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Review

Integrating Emerging Technologies with Digital Twins for Heritage Building Conservation: An Interdisciplinary Approach with Expert Insights and Bibliometric Analysis

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Abstract: This review paper presents an interdisciplinary exploration of integrating emerging technologies, including digital twins (DTs), building information modeling (BIM), 3D laser scanning, machine learning (ML), and the Internet of Things (IoT), in the conservation of heritage buildings. Through a comprehensive literature review spanning from 1996 to 2024, expert interviews, a bibliometric analysis, and content analysis, the study highlights a significant shift toward a preventive approach to conservation, focusing on less invasive methods to ensure long-term preservation. It highlights the revolutionary impact of detailed digital representations and real-time monitoring on enhancing conservation efforts. The findings underscore significant research gaps, such as the need for standardized information protocols and the integration of DTs with BIM, while pointing to the potential of AR and VR in enriching heritage experiences. The paper advocates for a multidisciplinary approach to effectively harness these technologies, offering innovative solutions for the sustainable preservation of cultural heritage.

Keywords: digital twins; building information modeling; 3D laser scanning; machine learning; internet of things; heritage conservation; augmented reality; virtual reality

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Citation: Mazzetto, S. Integrating Emerging Technologies with Digital Twins for Heritage Building Conservation: An Interdisciplinary Approach with Expert Insights and Bibliometric Analysis. *Heritage* **2024**, *7*, 6432–6479. https://doi.org/10.3390/heritage7110300

Academic Editor: Jason J. Jung

Received: 27 September 2024
Revised: 31 October 2024
Accepted: 15 November 2024
Published: 20 November 2024

1. Introduction

The preservation of heritage buildings is a critical link to cultural, historical, and architectural lineage, serving as windows into the lives, technologies, and esthetics of past civilizations [1,2]. The task of conserving these structures is fraught with unique challenges, including their advanced age, the materials used in their construction, and the need to maintain historical authenticity while accommodating modern functionalities [3,4]. Looking into the future, the integration of historical architectural assets into the fabric of global and European development agendas becomes increasingly crucial [5,6]. Initiatives such as the European Green Deal [7] and the 2030 Digital Compass [8] underscore the importance of preserving these assets, not just for their intrinsic value but also as part of broader efforts to address challenges like climate change, urbanization, and mass tourism. The conservation community is gradually shifting from reactive restoration practices towards a preventive paradigm, emphasizing the early identification and mitigation of deterioration [9]. This approach seeks to extend the lifespan of heritage structures with minimal interventions, thereby reducing costs and preserving their original integrity.

The integration of building information modeling (BIM) into this framework further enhances the conservation process [10]. BIM's detailed digital representations provide a holistic view of a building's structure, materials, and history, allowing for precise planning and implementation of conservation efforts [11]. In addition, the advancements in 3D laser scanning technology have revolutionized the documentation of heritage buildings in combination with BIM, capturing their intricate details with unprecedented precision [12]. These high-resolution 3D models serve as an invaluable resource for conservation, enabling the identification of vulnerabilities and informing restoration strategies [13]. Moreover, the adoption of machine learning and the IoT in the field of heritage conservation introduces predictive and real-time monitoring capabilities [14,15]. Machine learning algorithms, trained on data from IoT sensors and other sources like laser scanners, can predict deterioration, guiding preemptive conservation actions [16,17].

The digital twin (DT) concept (Figure 1), characterized by the tripartite model of the physical asset, its digital counterpart, and the dynamic data exchange between them, has become a cornerstone of this technological integration [18].

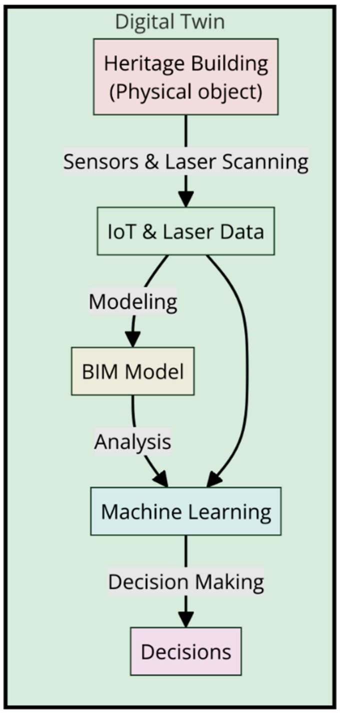

Figure 1. A framework of the Heritage Building Digital Twin (HBDT) Model as envisioned in this study, incorporating machine learning, IoT technologies, laser scanning, BIM, and decision-making processes.

Figure 1 illustrates the "Heritage Building Digital Twin (HBDT) Model" framework, showcasing the integration of machine learning, IoT technologies, laser scanning, BIM, and decision-making processes. This model supports the argument for a shift from reactive to proactive conservation, as each component contributes to a more comprehensive conservation strategy. For example, BIM's digital representations facilitate precise planning, while IoT technologies enable real-time monitoring, addressing early deterioration detection as discussed above. Despite its broad applicability, the precise definition and implementation of DTs in heritage conservation remain subjects of ongoing research and debate.

Out of the above, this paper aims to explore the intersection of DT technology with heritage conservation, examining innovative applications and methodologies that have begun to emerge. Through a comprehensive review of current literature and identification of emerging trends, this study highlights the potential of DTs, BIM, laser scanning, machine learning, and IoT technologies to revolutionize the field of heritage conservation. This multifaceted approach, bridging traditional architectural and archeological practices with the latest in computer science and engineering, offers a new paradigm for tackling the complex challenges inherent in preserving heritage buildings. The potential of these technologies to enhance damage assessment, improve public engagement through augmented and virtual reality, and navigate the ethical considerations of digital replication underscores their transformative impact on heritage conservation.

This paper differentiates itself from the work of Annalaura Vuoto et al. [19] by extending the exploration of DT technology in the conservation of heritage buildings to include a wider array of emerging technologies such as BIM, 3D laser scanning, machine learning, and the IoT. It explores the synergistic integration of these technologies with DTs to foster more effective conservation strategies, highlighting their collective potential in proactive preservation efforts. Unlike [19] systematic literature review, this approach is also enriched by conducting interviews with experts in the field and employing bibliometric analysis over a period of 28 years between 1996 and 2024 to map out the past and current research landscape and trends.

2. Methodology

The methodological research approach, depicted in Figure 2, follows a meticulously organized six-phase procedure designed to systematically gather literature related to DT technology for heritage buildings from 1996 to 2024. Figure 2 visually represents the structured six-step framework guiding the literature review process in this study. Beginning with the formulation of targeted search phrases, this methodology ensures the precise identification of relevant studies at the intersection of DT technology and heritage conservation. As shown in Figure 2, phases such as document screening and bibliometric analysis allow for a comprehensive and unbiased selection of literature. Each step contributes to refining the selection from an initial pool of 457 documents to 186, as specified later in Table 1, underscoring the rigorous inclusion and exclusion criteria employed to maintain methodological rigor. Initially, a collection of search phrases was developed specifically designed to pinpoint the relevant cross-section between DT and heritage buildings. Following this, the third phase involved conducting an extensive search for literature across various databases, such as Web of Science, Scopus, and Google Scholar, to accumulate a wide range of potential articles as the research started with 457 documents, including journal papers, conferences, books, and theses, and ended up with 186 documents based on the criteria shown in Table 1.

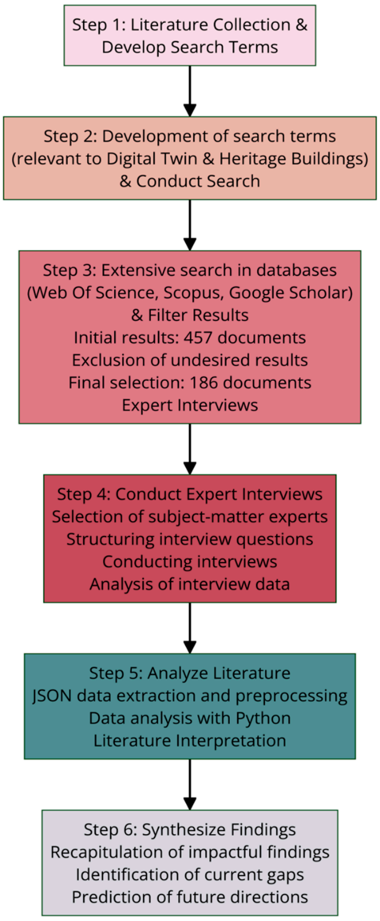

Figure 2. Six-step methodological framework for literature review on DT for heritage buildings.

Table 1. Criteria for systematic review of DT applications in heritage building conservation.

Criteria Category	Specific Criteria	Inclusion Parameters	Exclusion Parameters
Study Design	- Empirical research - Conceptual analysis - Methodological approach	- Use of DT, laser scanning, machine learning, IoT, and BIM in analysis or synthesis—DT as a central theme	- Studies where DT is peripheral - Literature reviews without original analysis
Subject Focus	- DT applications - DT, laser scanning, machine learning, IoT, and BIM in heritage conservation - DT for structural analysis	- Studies focusing on DT for management or conservation of heritage assets - DT in assessing structural integrity	- Studies with vague or indirect relation to DT - DT applied to non-heritage contexts
Asset Type	- Heritage buildings - Archeological sites - Cultural landscapes - Artifacts within historical context	- Studies centered on DT, laser scanning, machine learning, IoT, and BIM management of the above assets - Analysis on DT's role in conservation	- Studies on new constructions - DT applied to non-cultural or non-historical sites
Temporal Scope	- Longitudinal studies - Cross-sectional studies within the date range	- Studies covering DT evolution within the timeline - Snapshots of DT applications at specific time points	- Studies outside the set temporal range - Future predictions without historical data
Methodological Rigor	- Use of validated instruments - Clear analytical frameworks - Replicable study designs	- Studies with robust methodology - Clear definition and application of DT	- Studies with methodological flaws - Inadequate definition of DT usage
Geographic Relevance	- Studies in areas with known heritage sites - DT applied in diverse cultural settings	- DT, laser scanning, machine learning, IoT, and BIM studies reflect the geographical diversity of heritage sites - Case studies from regions with high heritage significance	- Studies with no clear geographical linkage to heritage sites - DT studies in areas without significant heritage presence

Table 1 outlines the detailed criteria used for selecting documents in the systematic review, specifying parameters such as study design, subject focus, asset type, and temporal scope. Each category is broken down into specific inclusion and exclusion parameters, ensuring that selected studies focus on DT applications for heritage buildings, incorporating essential technologies like laser scanning, BIM, and machine learning. For instance, studies applying DT in non-heritage contexts were excluded, while those exploring its role in structural analysis or conservation within historical sites were included. This table clarifies the methodical filtering process, enhancing transparency in the study selection. The literature search strategy aimed for inclusivity, extending beyond author-specified keywords to include titles and abstracts and expanding to all document fields in further searches. This approach is intended to maximize relevant paper inclusion, addressed by thorough manual screening. The search strategy was designed with precision, utilizing a strategic mix of key terms specifically focusing on DTs, BIM, laser scanning, machine learning, and heritage buildings within the AEC (architecture, engineering, and construction) industry. Keywords employed in the search included "DT", "BIM integration", "Laser Scanning in Construction", "Machine Learning in Heritage Conservation", "Heritage Building Restoration", "Digital Preservation", "3D Modelling in Heritage Buildings", "BIM for Heritage Conservation", "DT Applications in Historic Buildings", "Machine Learning for Architectural Analysis", and "Laser Scanning for Structural Analysis". Boolean operators "AND" and "OR" were strategically used to narrow the search to documents that contain essential concepts jointly and to expand the search to cover a wide range of related subjects.

