the authenticity of heritage and the aesthetics of virtual environments.

In parallel, research in the area of cultural heritage and tourism highlights that artificial intelligence and advanced digitalization have become central elements in the development strategies of smart destinations and "phygital" cultural experiences, in which the boundary between physical and digital space is deliberately blurred (Deng, 2025; Jia et al., 2025; Barile et al., 2025).

The dimension of sustainability and governance is present within this research area. The literature studies inclusive museums together with audiovisual technology for people with learning disabilities and hearing impairments, as well as universal design, demonstrating how artificial intelligence and digital systems enable wider access while reducing barriers to cultural participation (Materazzini et al., 2024; Kim et al., 2024; Ai & Phaholthep, 2025). Authors Pruumann-Vengerfeldt (2022), Baradaran (2024) and Sengunalp & Kucukosman (2025) show how the collection of visitor data, together with the use of artificial intelligence in the art and museum ecosystem, creates social, political and economic outcomes, which they analyze through power dynamics, decolonization, algorithmic

transparency and effects on the art market. The contributions of the strategic framework, together with research on AI management in museums, demonstrate, through their work on the Human AI Compass for art museums (Avlonitou et al. 2025) and their research on professional attitudes towards social robots and visitor-focused AI (Modlinski et al., 2024; Derda & Predescu, 2025; Nisiotis et al., 2024), that organizations need to redefine their institutional responsibilities and public interactions resulting from digital transformation.

CONCLUSIONS

The bibliometric and qualitative analyses conducted in this study provide a coherent answer to the research questions and show how artificial intelligence and digital technologies are reshaping the museum field. First, in relation to RQ1, the results indicate a clear expansion of research between 2016 and 2026, together with growing international visibility and increasing interdisciplinary engagement across museum studies, cultural heritage, tourism, education, and human–computer interaction. Such development suggests that AI in museums has evolved from a niche topic into a broader research area situated at the intersection of technological innovation and cultural practice.

Second, with regard to RQ2, the findings show that the literature is moving from isolated digital applications toward more integrated digital ecosystems, in which immersive technologies, visual analytics, and data infrastructures are increasingly connected with curatorial, educational, and managerial processes. The thematic analyses highlight the central role of concepts such as virtual reality, visitor engagement, machine learning, deep learning, computer vision, digital twins, gamification, and sustainability, confirming a research paradigm centered on the interaction between people, technology, and institutional transformation.

Third, in response to RQ3, the study identifies three emerging thematic directions that reflect both current developments and future trajectories of research on digital technologies in museums. The first direction focuses on immersive experiences and human–computer interaction, where virtual, augmented, and mixed reality, virtual museums, the metaverse, and interactive exhibition design are redefining the relationship between visitors and museum collections, transforming museums into narrative, participatory, and multisensory spaces. The second direction concerns artificial intelligence and visual analytics for collections and visitors, including image recognition, 3D reconstruction, digital twins, knowledge graphs, and related methods that support heritage documentation, conservation monitoring, visitor analysis, and personalized interpretation. The third direction addresses gamification, sustainability, and the digital transformation of museum offerings, showing how digital technologies are used to strengthen long-term engagement, support inclusion and accessibility, and reposition museums as hybrid actors within the cultural and tourism ecosystem.

At the same time, the study shows that technological innovation in the literature often advances more rapidly than its implementation in practice, especially in organizations operating under financial, technical, and human-resource constraints. This gap points to the need for more implementation-oriented research that examines costs, professional acceptance, governance models, and the differential effects of AI-based systems on diverse visitor groups. Future digital strategies in museums should therefore address not only innovation and efficiency, but also data governance, algorithmic transparency, ethical responsibility, and the protection of visitor rights. In this context, the sustainable integration of artificial intelligence into museum workflows should be guided by the mission, capacities, and public role of each institution, so that digital transformation contributes to meaningful cultural value rather than to technologization for its own sake.

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