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BRIDGING TRADITION AND TECHNOLOGY: A SYSTEMATIC REVIEW OF DIGITAL INNOVATIONS IN CULTURAL HERITAGE PRESERVATION

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ABSTRACT

This study evaluates the integration of advanced technological tools for the purpose of preserving a cultural heritage, emphasising innovative strategies relevant to the digital era. Despite considerable technological advancements, significant gaps remain regarding the full implications of these tools for data preservation and long-term accessibility. Consequently, this research investigates how advanced technologies can effectively enhance preservation practices and overcome existing challenges. Specifically, it analyses core themes such as the efficacy of digital technologies, levels of public engagement, sustainability considerations, integration barriers, and strategic investment opportunities. The findings highlight that tools such as artificial intelligence (AI), photogrammetry, and virtual reality (VR), substantially enhance heritage documentation accuracy and accessibility. Nevertheless, persistent issues related to data preservation and consistent accessibility warrant continued investigation. This systematic review critically analyses 50 selected articles from an initial dataset of 2,476 articles using the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) framework. The study also emphasises the value of existing initiatives such as 4CH and Twin-IT, underscoring the need for harmonising traditional preservation techniques with innovative digital solutions, thereby offering essential guidance for future cultural heritage preservation efforts.

Introduction

Digital tools have revolutionised the field of cultural heritage conservation, offering innovative solutions for preservation, documentation, and restoration. By harnessing the power of digital technology, cultural heritage professionals can now engage in unprecedented levels of collaboration, research, and public outreach, ensuring the preservation of our diverse heritage for future generations (Biryukova & Nikonova, 2017).

The European Commission has been a pivotal force in promoting digitisation within cultural heritage preservation through strategic initiatives that address key challenges and opportunities. A landmark effort is the Commission Recommendation of 27 October 2011, which underscores the importance of digitisation, online accessibility, and digital preservation of cultural material (European Commission, 2011). This recommendation has laid the groundwork for advancing digital methodologies in this dynamic field. Big data analytics play an important role in monitoring and protecting cultural heritage sites by providing insights into preservation efforts and identifying areas of concern for targeted

intervention. Digital tools not only facilitate heritage preservation but also democratise access and participation in conservation efforts (Kopalle *et al*., 2020).

Digital technologies such as 3D, cloud computing, virtual reality (VR), and augmented reality (AR), have been identified as offering unprecedented opportunities for engagement, online access, and digital preservation, necessitating an integrated approach that caters to the needs of site managers, local curators, and communities (Bekele *et al*., 2018). The heritage site manager or the cultural institution can create storytelling (from the supply side) through digital tools to create additional narratives. The overall vision of the conceptual model in Figure 1 is grounded on an efficient use of digital technologies, to be provided to heritage site managers, municipalities, local administrations, or cultural institutes needing to increase sustainable tourist flows, achieved through the integration of bottom-up and top-down approaches, complemented by tools that foster social participation (Maietti, 2023).

This systematic review, guided by the PRISMA framework, navigates through the existing research landscape from 2019 to 2023 to evaluate the effectiveness of digital tools, identify technology usage, analyse the influence of technology on public engagement, assess long-term impact, identify integration challenges, and explore future technologies. An initial pool of 2,476 articles from Scopus and Web of Science, selected for their comprehensive, high-quality, peer-reviewed research, was carefully reviewed to select 50 studies offering significant insights into digital technologies' current state and prospects in this field.

Research Aim

This systematic review aims to analyse current research trends and identify prominent themes, frameworks, and relevant examples in the field. It evaluates the effectiveness of various digital tools utilised in cultural heritage conservation such as 3D technologies, cloud computing, VR, and AR. The study seeks to determine ways digital technology can be leveraged more effectively for heritage conservation and to establish best practices. Additionally, this review examines how technological advancements

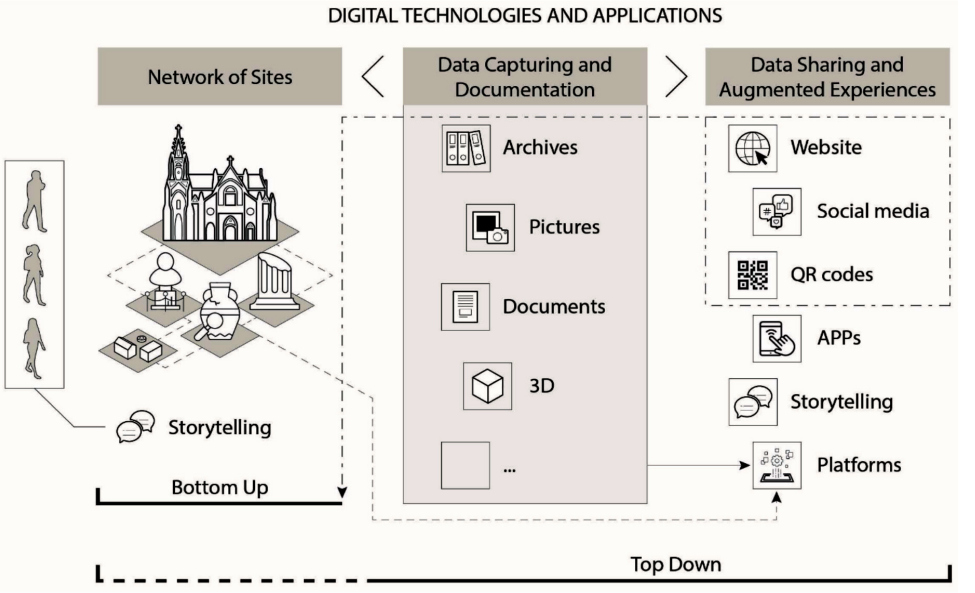

Figure 1: Integrative digital strategy model for storytelling in heritage management
Source: Maietti (2023)