To conduct a thorough and impartial review, a tripartite analysis strategy combining quantitative [20] and qualitative [21] methods was adopted. This approach is instrumental in reducing biases and subjective interpretations, promoting a balanced and extensive comprehension of the subject. Echoing previous research recommendations, this method underscores the benefits of integrating different analytical techniques for a nuanced understanding of topics. The analysis began with a bibliometric review of the 186 articles fitting the criteria, evaluating aspects such as publication frequency, contributing countries, and keyword trends. The next phase involved a qualitative assessment of article contents, organizing the literature by construction phases and DT applications within those contexts.

In analyzing the selected documents for this study, we adopted a methodological approach that utilizes JSON (JavaScript Object Notation) data formats and Python programming to process data extracted from the literature. This digital method facilitated the efficient management of the extensive information from 186 documents in the primary dataset. Python and JSON integration improved the precision and speed of the quantitative analysis and enhanced the depth of the qualitative review. Through tailored scripts and algorithms, the research integrates data from diverse sources, blending existing knowledge with fresh insights.

In step 4, as part of the in-depth study on DT's effectiveness for heritage buildings, a detailed survey was developed to gather expert opinions on various aspects of DT's application. The survey, designed with questions on a Likert scale from 1 to 5 in addition to open-ended questions, aimed to evaluate DT's effectiveness in heritage buildings. A wide range of architecture, engineering, and construction (AEC) professionals, including architects, engineers, and project managers, were invited to participate through professional networks and social media, ensuring a diverse and informed set of responses. Experts, chosen for their experience and engagement with heritage buildings, were given access to an online survey platform (SurveyXact [22]), emphasizing ease of use and confidentiality. The survey was available for two weeks, with reminders sent to encourage participation and highlight the value of their insights for advancing DT's understanding of heritage buildings. Participants were informed through the consent form about the purpose of the research, how their data would be used, and the steps taken to ensure confidentiality. They were assured that all findings would be reported in aggregate form, without any possibility of individual identification. Table 2 shows the profile and roles of the experts who answered the survey, as that was asked throughout the survey. Table 2 details the profiles and expertise of the 23 survey participants, including their roles in conservation and specific technologies used. The table highlights diversity among participants, with professionals from architecture, engineering, and conservation disciplines contributing insights on DT, BIM, and laser scanning for heritage building preservation. For example, the eight architects and architectural historians primarily focus on documentation and restoration, using BIM and laser scanning. This diverse representation ensures that the survey responses reflect a broad spectrum of perspectives on the applicability of these technologies in heritage conservation.

Table 2. Expert profiles based on the 23 participants in the survey.

Expert Profile	Role in Conservation	Technologies Used	Number of Experts
Architects and Architectural Historians	Restoration, preservation, and documentation of heritage buildings	BIM and Laser Scanning	8
Civil and Structural Engineers	Assessing the physical condition of heritage structures	Machine Learning and Laser Scanning	5
Conservation Specialists	Conservation and restoration of heritage sites	DTs	6
Project Managers	Overseeing conservation projects	Various Technological Tools	4

After the survey closed, responses from the 23 experts (originally 150 were invited, as in Table 3) were analyzed to calculate average effectiveness ratings for each DT application area. Table 3 presents the survey's engagement metrics, showing that, out of 150 invited experts, 23 responded, resulting in a completion rate of 15.3%. While the sample size may limit the generalizability of the findings, the participants' collective expertise provides valuable insights into the effectiveness of DT, laser scanning, machine learning, and BIM in heritage conservation. This table underscores the survey's reach and highlights potential areas for increasing engagement in future studies. The analysis of survey responses was conducted using a combination of statistical and qualitative methods using Python [23]. Thematic analysis [24] was applied to open-ended responses to extract common themes related to the benefits, challenges, and applications of the technologies in heritage conservation.

Table 3. Demonstrates the overall engagement and response rate for the survey.

Total Invited	Responses Received	Completion Rate
150	23	15.3%

The survey comprised a series of structured questions designed to elicit both quantitative and qualitative responses from the experts. The questions were divided into sections, each focusing on one of the emerging technologies (laser scanning, machine learning, BIM, and DTs) in the context of heritage building conservation. Examples of the questions include the following:

1. Quantitative (Likert scale) Questions:
    - "Rate the effectiveness of laser scanning in capturing accurate architectural details of heritage buildings (1–5)."
    - "How effective do you find machine learning algorithms in predicting structural vulnerabilities in heritage buildings (1–5)?"
    - "Evaluate the utility of BIM in the planning and execution of heritage conservation projects (1–5)."
    - "Assess the impact of DTs in enhancing the maintenance and preservation of heritage sites (1–5)."
2. Qualitative (open-ended) Questions:
    - "Describe a project where you utilized laser scanning for heritage conservation. What were the key benefits and challenges?"
    - "In your experience, how does machine learning contribute to the conservation of heritage buildings? Please provide examples."
    - "Discuss how BIM has changed the approach to heritage building conservation within your projects."
    - "Share your insights on the future potential of DTs in heritage conservation."

One notable limitation of this survey lies in its relatively small sample size of 23 experts, which, while providing valuable insights, may not capture the full spectrum of opinions and experiences within the broader field of heritage conservation. The extent to which these findings can be generalized to all professionals working with emerging technologies in heritage building conservation is therefore constrained. Moreover, the diversity of the respondents, in terms of their geographic locations, cultural backgrounds, and the specific nature of their work within the conservation domain, might not be adequately represented.

Furthermore, the survey's focus on specific technologies—laser scanning, machine learning, BIM, and DTs—while necessary for depth of analysis may overlook the interplay between these technologies and other traditional or emerging tools in heritage conservation. The rapid pace of technological advancement means that the relevance of the survey findings could diminish over time, as new tools emerge, and existing ones evolve. Additionally, the reliance on self-reported effectiveness ratings and experiences introduces subjective biases that could influence the overall interpretation of the technologies' impact. These limitations underscore the need for ongoing research, incorporating larger and more diverse samples, and a dynamic approach to technology evaluation in the conservation field.

This step was followed by an in-depth examination of the selected literature, extracting and preprocessing data, and then analyzing it with Python for a detailed and computational understanding of the research landscape. The last step synthesizes the literature analysis findings, summarizing key outcomes, pinpointing research gaps, and outlining future research directions.

3. Results

In this section, the paper explores the reviewed findings of DT for heritage buildings. The investigation, propelled by the ambition to bridge the gap identified in the previous literature, employs a combined methodological framework that encompasses both bibliometric and qualitative content analyses. This dual approach enables us to chart the progression, delineate the current landscape, and unveil the burgeoning potential of DT technology for heritage conservation.

3.1. Bibliometric Analysis

This section presents a bibliometric analysis of literature in the field of cultural heritage preservation, mapping the evolution and current state of research. Through an examination of publication trends over the years, this analysis identifies the most influential journals, prolific authors, and leading countries contributing to the discourse. The study of publication counts per year within top journals offers insights into the scholarly community's focus areas, while the distribution of articles across countries highlights global participation and interest. Additionally, a conceptual map synthesizes major themes and research gaps, guiding future inquiries in cultural heritage preservation.

3.1.1. Publication Trends in Cultural Heritage Preservation

The initial subsection of the bibliometric study begins by analyzing the trends in publications from 1996 to 2024, as depicted in Figure 3. This graph illustrates the growth in the number of publications over the years, reflecting a burgeoning interest and expanding research in the domain of cultural heritage preservation. The period from the early 2000s shows a gradual increase in output, with a significant rise observed in the last decade, indicating intensified scholarly activity and a potential increase in the field's prioritization. The peak in publication numbers around the early 2020s suggests a response to global cultural trends or technological advancements that may have facilitated more extensive research and discourse. Figure 3 captures the steady rise in publications from 1996 through 2024, highlighting surges over the last decade. This increase is indicative of growing scholarly and societal interest, with peaks in the early 2020s possibly aligned with advancements in conservation technologies or heightened global attention on cultural heritage. These trends suggest a potential shift in prioritizing research that integrates heritage preservation with modern, sustainable practices.

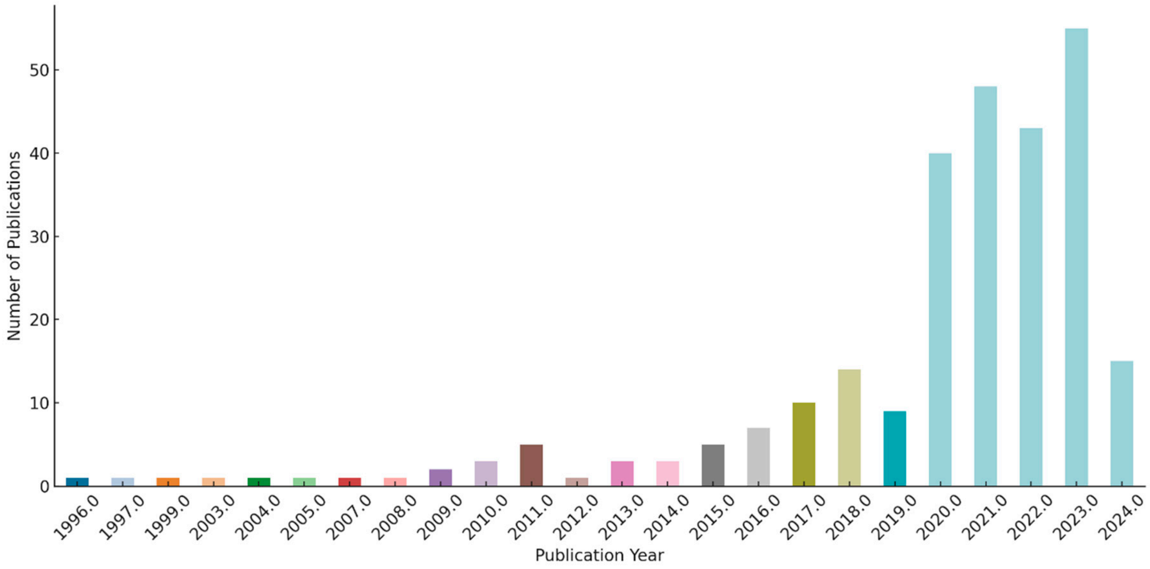

Figure 3. Publication trends over years.

3.1.2. Leading Journals, Authors, and Countries in Cultural Heritage Preservation Research

Continuing the bibliometric investigation, Figure 4 showcases the leading academic journals contributing to the discourse on cultural heritage preservation. Figure 4 ranks the top 10 journals publishing on cultural heritage preservation, with *Sustainability* leading, reflecting a cross-disciplinary approach focused on sustainable conservation. Figure 5 further breaks down publication patterns within these journals from 2015 to 2024, illustrating how contributions fluctuate with emerging conservation technologies or evolving academic focus areas. Significant spikes may align with breakthroughs in preservation technology or policy changes, highlighting how scholarly priorities adapt over time. Figure 4 bar graph enumerates the top 10 journals by the number of articles published. The *Sustainability* journal leads, indicative of a strong interdisciplinary focus on sustainable practices in heritage conservation. This is followed by *Automation in Construction* and the *Journal of Cultural Heritage*, highlighting the technological and cultural facets of the field, respectively. *Energies* and other journals listed reveal the multifaceted nature of research, spanning areas such as energy efficiency in heritage buildings and advanced remote sensing techniques.