influence public engagement and immersive heritage experiences, as well as their impacts on public awareness and education. It also assesses the long-term implications of using digital tools on the sustainability and resilience of cultural heritage, highlighting how these technologies contribute to risk mitigation. Furthermore, the study identifies challenges associated with integrating digital tools into conservation efforts, encompassing technical, financial, and social aspects. Finally, the review explores promising future technologies and strategic investments, highlighting potential innovations applicable to heritage conservation.

Research Question

Integrating digital technologies into cultural heritage conservation represents a transformative shift, offering innovative solutions to address complex challenges in heritage management. Despite significant technological advancements, critical gaps remain regarding the effective selection, implementation, and long-term impact of these digital tools. To bridge these knowledge gaps, this study proposes specific research questions aimed at systematically evaluating the effectiveness of digital tools, identifying patterns of technology usage, analysing the influence of technology on public engagement, assessing long-term impacts, identifying integration challenges, and exploring future technologies within the context of heritage preservation. The research questions guiding this study are as in Table 1.

Materials and Methods

This systematic review, following the PRISMA methodology, utilised a structured approach for conducting systematic reviews and meta-analyses (Moher *et al*., 2009; Urrútia & Bonfill, 2013). The methodology includes a 25-item checklist and a flow diagram encompassing four phases: Identification, selection, eligibility, and inclusion. Systematic literature reviews aim to consolidate and objectively integrate a body of research on a specific field of study (Sánchez Meca, 2010; Crisol-Moya *et al*., 2020). The review spans a 5-year period (2019–2023) and makes use of both the Scopus and Web of Science databases for comprehensive coverage. This review followed three stages: Planning, search, and documentation (Lozada Ávila & Betancur Gómez, 2017).

Heritage Building Information Modelling (HBIM) has emerged as a transformative digital tool for preserving and managing architectural heritage. By creating precise digital representations of historical structures, HBIM facilitates restoration planning, structural analysis, and efficient management of heritage assets. Its integration into conservation practices ensures that detailed architectural data is preserved for future restoration efforts, providing a critical bridge between

Table 1: Research questions

No.	Research Question (RQ)
1	What are effective digital tools for conservation cultural heritage?
2	How can digital technologies be employed to conserve heritage?
3	How do technological advancements impact public engagement and immersive heritage experiences?
4	What are the long-term effects of digital tools on sustainability and resilience, and how can they contribute to risk mitigation?
5	What challenges are encountered in integrating digital tools?
6	What are promising future technologies and strategic investments for heritage conservation?

traditional preservation techniques and modern technological advancements.

Planning Stage

The first stage involved defining the objectives and focus of the review. The investigative focus was carefully identified through a thorough review of relevant resources to ensure that no previous systematic reviews comprehensively covered the topic. In the absence of prior systematic reviews, a detailed search protocol was developed and executed within the Scopus and Web of Science databases, incorporating specific protocol descriptors to guide the search. These databases were selected for their extensive indexing of high-impact publications and broad coverage of multidisciplinary research in cultural heritage preservation. Their inclusion was a strategic choice, reflecting their strong reputation for hosting high-quality peer-reviewed research across diverse fields. This approach ensured the thematic relevance to the educational field while considering the accessibility and availability of the studies.

Search Stage

Specific search formulas were developed using Boolean operators (AND, OR) and keywords such as "Digital Heritage Conservation", "Cultural Heritage Digitisation", and "3D Scanning in Cultural Heritage". The search phase aimed to identify relevant literature based on the established inclusion and exclusion criteria. Specific search formulas were developed for the Scopus and Web of Science databases, considering various fields of study. Table 2 presents the keywords and descriptors used in this phase. This structured search retrieved 24,76 articles for initial consideration.

Derived from the research questions, the journal's criteria for study selection was meticulously outlined, focusing on inclusion, exclusion, and specific research areas (Table 3).

Documentation Stage

The final stage focused on evaluating and documenting the selected studies. The PRISMA model provided a systematic approach to evaluating the retrieved studies, ensuring comprehensive analysis. After screening and applying the inclusion criteria, 50 studies were selected for detailed analysis. Refer to Figure 2 for a visual overview of the study selection process.

The process begins with a strategic deployment of a broad array of keywords, meticulously curated to capture the essence of digital innovations in the conservation of cultural heritage. This search strategy, confined to articles published within the specified timeframe and documented in English within scholarly journals, ensures comprehensive exploration. The choice of Scopus and Web of

Table 2: Descriptors the search string used for the systematic review process

Databases	Keywords Used
Scopus	(TITLE-ABS-KEY ("Digital Heritage Conservation") OR TITLE-ABS-KEY ("Cultural Heritage Digitisation") OR TITLE-ABS-KEY ("Digital Tools in Conservation") OR TITLE-ABS-KEY ("Virtual Heritage") OR TITLE-ABS-KEY ("3D Scanning in Cultural Heritage") OR TITLE-ABS-KEY ("Augmented Reality for Conservation") OR TITLE-ABS-KEY ("Digital Documentation in Heritage Preservation") OR TITLE-ABS-KEY ("Conservation Technologies") OR TITLE-ABS-KEY ("Cultural Heritage Digitalisation") OR TITLE-ABS-KEY ("Heritage Information Technology"))
Web of Science	TS = ("Digital Heritage Conservation" OR "Cultural Heritage Digitisation" OR "Digital Tools in Conservation" OR "Virtual Heritage" OR "3D Scanning in Cultural Heritage" OR "Augmented Reality for Conservation" OR "Digital Documentation in Heritage Preservation" OR "Conservation Technologies" OR "Cultural Heritage Digitalisation" OR "Heritage Information Technology")

Table 3: Inclusion, exclusion, and research area criteria for study selection

Criteria	Scopus	Web of Science
Limited to	• Year: 2019–2023 • Document type: Articles • Publication stage: Final • Source type: Journal • Language: English	• Year: 2019–2023 • Document type: Articles • Publication stage: Final • Source type: Journal • Language: English
Index	• Scopus	• Science Citation Index Expanded (SCIE) • Social Science Citation Index (SSCI) • Emerging Sources Citation Index (ESCI) • Arts & Humanities Citation Index (AHCI)
Exclusion	• Book series, book, chapter in book, conference proceeding • Non-English • < 2019 and 2024	• Book series, book, chapter in book, conference proceeding • Non-English • < 2019 and 2024
Subject area	• Social Science	• Environmental Sciences Ecology • Science Technology Other Topics • Engineering • Arts Humanities Other Topics • Computer Science • Archaeology • Architecture • Biodiversity Conservation • Business Economics • Geography • Social Sciences Other Topics • Development Studies • Geology • Imaging Science Photographic Technology • Communication • Construction Building Technology • Remote Sensing • Sociology • Telecommunications • Urban Studies

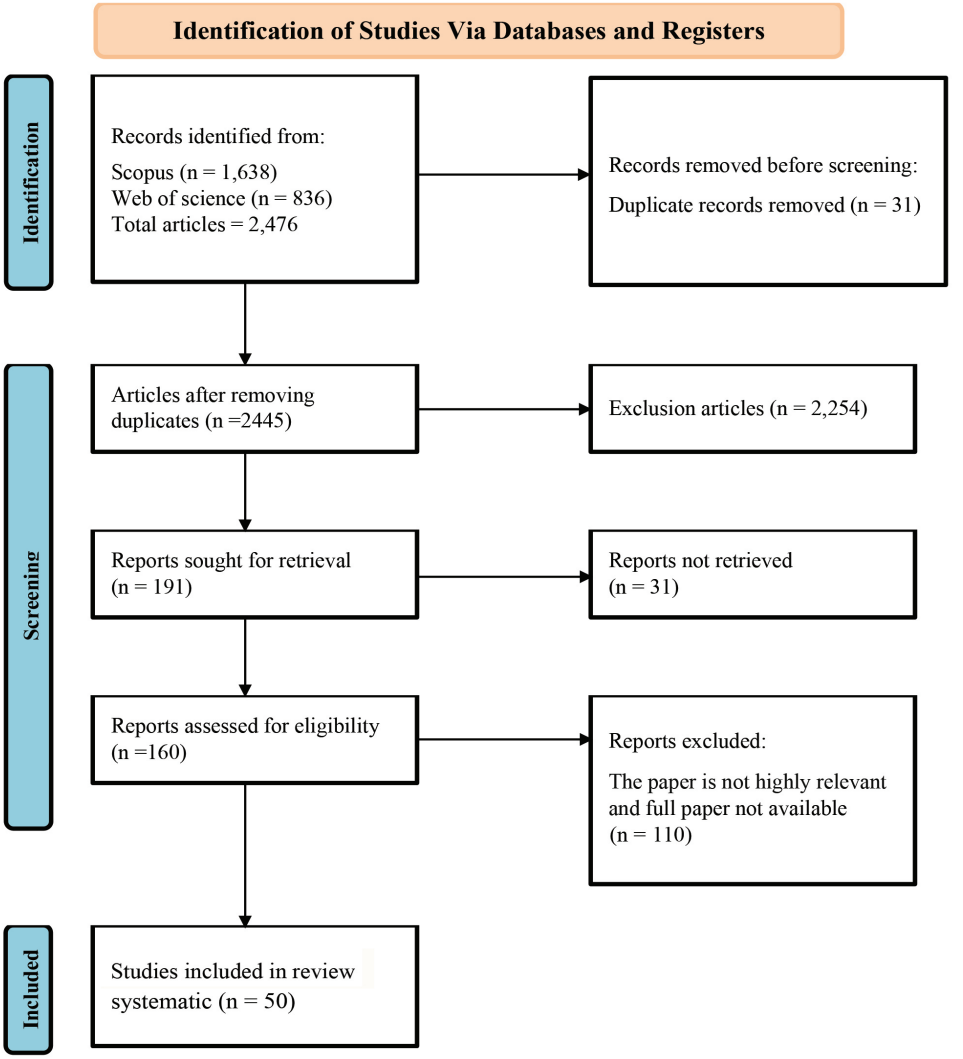

Figure 2: Flow of information through the different phases of a systematic review

Science as primary databases was motivated by their expansive scope and the quality of research they encompass, aiming to provide a robust foundation for the review.