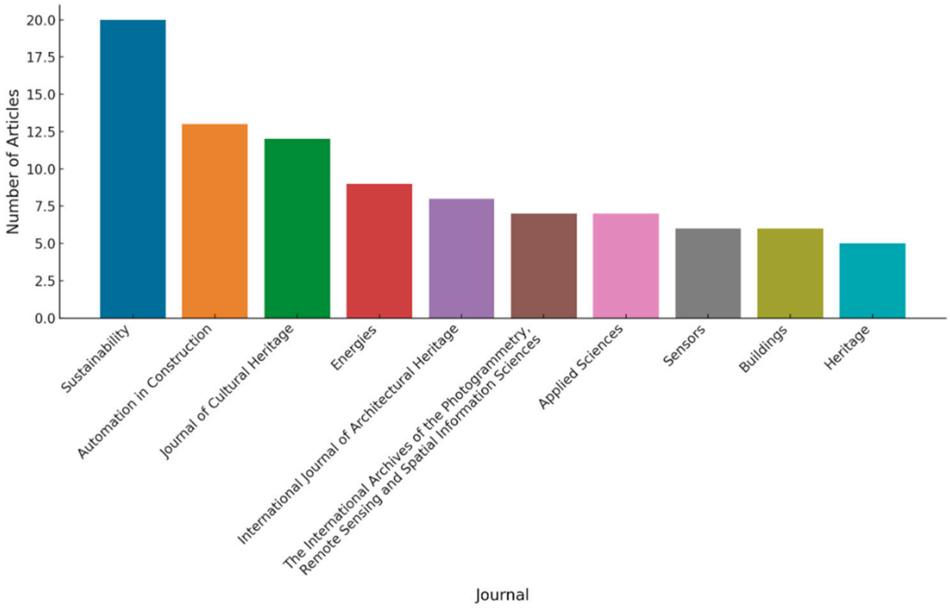

Figure 4. Top 10 journals.

Investigating deeper into the specifics, Figure 5 dissects the annual publication counts per year for the top 10 journals identified previously. This stacked bar chart reveals the dynamic contribution patterns of each journal over time, illustrating fluctuations and growth trends in published articles from 2015 to 2024. It highlights periods of increased research activity and potential shifts in the thematic emphasis of each journal. For instance, notable spikes in article counts for certain journals may correlate with key technological advancements or policy changes in the field of heritage preservation. This temporal analysis offers an insightful perspective on how the focus of research within each journal evolves and responds to the field's emerging challenges and opportunities.

Moreover, Figure 6 enumerates the top 10 authors who have made significant scholarly contributions to the field of cultural heritage preservation. The horizontal bar chart highlights the number of articles each author has published, serving as an indicator of their impact and activity within this research community. The evaluation of the top authors in Figure 6 is based on a comprehensive analysis of their scholarly productivity and the impact of their research within the field of cultural heritage preservation. This assessment considers both the number of articles published by each author and the citation metrics associated with their work, which collectively serve as indicators of their influence and activity in the research community. By incorporating both productivity and citation impact, the analysis provides a clearer understanding of the contributions made by these researchers, highlighting their significance in advancing knowledge and practices in cultural heritage preservation. Figure 6 showcases the most prolific authors in the field, providing a benchmark for influential voices shaping research trends and guiding conservation practices. This chart not only signals the field's active contributors but also underscores the collaborative, cumulative effort driving innovation in heritage preservation. The authors listed have contributed to advancing knowledge and understanding in this domain, with the chart reflecting the extent of each individual's academic engagement. Their collective work forms the backbone of current trends and developments, influencing both the academic and practical aspects of heritage preservation.

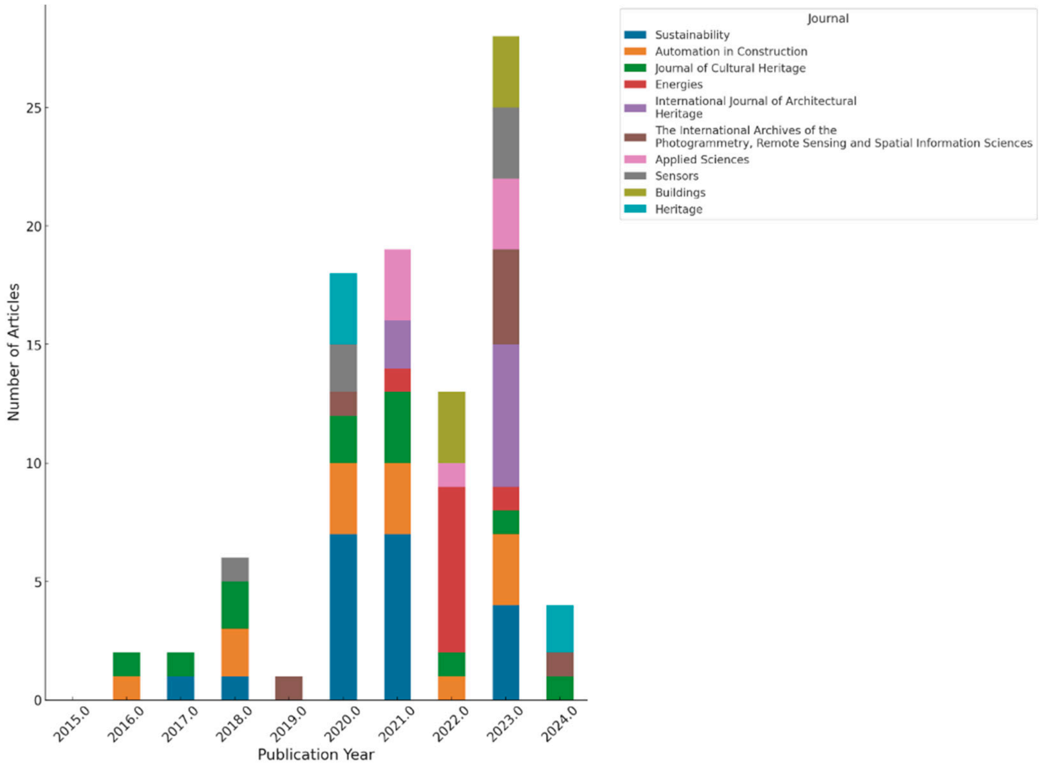

Figure 5. Publication counts per year for the top 10 journals.

Furthermore, Figure 7 provides a visual distribution of the percentage of articles contributed by the top five countries in the field of cultural heritage preservation. The gradient-colored bar chart delineates the proportionate academic output, with China leading significantly, followed by Italy, the United Kingdom, Spain, and India. These statistics reveal the geographical diversity in research and the varying degrees of emphasis placed on cultural heritage preservation across different nations. This information is critical for understanding the global landscape of cultural heritage research, including the identification of regions with high research outputs and potential collaborative opportunities. Figure 7, which outlines the percentage of articles by the top five contributing countries, reveals China's substantial output, followed by Italy, the UK, Spain, and India. This geographic distribution highlights the emphasis placed on heritage preservation in these countries, likely driven by each nation's wealth of heritage sites and their vested interest in preservation. This insight into global academic participation signals potential international collaboration opportunities in addressing shared conservation challenges.

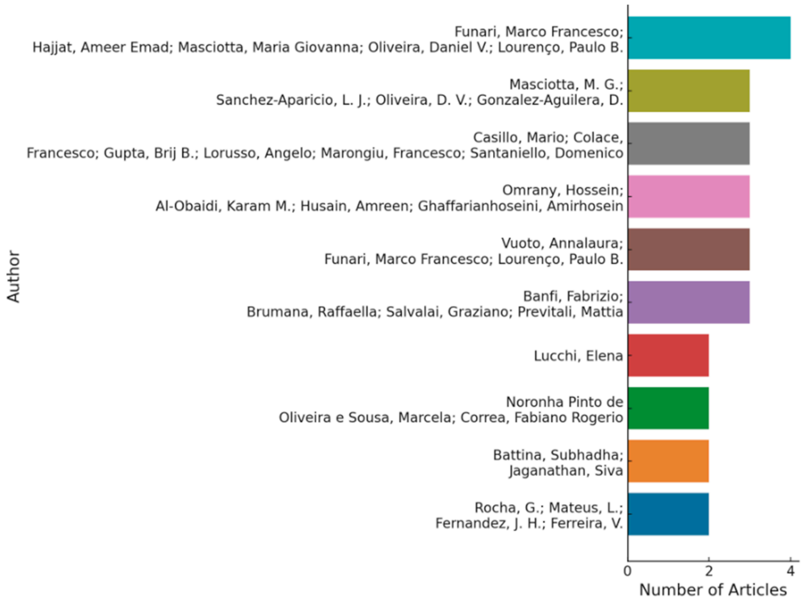

Figure 6. Top 10 authors based on [12,14,18,19,25–30].

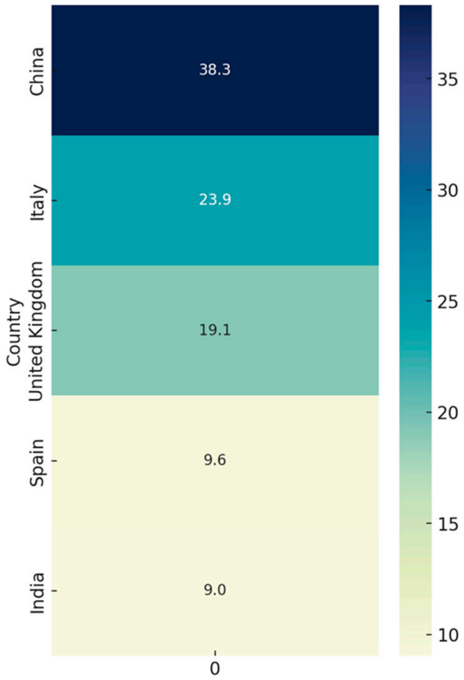

Figure 7. Percentage of articles per top 5 countries.

3.1.3. Research Gaps in Heritage Preservation

Based on the bibliometric analysis, the conceptual map (Figure 8) captures the landscape of current research gaps in cultural heritage preservation, pointing to areas such as advanced digital documentation techniques, the integration of digital twin technology with building information modeling, and the ethical dimensions of technological application. Highlighting the synergy between various advanced methodologies, it underscores the need for a multidisciplinary approach to conservation practices. Figure 8 visually synthesizes key research gaps within the domain, including digital documentation, digital twin integration with building information modeling (BIM), and ethical considerations in technological applications. This map emphasizes the necessity for interdisciplinary solutions and provides direction for research that could close these gaps, integrating technological advancement with traditional conservation practices. The importance of energy efficiency, the application of IoT in preventive conservation, and the potential of non-destructive technologies in the restoration of cultural heritage also feature prominently.

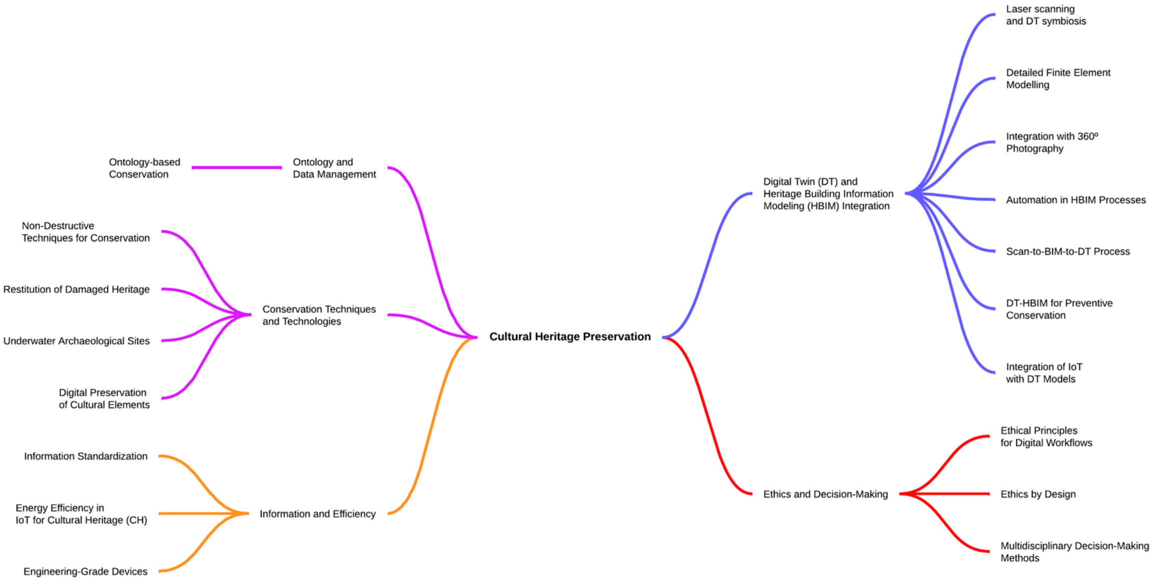

Figure 8. Conceptual map for cultural heritage preservation, outlining the key research gaps based on the review documents.

The subsequent sections will offer a comprehensive analysis of these identified gaps. Through in-depth discussions, each theme will be explored, situating current research within a broader context and proposing directions for future inquiries.

3.2. Content Analysis

The bibliometric analysis enabled us to identify research gaps in the field of heritage conservation, as illustrated in Figure 9. These gaps are categorized into three main areas: expert insights and professional perspectives, emerging technologies synthesis, and bridging disciplines. The paper will explore each category in greater detail in the subsequent sections.

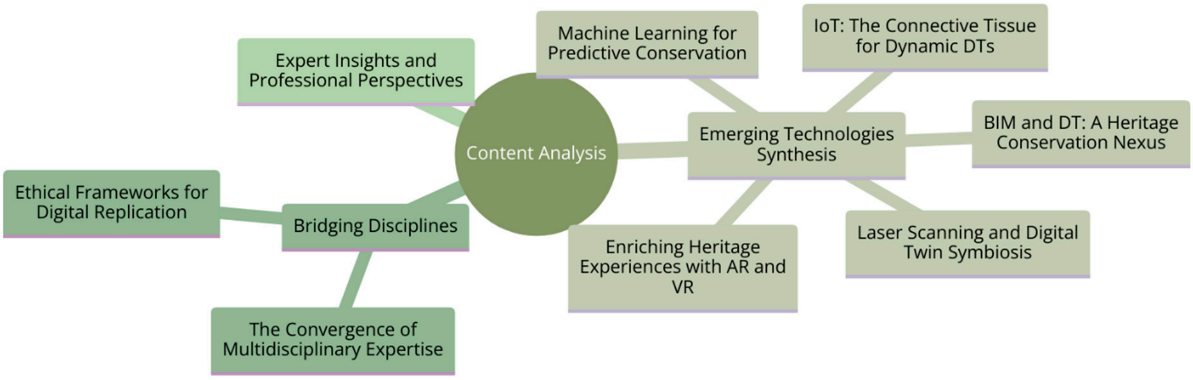

Figure 9. Mindmap of "Content Analysis", showcasing the hierarchical structure of expert insights, emerging technologies, and interdisciplinary bridges within the context of heritage conservation and digital replication technologies.

Expert Insights and Professional Perspectives

The survey conducted among professionals involved in heritage conservation revealed insightful data on the perceived effectiveness of DT technology across various conservation activities. Participants from diverse disciplines such as architecture, engineering, and conservation were asked to rate the effectiveness of DT on a Likert scale from one (not effective) to five (highly effective) in areas such as structural analysis, historical research, restoration planning, and visitor engagement.

As can be seen in Figure 10, the survey results were compiled into a statistical overview, which highlighted a strong consensus on the effectiveness of DT in structural analysis, with the majority rating it between four and five. Figures 9 and 10 dive into expert perspectives, showing DT technology's perceived effectiveness across fields like structural analysis, restoration planning, and visitor engagement. These findings suggest that DT's strongest impact lies in structural analysis, while further research and collaboration are needed to improve its efficacy in historical research and public engagement. This suggests a high level of confidence in DT's ability to provide precise and actionable insights into the structural health of heritage buildings. However, in the field of historical research, DT was rated slightly lower, averaging around 3.5, indicating moderate to high effectiveness. The technology's capability to visualize and simulate historical buildings and contexts, although appreciated, pointed to a need for more interdisciplinary work to increase its usefulness for historians. For restoration planning, DT received an effectiveness rating that closely mirrored its reception in structural analysis, with many professionals emphasizing its ability to accurately assess the condition of buildings and facilitate the planning of conservation interventions. Visitor engagement was the area with the broadest range of responses, averaging a three. This variance could be attributed to the emergent state of applying DT in public engagement contexts. Professionals acknowledged the potential of DT to revolutionize visitor experiences through interactive and immersive storytelling but also recognized the current limitations in widespread implementation.

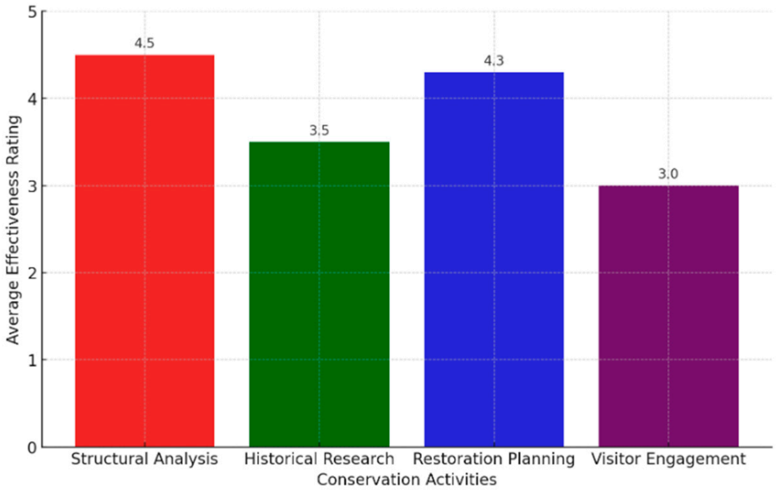

Figure 10. The effectiveness of DT through different fields related to heritage buildings.

At the outset in Figure 11, with 1–5 years of experience, ratings oscillate dramatically between five (highly effective) and lower ratings like two (slightly effective), suggesting a divided opinion among newcomers to the field. This variability reflects differing initial expectations of DT's capabilities or varied exposure to DT in practical scenarios. Figures 11 and 12 explore expert ratings on technologies such as laser scanning, BIM, and machine learning. High ratings for laser scanning and BIM reflect their utility in creating detailed, accessible models of heritage sites, essential for preservation. However, Figure 12's variability in machine learning ratings signals ongoing skepticism and a need for refinement before AI-driven approaches become mainstream in heritage conservation.

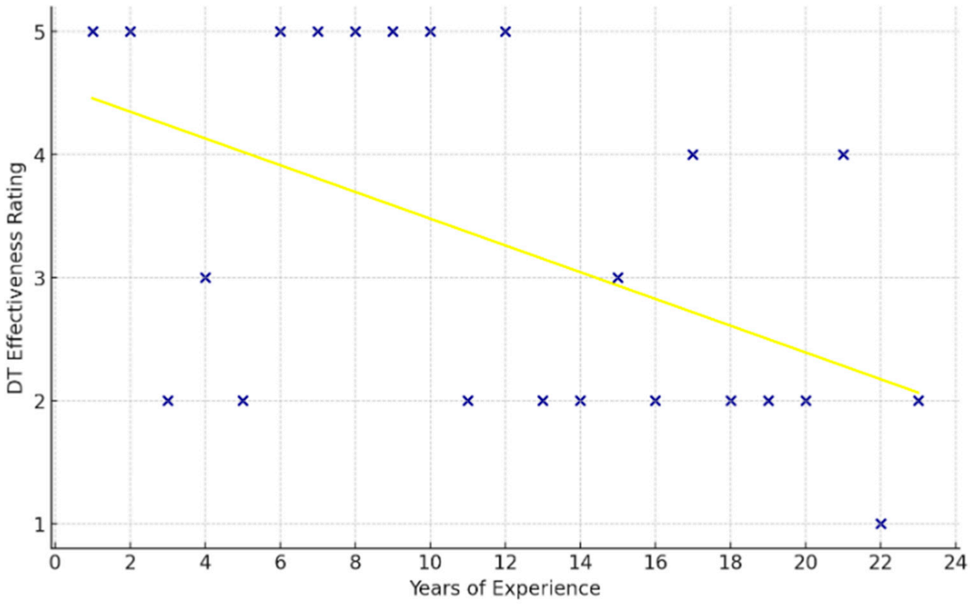

Figure 11. The relation between years of experience and DT effectiveness rating.

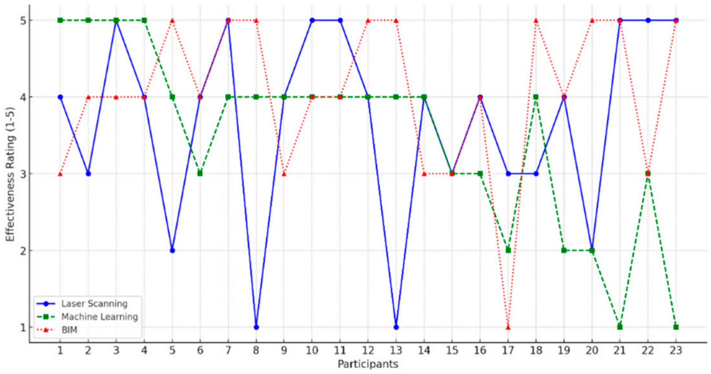

Figure 12. The effectiveness ratings given by various participants for three different technologies: laser scanning (blue), machine learning (green), and BIM (red), in the context of heritage conservation.

Interestingly, there are instances of high ratings [5] even among participants with 6–15 years of experience, indicating that some mid-career professionals still find significant value in DT applications. However, the general trend still shows a movement towards lower ratings as experience increases, with more ratings clustering around two and occasional ones (not effective) and fours appearing towards the tail end of the experience spectrum.

According to Figure 12, experts generally view both laser scanning and BIM as helpful technologies in the conservation of heritage buildings, as indicated by the high ratings clustered towards the top of the scale. Laser scanning is perceived as particularly beneficial, likely due to its ability to capture detailed and accurate representations of existing structures, which is crucial for any restoration or conservation work. Precise 3D models created through laser scanning are invaluable for architects and conservators in understanding the condition of heritage buildings and planning appropriate interventions. BIM also receives high effectiveness ratings, reflecting its comprehensive approach to modeling and managing building information. Its utility for heritage buildings may stem from its capacity to centralize and streamline data, which aids in the planning and execution required for conservation projects. However, the occasional dips in ratings for both technologies suggest some concerns among experts. These could be due to the complexity of integrating these high-tech tools into traditional conservation processes, the need for specialized training, or the high costs associated with their implementation.