Upon retrieving 2,476 articles, a thorough screening process was conducted, removing duplicates and narrowing down the selection based on predefined criteria. This critical stage refined the selection to 50 highly relevant studies for detailed analysis. The methodology for data extraction and analysis was based on the principles of the PRISMA model, providing a structured framework for evaluating the selected studies and assessing their relevance.

The culmination of this rigorous process led to a synthesis of findings that illuminated emerging themes and trends in the application of digital tools for cultural heritage conservation. This analysis not only highlighted innovations in the field but also underscored the potential and challenges of integrating technology into preservation efforts. Acknowledging inherent limitations such as potential bias in article selection and constraints posed by language

and publication date parameters, this study reflects on the implications these may have on the findings. It offers contemplation on how future research could navigate these challenges to enhance the robustness of systematic reviews in this evolving field.

This review underscores the pivotal role of digital tools in the conservation of cultural heritage, providing a comprehensive overview of the current landscape and shedding light on potential pathways for future inquiry. The findings contribute to both theoretical discourse and practical advancements in conservation practices, marking a significant step forward in technology-driven heritage preservation.

Discussions

Thematic Overview of Digital Tools in Heritage Conservation

The thematic categorisation of articles in this review is critical for understanding the role of digital tools in cultural heritage conservation. This approach groups each scholarly work into six key themes: Effectiveness of digital tools, practical deployment in conservation tasks**,** technological advancements and public engagement, sustainability and resilience, challenges in integrating new technologies, and emerging technologies and strategic funding. These themes represent central areas of focus, covering various issues, and opportunities within the field.

The evaluation of articles, summarised in Table 4, highlights their alignment with these themes, offering a concise overview of the current research landscape. This categorisation emphasises the diverse applications of digital tools, their contributions to sustainability and resilience, and the potential of emerging technologies to drive future advancements in the field.

Each research article is evaluated based on its relevance to six key themes related to digital technology and cultural heritage conservation. The process involves assessing whether an article contributes to any of these predefined themes. To make this analysis clear and easy

Table 4: Thematic synthesis for systematic review

Theme	Research Question	Article ID
Effective digital tools	What are effective digital tools for conserving cultural heritage?	1, 2, 3, 4, 5, 6, 8, 9, 11, 12, 13, 14, 15, 16, 17, 19, 21, 22, 23, 25, 26, 27, 28, 30, 32, 35, 36, 37, 38, 39, 40, 41, 43, 44, 45, 47, 48, 50
Employing digital technologies	How can digital technologies be employed to conserve heritage?	1, 2, 3, 4, 5, 6, 8, 9, 11 ,12, 13, 14, 15, 16, 17, 19, 21, 22, 23, 25, 26, 27, 28, 30, 32, 35, 36, 37, 38, 39, 40, 41, 43, 44, 45, 47, 48, 50
Technological advancements and public engagement	How do technological advancements impact public engagement and immersive heritage experiences?	1, 2, 3, 4, 6, 8, 9, 12, 13, 14, 15, 16, 17, 19, 20, 21, 22, 23, 25, 26, 27, 28, 29, 31, 32, 35, 36, 37, 40, 41, 43, 44, 45, 47, 48, 49
Sustainability and resilience	What are the long-term effects of digital tools on sustainability and resilience, and how can they contribute to risk mitigation?	1, 2, 3, 7, 13, 14, 18, 19, 21, 32, 42, 45, 46, 48
Challenges in integrating digital tools	What challenges are encountered in integrating digital tools?	1, 2, 3, 4, 5, 9, 11, 13, 14, 17, 19, 21, 27, 30, 31, 32, 39, 45, 46, 48
Future technologies and strategic investments	What are promising future technologies and strategic investments for heritage conservation?	1, 2, 3, 5, 6, 9, 11, 12, 13, 14, 15, 16, 17, 19, 21, 22, 23, 25, 26, 27, 28, 30, 32, 35, 36, 38, 39, 40, 41, 43, 44, 45, 46, 47, 48, 49, 50

to understand, the table employs a simple visual system, checkmarks are placed next to each theme that an article covers. This method provides a straightforward way to see at a glance how each piece of research contributes to the broader field, as demonstrated in Table 5.

In Table 5, it is observed that 10 authors have covered all thematic categories, indicating their comprehensive coverage of all thematic categories related to digital tools in cultural heritage conservation. This signifies that their work addresses a broad spectrum of issues and opportunities within the field. Each of these 10 authors contributes uniquely to the field, whether it be through developing new methodologies, Hanes *et al*. (2019), who proposed using serious games for heritage education, or through technical innovation such as Kuzio *et al*. (2022), who focused on the preservation aspect with a portable multispectral imaging system. These studies emphasised the diverse applications of digital technologies for heritage conservation, including improving accessibility, enhancing engagement, and addressing conservation challenges**.**

The exploration of digital tools in the enhancement of cultural heritage engagement presents a groundbreaking shift in the academic discourse on heritage conservation. Innovatively, Bekele and Kassahun (2021) presented a foray into the realm of interactive mixed reality, elucidating its capacity to elevate user engagement with cultural content. Their study explores how digital methodologies can address user interaction challenges, contributing to advancements in cultural engagement.