Machine learning exhibits the most significant variability in effectiveness ratings, indicating mixed opinions among experts. High ratings may be attributed to the potential of machine learning to analyze large datasets, predict structural weaknesses, and optimize maintenance schedules. Nevertheless, the lower ratings and variability suggest skepticism or concern, which could be due to several factors such as the current immaturity of AI applications in heritage contexts, a lack of reliable data to train algorithms, or challenges in interpreting machine learning outputs in a way that is meaningful for heritage conservation. The concerns reflected in the variability of ratings highlight the necessity for ongoing research and development, better integration of these technologies into conservation workflows, and the importance of addressing any potential barriers to their effective use, such as ensuring data quality, refining AI models for the specific nuances of heritage buildings, and fostering a better understanding of these tools among conservation professionals.

Regarding the open-ended questions, experts utilizing laser scanning for heritage conservation projects often highlight its precision and ability to capture detailed measurements of complex structures as key benefits. This technology allows for the creation of accurate 3D models of heritage sites, enabling conservators to analyze the architectural features and structural integrity without physically interacting with the fragile structures, thus minimizing the risk of damage. However, challenges include the high cost of equipment and the need for specialized training to interpret the data effectively. Additionally, managing the massive volumes of data generated and ensuring its long-term storage and accessibility remain significant concerns.

In the context of machine learning's contribution to heritage building conservation, professionals discuss its role in analyzing vast datasets derived from various sources, such as laser scans, photographs, and environmental sensors. Machine learning algorithms can identify patterns and anomalies that would be impossible for humans to detect manually, such as predicting areas at risk of deterioration. Examples include the use of machine learning to monitor changes over time in the structural health of buildings or to analyze historical climate data to predict environmental conditions that could affect heritage sites. The integration of machine learning accelerates decision-making processes and enhances predictive maintenance strategies, though it requires substantial datasets and interdisciplinary collaboration to train effective models.

Regarding BIM's impact on heritage conservation, experts note how BIM facilitates a more integrated and holistic approach to the management and preservation of heritage buildings. BIM enables stakeholders to collaborate more effectively and make informed decisions by creating detailed digital representations that include geometric dimensions and historical, material, and condition-related information. This has transformed the conservation process, making it more dynamic and responsive to the needs of heritage buildings. Challenges include the adaptation of BIM tools to accommodate the unique aspects of heritage structures and the need for extensive documentation to populate BIM models with accurate data.

Furthermore, when discussing the potential of DTs in heritage conservation, experts envision a future where digital replicas of heritage sites are used for various purposes, including virtual tourism, disaster risk assessment, and the monitoring of structural health in real-time. DTs can offer immersive experiences that allow for the exploration of heritage sites from anywhere in the world, potentially democratizing access to cultural heritage and generating public interest and support for conservation efforts. They also hold the promise of enabling more proactive conservation strategies by simulating the impact of environmental changes and human activities on heritage sites. The challenges lie in creating accurate and comprehensive DTs that are updated in real-time and ensuring that the technology is accessible and beneficial to all stakeholders involved in heritage conservation. Figure 13 illustrates the frequency of reported benefits and challenges associated with four prominent technologies—laser scanning, machine learning, BIM, and digital twins (DTs)—in heritage conservation. This bar chart highlights the significant advantages each technology offers, such as increased precision and enhanced predictive analytics, as well as key obstacles, including financial demands and data management complexities. By visualizing expert insights, this figure underscores the multifaceted impact of emerging technologies and the areas where additional support and refinement are needed to optimize their application in heritage conservation.

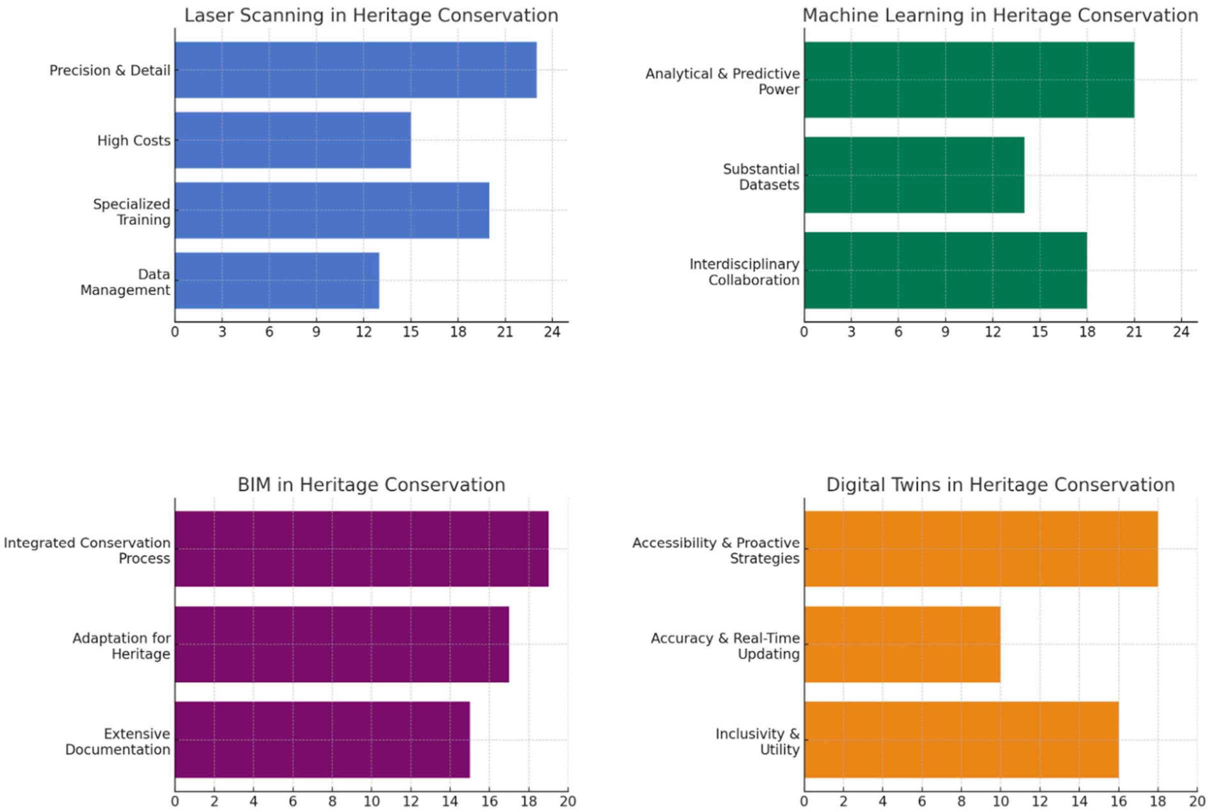

Figure 13. Visualization of the frequency of benefits and challenges associated with four key technologies—laser scanning, machine learning, building information modeling (BIM), and digital twins (DTs)—in heritage conservation, based on expert insights.

Figure 13 results from the thematic analysis of the open-ended questions and responses from experts in the field of heritage conservation, showcasing a detailed exploration into the integration of advanced technologies. Through this analysis, the figure presents a series of bar charts that illustrate the frequency of both benefits and challenges as highlighted across four key technological areas: laser scanning, machine learning, building information modeling (BIM), and digital twins (DTs). This visualization shows the significant advantages such technologies offer (like increased precision, enhanced predictive analytics, and improved collaborative processes) and brings to light the various obstacles encountered, including financial burdens, complexities in data management, and the need for specialized expertise.

3.3. Emerging Technology Synthesis for Heritage Conservation

The integration of emerging technologies into heritage conservation represents a pivotal shift towards more informed, precise, and sustainable preservation practices. This section explores the convergence of DTs, laser scanning, the IoT, machine learning, and BIM within the context of safeguarding cultural heritage. This section explores how these technologies, through a synergistic application, offer the potential to revolutionize the field by enhancing documentation accuracy, enabling real-time monitoring, facilitating predictive maintenance, and ensuring the participatory involvement of stakeholders.

3.3.1. Laser Scanning and DT Symbiosis

The convergence of laser scanning and DTs represents a frontier in heritage conservation, offering a digital symbiosis that could revolutionize how we preserve historical structures [31]. This fusion enables an unparalleled level of detail and accuracy in modeling heritage sites, ensuring that every nuance is captured and maintained for future generations [32]. However, the synergy between these technologies also presents unique challenges and research gaps that necessitate careful investigation and innovative solutions to fully harness their combined potential [33]. Table 4 provides an overview of the existing research gaps and outlines critical areas where further development and standardization are necessary to enhance the effectiveness of technology in preserving heritage buildings. Table 4 documents specific research gaps, focusing on areas like standardized protocols for data integration, hybrid data processing, and automation in HBIM processes. Addressing these gaps could streamline technological integration, fostering a more cohesive and efficient conservation workflow.

Table 4. Identified research gaps in enhancing laser scanning and digital twin integration for heritage conservation.

Research Gap	Description	References
Information Standardization	The lack of standardized information protocols for integrating laser scanning data with DTs.	[34,35]
Detailed Finite Element Modeling	The need for detailed finite element models that accurately represent the structural aspects of heritage buildings from laser scanning data.	[25]
Integration with 360° Photography	Challenges in enriching DTs with 360° photography to capture the essence and details of heritage buildings.	[12]
Automation in HBIM Processes	The necessity for automated processes in Heritage Building Information Modeling (HBIM) to streamline data conversion and management.	[18]
Hybrid Processing of Laser Scanning Data	The development of unified technologies for processing combined laser scanning and photography data for historical buildings.	[36]

3.3.2. Information Standardization

The adoption of DT technology in the construction sector, especially for heritage buildings, is significantly impeded by the absence of uniform information protocols [26]. Heritage buildings, with their unique historical contexts and conservation needs, require meticulously detailed data for their DTs to function effectively [29]. However, the current landscape of data management lacks a cohesive framework, leading to disparate data formats and standards that come from different types of laser scanners as well as sensors. This inconsistency complicates the integration of physical and digital spaces, as DTs rely on precise, real-time data to mirror and predict the physical state of a building accurately [37].

Furthermore, the management of heritage buildings involves various stakeholders, including conservators, architects, and engineers, each contributing different types of data [38]. The absence of standardized information protocols makes it challenging to aggregate and synchronize these data effectively, thereby limiting the potential of DTs to facilitate predictive maintenance, energy efficiency optimization, and structural health monitoring [39]. As a result, the gap between the real and digital representations of heritage buildings widens, undermining the utility of DTs in preserving and enhancing the value of historical structures [40].

Addressing this challenge necessitates a concerted effort to develop and implement industry-wide data standards that cater to the unique requirements of heritage building management [41]. Such standards must encompass the technical aspects of data formats, interoperability, and the understanding of historical significance and conservation principles that are crucial for heritage buildings [42]. Only through such standardization can the construction sector fully harness the power of DTs, ensuring that these technological marvels serve as effective tools in the stewardship of architectural heritage [43].

In Figure 14, the paper proposes a conceptual framework for integrating various data formats (including laser scanning data) and stakeholder inputs into a unified digital representation. The framework employs a knowledge graph, which standardizes data sources and promotes interoperability among stakeholders, allowing heritage buildings' complex data to be unified into a cohesive digital representation. This integrated approach facilitates efficient data handling and enhances the precision of digital twins (DTs) in reflecting the current condition of heritage buildings. The process begins with stakeholders, such as conservators, architects, and engineers, who provide data that is formatted appropriately. These data, alongside the articulated conservation needs, feed into the development of standardization protocols using what is called a knowledge graph [44]. These protocols are essential for ensuring that the data from diverse sources and formats can be utilized cohesively. The standardized data then informs the creation of interoperability frameworks, which allow for the different data types and systems to work together effectively. The ultimate goal of this workflow is to culminate in a unified digital representation, presumably of a building or a set of buildings, which integrates all stakeholder inputs and conservation needs into a single cohesive model.