Karbol *et al*. (2021) investigated the utility of virtual reality in urban planning and heritage preservation, highlighting its role in public engagement and historical preservation. Champion *et al*. (2019) and Champion *et al*. (2020) explored digital heritage accessibility, providing insights into improving 3D model repositories and addressing gaps in digital heritage preservation methodologies. Their work suggested enhancements to usability and engagement, setting standards for future digital preservation efforts.

Zeng *et al*. (2023) delved into the digitisation of ancient Egyptian theological totems. Their groundbreaking work illuminated the instrumental role of digital technology in redefining heritage innovation and dissemination, thus reinvigorating the exploration and narrative of cultural heritage through a digital lens. Oke *et al*. (2021) illuminated the practical applications of augmented reality in the conservation of architectural heritage, particularly emphasising the revitalisation of semi-collapsed structures. This exploration underscored the pivotal role of digital tools in democratising access to heritage sites, thereby enhancing their visibility and appreciation among a global audience.

In a pioneering approach, Rihani and Nemeh (2023) delved into the digital reconstruction of obliterated heritage sites via crowdsourced imagery. This methodology underscores the transformative power of community engagement in heritage restoration, epitomising a collaborative venture that harnesses collective efforts towards the conservation of cultural legacy. Furthermore, Lim *et al*. (2020) embarked on an innovative exploration of crowd simulation in digital cultural heritage. Their research offers a vivid visualisation of past human activities, thereby vivifying historical sites and facilitating a profound understanding and appreciation of historical narratives.

This synthesis highlights the diverse impact of digital tools across thematic domains, including the conservation of cultural heritage, enhancement of public engagement, and promotion of sustainability and resilience at heritage sites. It addresses the challenges of integrating digital tools in heritage preservation while exploring opportunities for future technological advancements. By improving accessibility, fostering innovation, and enhancing public interaction, digital technologies are redefining how cultural heritage is preserved, experienced, and interpreted.

Table 5: Analysis of 50 articles based on author and theme

ID	Author and Year	Effective Digital Tools	Employing Digital Technologies	Technological Advancements and Public Engagement	Sustainability and Resilience	Challenges in Integrating Digital Tools	Future Technologies and Strategic Investments
1	Bekele and Kassahun (2021)	✓	✓	✓	✓	✓	✓
2	Karbol *et al*. (2021)	✓	✓	✓	✓	✓	✓
3	Champion *et al*. (2019)	✓	✓	✓	✓	✓	✓
4	Nyhlén *et al*. (2019)	✓	✓	✓		✓	
5	Barrile *et al*. (2022)	✓	✓			✓	✓
6	Basaraba and Nicole (2022)	✓	✓	✓			✓
7	Mabrouk *et al*. (2023)				✓		
8	Atzeni *et al*. (2022)	✓	✓	✓			
9	Tapavički-Ilić *et al*. (2021)	✓	✓	✓		✓	✓
10	Luo *et al*. (2019)						
11	Ognjanović *et al*. (2019)	✓	✓			✓	✓
12	Valenti *et al*. (2021)	✓	✓	✓			✓
13	Champion *et al*. (2020)	✓	✓	✓	✓	✓	✓
14	Hanes *et al*. (2019)	✓	✓	✓	✓	✓	✓
15	Vozzola and Mariapaola (2021)	✓	✓	✓			✓
16	Selim *et al*. (2022)	✓	✓	✓			✓
17	Turillazzi, *et al*. (2021)	✓	✓	✓		✓	✓
18	Borin *et al*. (2023)				✓		
19	Kuzio *et al*. (2022)	✓	✓	✓	✓	✓	✓

20	Ghani *et al*. (2020)			✓			
21	Zeng *et al*. (2023)	✓	✓	✓	✓	✓	✓
22	Bekele *et al*. (2021)	✓	✓	✓			✓
23	Pietroni *et al*. (2021)	✓	✓	✓			✓
24	Colonnese and Fabio (2022)						
25	Selim *et al*. (2022)	✓	✓	✓			✓
26	Bekele and Kassahun (2021)	✓	✓	✓			✓
27	Previtali *et al*. (2020)	✓	✓	✓		✓	✓
28	Palčák *et al*. (2022)	✓	✓	✓			✓
29	Leshkevich *et al*. (2022)			✓			
30	Bacci *et al*. (2023)	✓	✓			✓	✓
31	Nyhlén *et al*. (2019)			✓		✓	
32	Oke *et al*. (2021)	✓	✓	✓	✓	✓	✓
33	Sintov *et al*. (2019)						
34	Wight *et al*. (2021)						
35	Pietroni *et al*. (2021)	✓	✓	✓			✓
36	Gonzalez Vargas *et al*. (2020)	✓	✓	✓			✓
37	Pietroni and Eva (2021)	✓	✓	✓			
38	Babilio *et al*. (2023)	✓	✓				✓
39	Batchelor *et al*. (2021)	✓	✓			✓	✓
40	Popovici *et al*. (2022)	✓	✓	✓			✓

41	Okanovic *et al.* (2022)	✓	✓	✓						✓
42	López Sánchez *et al.* (2021)				✓					
43	Liritzis *et al.* (2021)	✓	✓	✓						✓
44	Demetrescu *et al.* (2021)	✓	✓	✓						✓
45	Rihani and Nemeh (2023)	✓	✓	✓	✓		✓			✓
46	Hahn *et al.* (2022)				✓		✓			✓
47	Puig *et al.* (2020)	✓	✓	✓						✓
48	Lim *et al.* (2020)	✓	✓	✓	✓		✓			✓
49	Li *et al.* (2023)			✓						✓
50	Kaplan and Kayhan (2022)	✓	✓							✓

Summary of Key Themes with Examples

In the research trend section of the systematic literature review, a broad range of key research areas is highlighted, demonstrating where scholarly focus has been directed. This is detailed in Tables 3 and 4, which summarises the primary research trends identified. This methodological approach not only maps out the breadth of the research landscape but also pinpoints those contributions that significantly advance the understanding of the use of digital tools in cultural heritage preservation. This careful examination distinguishes between general thematic alignment and direct relevance. These particular studies were selected for in-depth analysis because of their significant impact on addressing the research question.

Emerging Research Trends in Digital Heritage Preservation

The thematic analysis uncovered a broad spectrum of research trends, addressing the question, "What are effective digital tools for conserving cultural heritage?" among these, "Effective Digital Tools" emerged as a key area of focus, garnering significant interest from scholars. Of the 50 studies analysed, 38 discussed or were relevant to this theme, highlighting its critical role in the conversation about preserving digital heritage.

Upon detailed examination, a select group of these articles, particularly studies by Kuzio *et al*. (2022), Rihani and Nemeh (2023), and Bekele and Kassahun (2021), delivered essential insights that directly responded to the research question associated with the 'Effective Digital Tools' theme. These contributions extended beyond general discussion, presenting key findings that demonstrated the practical application of digital tools in the conservation of cultural heritage.

Kuzio *et al*. (2022) focused on the democratisation of spectral imaging for cultural heritage documentation using accessible tools and software. This approach is pivotal for institutions with limited resources, enhancing

the accessibility and broadening the scope of scientific imaging in heritage preservation. Rihani and Nemeh (2023), on the other hand, utilised crowdsourced images and 3D photogrammetric processes for the digital reconstruction of the Temple of Bel in Palmyra, Syria, emphasised the role of VR in providing immersive experiences of destroyed heritage sites. This study demonstrated the feasibility and emotional impact of using VR to recreate and interact with lost monuments, leveraging publicly available digital imagery for detailed reconstruction.

Overview of Research Areas with Trends Identified

As a second point, the question "How can digital technologies be employed to conserve heritage?" led to the identification of various research pathways. Notably, "Employing Digital Technologies" emerged prominently as a key theme. Of the 50 articles analysed, 38 discussed or were relevant to this theme, highlighting its critical role in the conversation about conserving digital heritage. This emphasised the significant interest and the paramount importance of this theme in the discourse on digital heritage preservation.

A closer examination identified three studies that provided pivotal insights directly addressing the question of how digital technologies can be employed to conserve heritage. These studies contribute not just to the broader discussion but highlight specific findings that illuminated the effective usage of digital technologies for heritage preservation. The integration of digital technologies in heritage conservation represents a paradigm shift in how we interact with and preserve cultural legacies.

Zeng *et al*. (2023) explored the use of virtual reality for the digital reconstruction of ancient Egyptian totems, underscoring the potential of immersive experiences in enhancing heritage appreciation. Oke *et al*. (2021) demonstrated augmented reality's efficacy at preserving the architectural heritage of the Aqueduct Kuru Kopru in Turkey, advocating for AR's role in augmenting public engagement with historical structures. Furthermore, Karbol *et al*. (2021) discussed the virtual city's role in urban development and cultural heritage preservation, highlighting the technology's capacity to simulate and safeguard urban environment and cultural narratives digitally.

Collectively, these studies illustrate the transformative impact of digital technologies in heritage conservation, offering new methodologies for engaging with and preserving our cultural heritage in the digital era.

Challenges and Opportunities in Digital Heritage Conservation

As the third point of discussion, the inquiry into "How do technological advancements impact public engagement and immersive heritage experiences?" highlighted that "Technological Advancements and Public Engagement" is a significant theme in the conversation on conserving digital heritage. This theme attracted considerable scholarly attention, with 36 out of the 50 articles analysed touching upon its relevance, thereby underscoring the significant impact of technology on engaging the public and enhancing immersive heritage experiences.

Machine learning offers significant potential in cultural heritage conservation, particularly in predictive analysis for structural health monitoring and automated artifact classification. These technologies enable the identification of structural vulnerabilities and patterns in artifact degradation, supporting proactive conservation efforts. Machine learning algorithms can also automate the categorisation and analysis of large datasets, enhancing the efficiency and accuracy of heritage management.

For example, Champion and Rahaman (2019), Nyhlén and Gidlund (2019), and Basaraba (2022) suggested that while technological innovations in digital and virtual heritage have the potential to enhance public engagement and create immersive experiences, the effectiveness of these technologies depends on their integration with sustainable scholarly practices, critical design methodologies, and

community-driven narratives. Technological tools alone are not sufficient; their application must be thoughtfully aligned with efforts to challenge existing norms, engage diverse communities, and preserve the authenticity of cultural narratives for truly transformative heritage experiences.