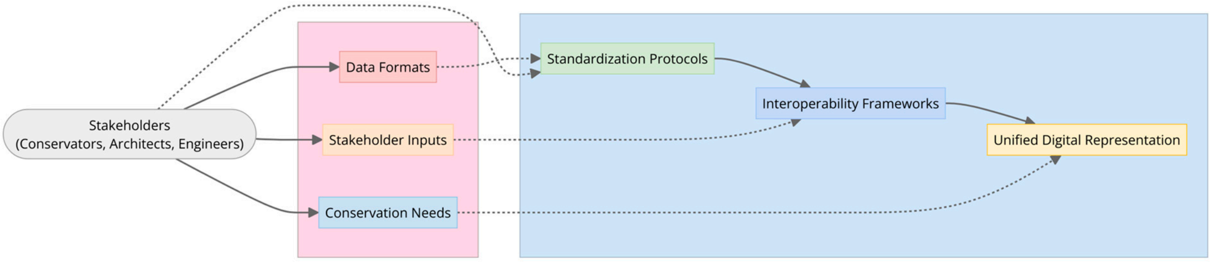

Figure 14. Proposed workflow for integrating stakeholder inputs into a unified digital representation for conservation.

To clarify more, the knowledge graph serves as a sophisticated framework for integrating various types of data, including that from laser scanning, into a comprehensive digital representation [45]. As a specific example, a knowledge graph that incorporates the CIDOC (the International Committee for Documentation Conceptual Reference Model, which is an ontological framework designed to facilitate the integration, mediation, and interchange of heterogeneous cultural heritage information) and Conceptual Reference Model (CRM) protocol can be considered [46]. CIDOC CRM is designed to enable information integration for cultural heritage data and provides a standardized way to describe the implicit and explicit concepts and relationships used in cultural heritage documentation [47].

Laser scanning data, which offers high-fidelity three-dimensional representations of heritage sites, can be encoded within a knowledge graph using CIDOC CRM to create nodes that represent the physical structure of a site [48]. These nodes could be linked to other nodes representing historical information, conservation requirements, and stakeholder contributions [49]. This approach facilitates the construction of a comprehensive knowledge graph that aggregates all essential documentation from numerous laser-scanned sites into a singular, cohesive repository [50].

3.3.3. Detailed Finite Element Modeling

The digitalization of historic masonry buildings into accurate 3D finite element models (FEM) represents a significant challenge due to their unique architectural features and the heterogeneity of their materials [25]. Traditional methods often fall short in capturing the complex geometries and material inconsistencies inherent in these structures [51]. This gap is notably bridged by the adoption of a parametric Scan-to-FEM approach (Figure 15), which leverages advanced scanning technologies to map the intricate details of masonry buildings. Figure 15 demonstrates the application of the parametric Scan-to-FEM approach in preserving heritage buildings, using the case study of St. Torcato Church. The figure showcases the intricate digital capture of architectural details through point cloud views, followed by a color-coded finite element model (FEM) that visualizes structural analysis outcomes. This model serves as a valuable resource for identifying structural vulnerabilities and assessing potential restoration interventions, a critical step in the preventive conservation of historic masonry buildings. This technique allows for the transformation of detailed scans into parametric models that can be directly used for structural analysis and simulation purposes.

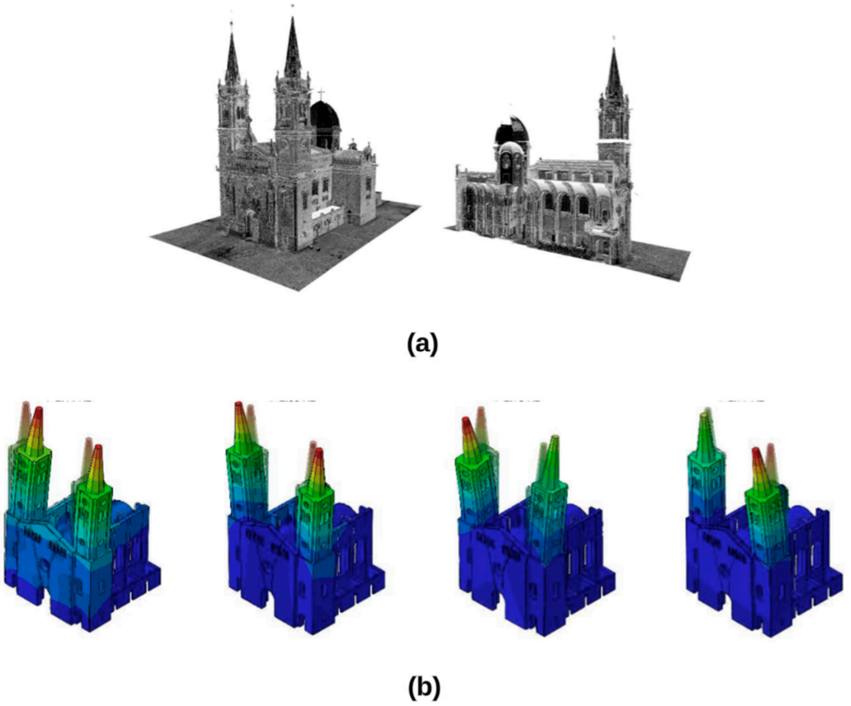

Figure 15. Integrated digital assessment of St. Torcato Church. (**a**) Presents two-point cloud views of St. Torcato Church, illustrating the detailed digital capture of the architectural features. (**b**) Displays finite element modeling (FEM) of the church, color-coded to indicate structural analysis outcomes across multiple viewpoints. The figure is reproduced from [25].

Despite its advantages, the current application of the parametric Scan-to-FEM approach reveals a critical gap in its capability to efficiently process and convert the extensive data collected from scans into models that accurately reflect the structural behavior of historic buildings [25]. This process often requires significant manual intervention to correct inaccuracies and to input material properties that are not directly discernible from scans [52]. Furthermore, the method's effectiveness in predicting future scenarios and assessing the potential impact of structural interventions remains limited by its current reliance on generalized assumptions about material characteristics and behavior [53].

Addressing this gap necessitates further research and development towards more sophisticated algorithms that can automate the identification and classification of materials and structural damages from scan data [54]. Additionally, the integration of machine learning techniques could enhance the model's predictive accuracy by enabling it to learn from a database of documented interventions and their outcomes [55]. Ultimately, advancing the parametric Scan-to-FEM approach promises to significantly improve the preservation and restoration efforts of historic masonry buildings by providing a more reliable foundation for decision-making regarding structural interventions [25].

3.3.4. Integration with 360° Photography

The fusion of laser scanning and 360° photography stands out as a pivotal advancement in the field of digital preservation, particularly for heritage buildings [12]. Figure 16 highlights various advanced imaging tools employed in heritage conservation, including terrestrial laser scanners, aerial scanning devices, and 360° photography systems. These tools offer a comprehensive suite of data collection capabilities, enabling conservation teams to capture high-resolution 3D models alongside panoramic photographic detail. By combining precise geometric data with rich visual context, these technologies significantly enhance the accuracy and effectiveness of digital conservation models. While laser scanning offers a robust foundation for capturing the geometric intricacies of structures, the incorporation of 360° photography (Figure 16) is essential for adding a layer of visual and textural detail that is often missed by traditional scanning techniques. This combination results in enriched digital models that facilitate a comprehensive understanding of the physical condition of heritage sites and significantly support the development of preventive conservation plans.

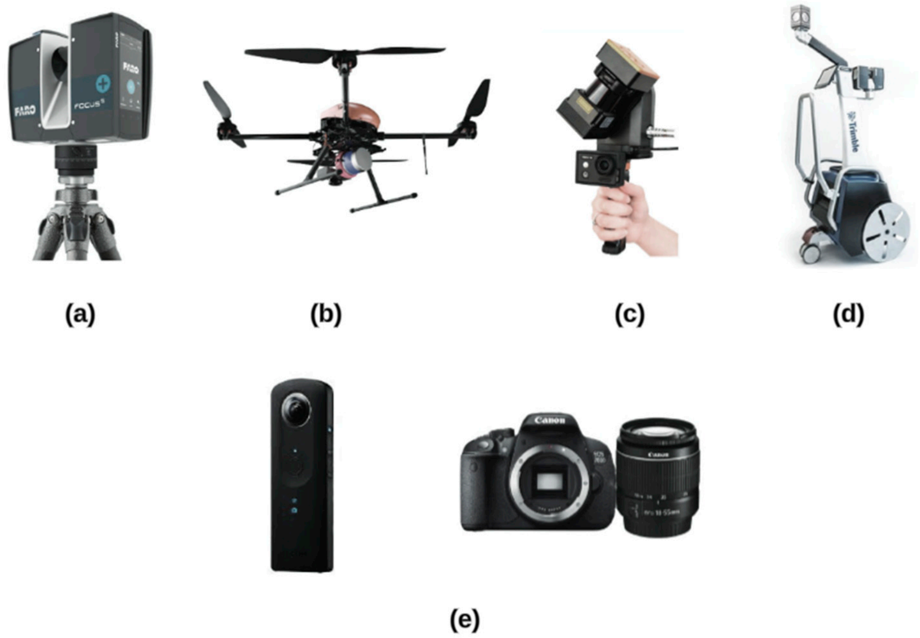

Figure 16. Advanced imaging equipment for digital heritage conservation. Top row showcases laser scanning systems: (**a**) a FARO Focus terrestrial laser scanner for high-precision 3D modeling; and (**b**) an unmanned aerial vehicle (UAV) equipped for aerial scanning, providing expansive site coverage. Top and bottom rows illustrate portable mobile mapping systems: (**c**) a handheld device for agile and flexible data collection; and (**d**) a trolley system for steady and systematic scanning in larger areas. The final set (**e**) presents panoramic photography systems: on the left, a dual fisheye lens sensor device for 360-degree imaging, and on the right, a DSLR camera with a fisheye lens for wide-angle shots. Based on [12].

While there have historically been challenges in merging geometric data with high-resolution photographic images [56]. Recent publications indicate that effective methods for integrating laser scanner data with photographic input now exist [57]. Therefore, it is important to acknowledge these developments and recognize that the integration process is evolving with the availability of new techniques and technologies [12]. However, this challenge stems from the difficulty in aligning detailed photographic textures with their corresponding 3D models, a process that requires precision to ensure the accurate representation of the building's features [58]. Moreover, there is a critical need for advanced tools that can handle the vast amounts of data generated from both scanning and photography without compromising on detail or accuracy [59].

To address these issues, further innovation is needed to develop more efficient algorithms for data fusion that can automatically align and integrate 360° photographs with laser scans [60]. Additionally, the exploration of new data compression techniques could facilitate the handling and storage of enriched models, making them more accessible for stakeholders involved in the conservation process [61]. Enhancing the integration of laser scanning and 360° photography will undoubtedly elevate the quality of DTs for heritage buildings, offering a more dynamic and informative tool for preventive conservation efforts [62].