Address Technological Limitations and Solutions

Subsequently, the exploration of "What are the long-term effects of digital tools on sustainability and resilience, and how can they contribute to risk mitigation?" brought to light "Sustainability and Resilience" as a key and distinct theme. This was based on a thematic analysis of 50 articles centred on digital heritage, reflecting an increasing academic interest in the enduring influence of digital tools on cultural heritage's preservation and resilience. Notably, 14 studies were identified as discussing or being relevant to this theme, underlining its importance in ongoing discussions about sustainable practices in the field of digital heritage conservation. Within this thematic realm, three studies stood out for their contributions to understanding and advancing sustainability and resilience in digital heritage preservation.

For instance, Lim *et al*. (2020), Hahnet *et al*. (2022), and López Sánchez *et al*. (2021), all indicated that digital technologies and methodologies like crowd simulation, technology needed assessment, and GIS-based mapping are pivotal in bridging the gap between heritage conservation and public engagement. They suggested that technology not only enhances the accessibility and understanding of cultural heritage but also addresses conservation challenges by fostering collaborative approaches and integrating digital documentation into heritage management. These advancements promise to make heritage experiences more immersive and engaging for the public while ensuring the sustainable preservation of cultural landscapes.

These studies address the query regarding the long-term effects of digital tools on sustainability and resilience, offering valuable insights into how digital technologies can be leveraged to mitigate risks and promote the sustainable preservation of cultural heritage. Their contributions highlight the evolving landscape of digital heritage conservation, where the integration of sustainable digital models, strategic preservation approaches, and innovative digitisation techniques are paramount for ensuring the resilience of cultural heritage in the face of changing environmental and technological conditions.

Future Directions and Recommendations

Following that, the investigation into "What challenges are encountered in integrating digital tools?" revealed "Challenges in Integrating Digital Tools" as a significant theme. This insight emerged from the thematic analysis of literature on digital heritage, highlighting the obstacles faced in the adoption and implementation of digital technologies in heritage conservation. This area garnered significant attention, with 20 out of the 50 analysed articles touching upon the difficulties and obstacles faced in the practical application of digital technologies in heritage conservation. The focus on this theme underscores the complexities and hurdles inherent in seamlessly integrating digital tools within the domain of cultural heritage preservation.

Key studies that have notably contributed insights into this theme include works by Champion *et al*. (2020), Bekele and Kassahun (2021), and Rihani and Nemeh (2023). These studies collectively address the question of what challenges are encountered in integrating digital tools into heritage conservation. They provide a detailed examination of the barriers to accessibility, the limitations posed by current technologies and resources, and the ongoing struggle to preserve digital assets effectively. Their findings offered crucial insights into

the obstacles that must be overcome to fully leverage digital tools in the service of cultural heritage preservation, pointing towards the necessity for innovative solutions that address these challenges head-on.

Highlight Key Areas for Future Research and Potential Funding Strategies

To close out the series of insights, the query "What are promising future technologies and strategic investments for heritage conservation?" led to the identification of "Future Technologies and Strategic Investments" as a deeply impactful theme. This theme was uncovered through a thematic analysis of digital heritage literature, spotlighting the potential advancements and strategic approaches vital for the preservation of cultural heritage. This theme captured the attention of a significant portion of the scholarly community, with 37 out of the 50 articles analysed addressing or touching upon the potential and necessity of forward-looking technologies and investments in the realm of heritage preservation. This robust scholarly interest underscores the collective recognition of the crucial role that innovative technologies and strategic planning play in shaping the future of cultural heritage conservation.

Among the diverse studies contributing to this theme, notable works by Karbol *et al*. (2021), Rihani and Nemeh (2023), Oke *et al*. (2021), Bekele and Kassahun (2021), and Hanes *et al*. (2019) provide pivotal insights into emerging technologies and strategic approaches. These highlighted studies collectively address the question of promising future technologies and strategic investments for heritage preservation. They shine a light on the advanced technological frontiers and strategic considerations that are poised to define the next phase of heritage conservation efforts.

By identifying key areas for investment and further development such as advanced photogrammetry, virtual reality, augmented and mixed reality applications, and serious games for education, these works pave the way for a future in which digital innovation and strategic planning play a pivotal roles in safeguarding and revitalising cultural heritage for generations to come.

Case Studies and Applications of Digital Tools in Heritage Conservation

The transformative potential of digital technologies in cultural heritage preservation is exemplified by the virtual reconstruction of the Temple of Bel in Palmyra, Syria. Utilising advanced 3D photogrammetry and VR, this initiative has enabled precise digital recreation, facilitating both restoration planning and immersive educational experiences for global audiences (Denker, 2017). These tools enable accurate documentation, potential future restoration, and immersive educational experiences, allowing global audiences to explore the site virtually. Illustrated in Figure 3, this initiative highlights the essential role of digital tools in addressing heritage destruction and promoting conservation awareness.

Heritage Building Information Modelling (HBIM) demonstrates the power of digital tools in preserving architectural heritage. At the National Archaeological Museum of Naples, point cloud data enhanced HBIM workflows, offering detailed structural insights (Martinelli *et al*., 2022). As shown in Figure 4, this approach supports informed restoration decisions, bridging documentation, and practical conservation.

These examples showcase the impact of digital tools in preserving cultural heritage, from virtual reconstructions to structural insights through HBIM. They underline the importance of investing in digital methods to address conservation challenges and protect heritage.

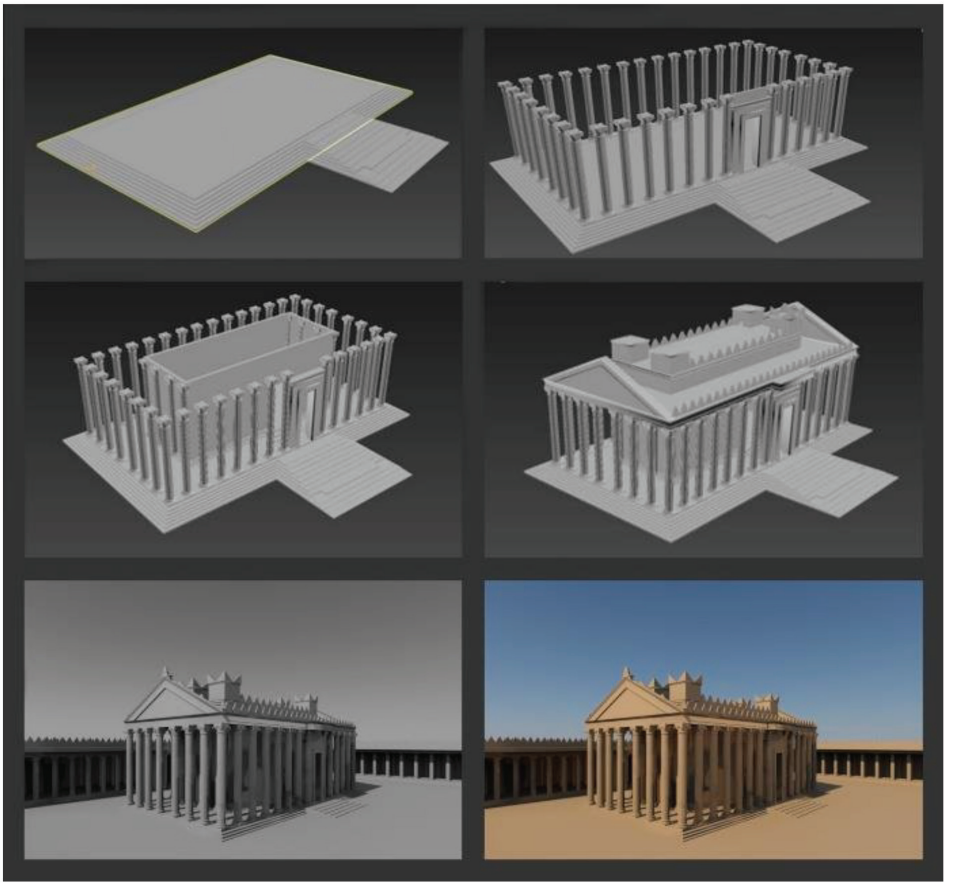

Figure 3: 3D reconstruction phases and final realistic visualisation of the Temple of Bel
Source: Denker (2017)

Figure 4: Point cloud superimposed on the HBIM model of the National Archaeological Museum of Naples
Source: Martinelli *et al*. (2022)

Conclusions

Main Findings

This systematic review highlights the growing role of digital tools in cultural heritage conservation, emphasising its increasing complexity and importance. This evolving field focuses on interrelated themes, including the effectiveness of digital technology, its application for conservation, advancements in public engagement, sustainability and resilience, integration challenges, and future technology investments. The effectiveness of digital tools and technology in preserving cultural heritage forms a primary focus area in the literature. An important aspect of integrating digital technology in cultural heritage conservation is its ability to transform public engagement and create immersive experiences. The literature highlights sustainability and integration challenges as critical concerns, emphasising the need for careful evaluation and optimisation of digital tools. Looking ahead, the literature underscores the importance of future technology and strategic investments in the field of cultural heritage conservation.

Limitations

While this study offers valuable insights into the integration of digital tools in cultural heritage conservation, it is subject to several methodological limitations that need to be considered. The main constraint is the reliance on the Scopus and Web of Science (WoS) databases, which, although comprehensive, may exclude important studies from other platforms or regional databases. The use of specific keywords to filter search results further exacerbates this limitation. The study design limits the inclusion criteria to publications in English, peer-reviewed journal articles, and works from the year 2019 to 2023.

Future Directions

Future research should emphasise the development and evaluation of advanced digital methodologies such as photogrammetry, AI-based conservation tools, and virtual reality applications. Expanding the range of referenced sources by incorporating regional databases and non-English publications can enhance the inclusivity and comprehensiveness of future reviews. The development of strategic policies is needed to establish ethical standards for the use of digital technology in conservation.

Implications and Contribution

The findings from this review underscore the critical role of digital technology in shaping the future of cultural heritage conservation. Stakeholders, including policymakers, practitioners, and researchers must collaborate to address the challenges and leverage the opportunities presented by these advancements.

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Conflict of Interest Statement

The authors declare that they have no conflict of interest.

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