3.3.5. Automation in HBIM Processes

The development of Heritage Building Information Modeling (HBIM) platforms is notably labor-intensive, particularly during the initial stages of converting raw data into functional models [63]. This complexity underscores the pressing need for automation within HBIM workflows to streamline the creation and management of digital representations of heritage buildings [64]. Artificial intelligence (AI) emerges as a potent tool in this domain, offering promising avenues for automating tasks such as data processing, feature extraction, and even the interpretation of architectural elements [65].

A significant gap in current HBIM processes is the manual effort required to interpret and model the data obtained from laser scanning [66]. This gap can be effectively addressed by integrating AI with laser scanning technologies [67]. While AI algorithms can be trained to recognize and classify architectural features automatically from point cloud data, significantly reducing the time and effort involved in manual data processing, it is important to note that this approach is still not fully effective due to the inherent complexity of certain architectural features. The variability in design, detail, and historical context can pose challenges for accurate recognition and classification. However, as advancements in AI technology continue and as more robust training datasets are developed, these methods are likely to become increasingly effective in the future, ultimately providing extraordinary support for the digitization of cultural heritage [68]. Moreover, the use of AI can enhance the accuracy of the models by minimizing human errors in the interpretation of complex geometries [69].

Incorporating DTs into the HBIM framework represents another frontier for automation [70]. DTs can offer dynamic, up-to-date models of heritage buildings through providing real-time data from laser scans and other monitoring technologies [71]. This integration facilitates the maintenance and preservation of heritage sites by providing detailed insights into their current state and enables the simulation of potential conservation interventions [72]. The predictive capabilities of DTs, powered by AI, can transform how heritage buildings are managed, allowing for proactive rather than reactive conservation strategies [62]. However, the integration of AI, laser scanning, and DTs within HBIM poses challenges, including the need for substantial computational resources and the development of specialized AI models that can understand and interpret the unique characteristics of heritage buildings [73]. Overcoming these challenges requires focused research on developing lightweight, efficient algorithms and harnessing cloud computing technologies to process and store the vast amounts of data generated by these processes [74]. Advancing automation in HBIM through AI, laser scanning, and DTs holds the key to more sustainable and effective preservation of cultural heritage [29]. Figure 17 outlines an AI-powered HBIM workflow designed to streamline the creation of digital twins for heritage buildings. The process begins with raw data acquisition through laser scanning, followed by AI-driven processing for feature extraction, which enhances the efficiency and accuracy of HBIM models. Integrating these models with real-time updates allows heritage managers to adopt proactive conservation strategies and plan interventions based on real-time data insights.

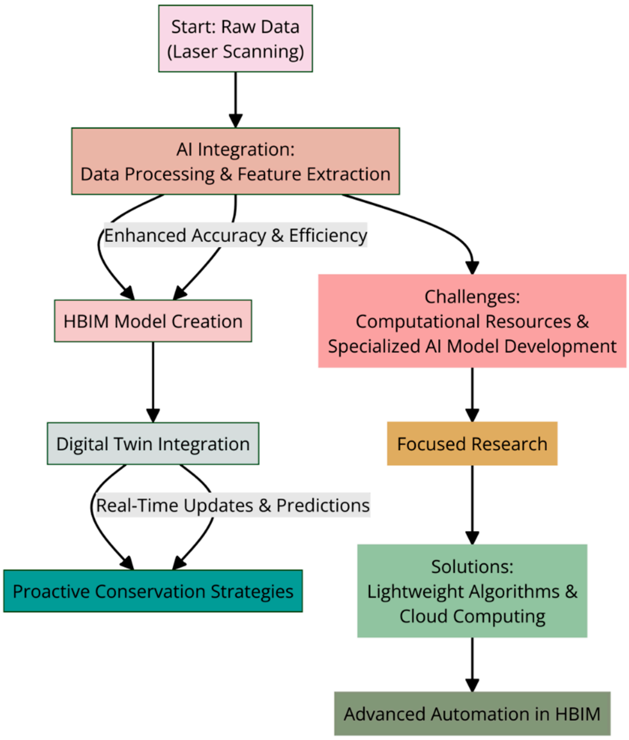

Figure 17. Proposed workflow for integrating AI with HBIM in the context of creating DTs for heritage buildings.

The workflow diagram in Figure 17 proposes an AI-driven solution to enhance HBIM by starting with the acquisition of raw data through laser scanning. These data undergo AI-powered processing and feature extraction, enhancing the efficiency of creating HBIM models while maintaining the inherent accuracy of laser scanner raw data. The AI algorithms facilitate the interpretation of the existing data rather than improving its accuracy, streamlining the process of transforming detailed point cloud information into comprehensive HBIM models. The enhanced models facilitate the seamless integration of DTs, enabling real-time updates and predictions [26]. This integration underpins the development of proactive conservation strategies, addressing the challenges of computational resource demands and specialized AI model development [75]. Focused research is recommended to overcome these challenges, with solutions such as lightweight algorithms and cloud computing paving the way for advanced automation in HBIM [67].

3.4. BIM and DT as a Heritage Conservation Nexus

The fusion of BIM and DTs forms a progressive nexus for the conservation of heritage buildings, offering a holistic framework to capture, manage, and utilize detailed data throughout a building's life cycle. This synthesis is at the heart of this section. Here, the paper explores the gaps shown in Table 5, which stands as a testament to the potential of integrating high-resolution data capture and analysis with dynamic, interactive models for comprehensive building management. Table 5 presents a structured overview of the research gaps in integrating building information modeling (BIM) and digital twin (DT) technologies for heritage conservation. Each entry highlights challenges, such as the need for seamless workflows from Scan-to-BIM-to-DT and the inclusion of cultural significance in HBIM models. These research gaps underscore the complexities in adapting BIM and DT technologies to meet the unique demands of heritage conservation, emphasizing areas where further innovation is needed.

Table 5. Overview of the research gaps areas in the nexus of building information modeling and DTs in the context of heritage building conservation.

Research Gap	Description	References
Scan-to-BIM-to-DT Process	The challenge of managing high levels of detail through the design, construction, and management phases, with a need for a process that allows users to interact with DT for improved building comfort and efficiency.	[27]
DT-HBIM for Preventive Conservation	Proposing a methodology to integrate cultural significance into HBIM models to support preventive conservation using DT principles.	[76]

3.4.1. Scan-to-BIM-to-DT Process

The Scan-to-BIM-to-DT process represents a transformative approach to managing heritage buildings by providing high levels of detail and information across all phases, from design through to construction and maintenance [27,77]. This method allows for enhanced interaction with the DT, facilitating improved building comfort, efficiency, and cost management [78]. Despite its potential, adapting these sophisticated technologies to heritage buildings introduces complexities not typically encountered in modern construction projects [79]. The challenge lies in ensuring that such advanced methodologies respect and preserve the historical accuracy and integrity of heritage structures [80]. This gap between technological potential and practical application in heritage conservation points to a critical area for further research and development [81].

In the field of construction management, the introduction of a DT-BIM hybrid model using artificial intelligence marks a significant advancement in addressing resource shortages and optimizing decision-making processes [82]. This hybrid model has the potential to revolutionize the management of construction projects, including those involving heritage buildings, by offering a more streamlined and efficient approach to resource allocation and project dispatch [83]. However, the unique characteristics of heritage buildings, which often require the use of traditional materials and methods, pose a significant challenge to the direct application of such a model [84]. The specific needs and constraints of heritage building conservation have yet to be fully addressed by this model, highlighting a notable gap in the field that demands attention [85].

Furthermore, the application of DTs for the life cycle assessment of infrastructure projects, as advocated in sustainability practices, presents an exciting opportunity for the conservation of heritage buildings [86]. DTs, seen as an advanced form of BIM, can play a crucial role in sustainability and vulnerability audits, potentially transforming practices in heritage building conservation [87]. Nonetheless, this approach necessitates a careful balance between embracing technological advancements and preserving the historical and cultural value of heritage structures [88]. The integration of DTs into heritage conservation practices requires a good understanding of both the technological and historical aspects, pointing to a substantial area for exploration and application [89].

The integration of BIM, the IoT, and DTs, with potential forays into the metaverse, identifies a promising research direction with implications for heritage building conservation [90]. The challenge lies in how these integrations can be applied to the conservation of heritage buildings, where documentation may be incomplete or non-standardized and construction techniques differ significantly from modern methods [91]. This situation calls for innovative approaches to document and manage heritage buildings effectively, using these technologies while addressing the gap between current capabilities and the needs of heritage conservation [92].

OpenBIM's approach to supporting dynamic asset management through real-time data integration offers insights into how DT and IoT can be better integrated within the context of heritage building management [93]. The potential of OpenBIM to enhance the management and preservation of heritage buildings is significant, yet the application of such technologies in contexts where as-built information is scarce or non-standard presents distinct challenges [94]. These challenges include the need for specialized methodologies to capture and integrate historical and architectural nuances into DT models, suggesting a pressing need for targeted research and development efforts [95].

Furthermore, the concept of data-driven construction, characterized by the use of DT information systems for closed-loop control, introduces a novel approach to construction management [96]. This approach holds considerable promise for enhancing the conservation and management of heritage buildings. However, defining the specific dimensions of information necessary for effective DT workflows in heritage conservation is an area that remains underexplored [97]. Addressing this gap requires a concerted effort to develop frameworks and methodologies that can accommodate the unique attributes of heritage buildings, thereby advancing the field towards more integrated and effective conservation practices [98].

Figure 18 presents a sophisticated digital workflow that can enhance the efficiency of heritage buildings inspired by [27]. The workflow begins with BIM ADD-IN, a tool that initiates the reconstruction process, seamlessly integrating with BIM MODELGENERATIVE techniques to accurately replicate the historic structures [27]. This is coupled with the INDOOR 4DBIM TOOL, providing the Forge API to provide detailed indoor environment modeling. Data flows into the HOMEBIM Live APP, which then synergizes with the HOMEBIM Cloud Platform, establishing a robust ecosystem for managing and analyzing building information.

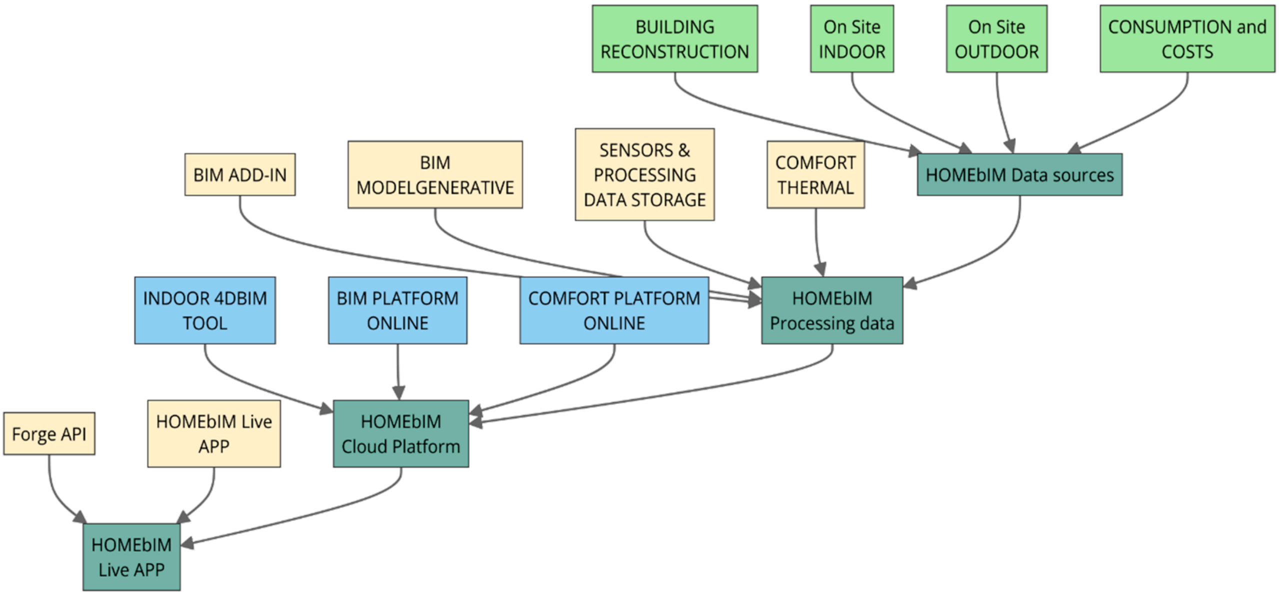

Figure 18. Digital workflow proposed for heritage buildings based on [27].

Central to this operation are the BIM PLATFORM ONLINE and COMFORT PLATFORM ONLINE, which together orchestrate a comprehensive strategy for assessing and improving thermal comfort, crucial for the preservation and sustainable use of heritage buildings. Sensors meticulously capture on-site indoor and outdoor conditions, feeding data back to the HOMEBIM platform, where it is processed and analyzed. This interplay of data from various sources, including consumption metrics and costs, is pivotal in adapting retrofitting strategies for heritage buildings [27]. It informs decision-making processes, ensuring that interventions respect architectural integrity while promoting energy efficiency [27]. This digital workflow, as depicted in Figure 18, provides a blueprint for the application of advanced technologies in the conservation of historic structures, aiming to reduce energy demand and CO_2 emissions in line with Italy's energy efficiency directives, thus fostering sustainable heritage building management. Figure 18 illustrates an advanced digital workflow tailored for managing heritage buildings, featuring integration between

BIM and sensor-based platforms for real-time data collection and analysis. This setup enables continuous monitoring of environmental conditions and energy consumption, which are essential for designing retrofitting strategies that balance preservation needs with sustainability goals. By using such workflows, heritage buildings can be managed to reduce their carbon footprint while maintaining architectural integrity.

3.4.2. DT-HBIM for Preventive Conservation

Preventive conservation refers to the strategies and actions designed to avoid the deterioration or damage of cultural heritage artifacts and historical structures [28]. It encompasses a broad range of activities, such as environmental control, risk management, and regular maintenance, aiming to extend the lifespan of these assets without altering their original state [99]. An example of preventive conservation is the controlled environment in museums that stabilizes temperature and humidity levels to prevent the degradation of artworks and artifacts [100].

Within this context, Digital Twin Historic Building Information Modeling (DT-HBIM) plays a crucial role in enhancing the effectiveness of preventive conservation strategies for historical buildings [101]. DT-HBIM creates a virtual counterpart of a physical building, integrating real-time data from various sensors to simulate and analyze the building's behavior under different conditions [102]. This allows for the early detection of potential issues that could lead to deterioration, enabling timely interventions [102]. Consequently, DT-HBIM supports the sustainable preservation of cultural heritage and optimizes the maintenance and management processes, ensuring that preventive measures are both effective and efficient [102].

3.5. IoT as the Connective Tissue for Dynamic DT

This subsection explores the role of the IoT as a foundational element in the evolution and operational efficiency of DTs for heritage buildings. It discusses the integration of IoT within DT models, emphasizing the critical task of accurately mirroring the ever-changing conditions of heritage structures.

3.5.1. Integration of IoT with DT Models

The integration of IoT with DT models holds immense importance for the conservation and maintenance of heritage buildings, bridging critical gaps in real-time monitoring and predictive maintenance [103]. This synergy is pivotal for the sustainable preservation of cultural heritage, enabling stakeholders to understand and anticipate the needs of these structures more effectively [104]. One of the most significant challenges in this integration lies in the nuanced application of IoT sensors within heritage sites [105]. These sensors must be deployed in a manner that respects the esthetic and structural integrity of the buildings, often requiring innovative solutions to avoid altering their historical fabric [106]. Moreover, the development of DT models that can dynamically reflect the real-time conditions of a heritage building based on IoT sensor data demands sophisticated software capable of complex data analysis and predictive modeling [107]. The integration of IoT with DT models, as described, is essential for the proactive conservation of heritage sites, especially for real-time monitoring and predictive maintenance (see Table 6). This table offers a detailed summary of sensor technologies and their applications, enabling conservation professionals to select tools tailored to specific preservation needs. For instance, 3D laser scanners and ground-penetrating radar (GPR) facilitate structural documentation and subsurface imaging, aiding in assessing the physical health of heritage sites non-invasively. Environmental sensors, pivotal in monitoring microclimate factors like humidity and temperature, support the preservation of fragile materials by controlling critical environmental variables. By providing insights into real-world applications, Table 6 underscores the technological advancements in IoT-enabled DT models that can dynamically reflect real-time conditions, helping conservators make data-driven decisions.

Predictive maintenance, as a specific application of this integration, exemplifies its potential benefits [108]. For instance, in the case of the ancient Alhambra Palace in Spain, predictive maintenance could involve the use of IoT sensors to monitor the humidity and temperature levels continuously [109]. These sensors could detect subtle changes in the microclimate that may predict the growth of mold or the deterioration of delicate frescoes before visible signs appear [110]. Advanced DT models would then simulate these conditions and predict their impact on the building, allowing conservators to implement targeted interventions, such as adjusting environmental controls or conducting minor repairs to prevent significant damage [111]. However, the gaps in achieving seamless integration and effective predictive maintenance are evident [112]. These include the need for more advanced algorithms for data analysis, capable of accurately predicting deterioration patterns, and strategies for non-intrusive sensor placement that do not compromise the building's historical value [113]. Moreover, ensuring data security and fostering interdisciplinary collaboration remain crucial challenges that need addressing to fully realize the potential of IoT and DT models in heritage building conservation [14]. Table 6 summarizes sensor technologies in heritage conservation, enabling quick identification of suitable tools for specific preservation tasks. It highlights seminal studies for deeper exploration and fosters an informed selection of methods for structural health monitoring and preventive conservation. Notably, 3D laser scanners capture precise geometric information, which can be integrated with data from various sensors to provide a holistic view of heritage sites.

Table 6. Overview of sensor technologies in heritage conservation.

Sensor Type	Application	Outcome	Reference
3D Laser Scanners	Detailed geometric documentation and structural analysis	Accurate 3D models for assessing structural health and planning conservation works	[30,114–116]
Wireless Sensor Networks (WSN)	Real-time health monitoring of architectural heritage	Non-invasive monitoring of environmental parameters crucial for the preservation of heritage buildings	[117,118]
Infrared Thermography (IRT)	Detection of moisture, insulation failures, and thermal anomalies	Identifying areas at risk of deterioration due to environmental factors, aiding in preventive conservation	[119]
Environmental Sensors	Monitoring microclimate conditions within heritage sites	Ensuring the preservation of materials by controlling temperature, humidity, and other environmental factors	[120]
Ground-Penetrating Radar (GPR)	Sub-surface imaging of foundations and buried structures	Non-invasive exploration of structural integrity and identification of hidden features without physical excavation	[121]
Digital Image Correlation (DIC)	Monitoring of deformations and displacement over time	Provides a detailed analysis of structural movement, critical for assessing the stability and integrity of heritage structures	[122]
Fiber Optic Sensors	Long-term structural health monitoring	Real-time, continuous monitoring of strains and stresses within structural elements, allowing for early detection of deterioration	[123]
Ultrasonic Sensors	Material characterization and flaw detection	Assessing the condition of materials and detecting voids, cracks, and other defects in building elements	[124]

3.5.2. Energy Efficiency in IoT for Cultural Heritage (CH)

Creating an energy-efficient IoT architecture specifically tailored for the preventive conservation of cultural heritage represents a significant gap in the current field of technology application within heritage preservation [125]. Addressing this gap involves the development of IoT solutions that minimize energy consumption while maximizing the monitoring and maintenance capabilities essential for the sustainable conservation of cultural heritage sites [86]. The core of this challenge lies in designing IoT devices and systems that operate on minimal power without compromising their ability to collect and transmit essential data [126]. This requires advancements in low-power sensor technology, energy-efficient data transmission protocols, and innovative power management strategies [127].

Energy efficiency is a crucial factor in IoT architectures for cultural heritage conservation. The section on energy-efficient IoT systems emphasizes the development of devices that consume minimal power without sacrificing data-gathering effectiveness. Such advancements include low-power wide-area networks (LPWAN) and energy-harvesting sensors, which prolong device operational life and reduce maintenance frequency—a priority in the context of non-intrusive heritage preservation. Table 6 reinforces this by listing low-power solutions like wireless sensor networks (WSNs) and fiber optic sensors, which provide continuous monitoring capabilities for heritage sites without excessive power demands.

For instance, deploying sensors that can harvest energy from environmental sources, such as solar, thermal, or kinetic energy, could significantly reduce the reliance on traditional battery power and enhance the sustainability of IoT deployments in cultural heritage sites [128].

Additionally, the architecture must incorporate energy-efficient communication protocols that optimize data transmission to conserve power [129]. This could involve the use of low-power wide-area network (LPWAN) technologies, which are designed to transmit small amounts of data over long distances with minimal energy consumption [130]. Implementing such protocols ensures that IoT devices can remain operational for extended periods, reducing the need for frequent maintenance or battery replacement, which is particularly crucial in the context of cultural heritage conservation, where minimal intrusion is desired [131]. Furthermore, the development of smart algorithms and edge computing capabilities is another key component of an energy-efficient IoT architecture [132]. The amount of data that needs to be transmitted to the cloud or central servers can be reduced by processing data locally on the IoT device or nearby edge computing nodes, thereby conserving energy [133]. Moreover, smart algorithms can enable devices to operate in a low-power sleep mode when active monitoring is not required, waking only to report significant changes or anomalies [134]. This intelligent management of operational states further enhances the energy efficiency of the system [135].

In addition, the integration of a centralized management platform that can analyze data from multiple sensors and devices in real-time, applying predictive analytics to optimize the conservation process, is essential [136]. Such a platform should also be capable of managing the energy consumption of the IoT architecture, dynamically adjusting settings and protocols based on the current needs and priorities of the conservation efforts [137]. Lastly, the development of this energy-efficient IoT architecture must involve a multidisciplinary approach that includes conservation scientists, IoT engineers, and energy management experts [138]. Collaboration between these fields can lead to innovative solutions that balance the conservation needs of cultural heritage sites with the sustainability goals of modern technology applications [96].

3.6. Machine Learning for Predictive Conservation

Machine learning for predictive conservation harnesses data-driven algorithms to forecast deterioration and inform the maintenance of cultural heritage assets. Machine learning for predictive conservation represents another significant innovation, blending advanced computational techniques with traditional conservation practices (see Table 7). Table 7 provides a comprehensive review of ML applications in heritage conservation, including damage assessment, predictive modeling, and virtual restoration. For instance, convolutional neural networks (CNNs) are applied to classify and localize damage, while generative adversarial networks (GANs) facilitate the virtual restitution of missing or damaged heritage elements. These techniques exemplify how ML can predict potential deterioration and assist in preemptive interventions, thus preserving cultural assets more effectively. The range of ML applications in Table 7 highlights the importance of interdisciplinary collaboration among ML experts, conservation scientists, and historians in achieving sustainable heritage conservation.

By consolidating such technology summaries and empirical findings, Tables 6 and 7 contribute valuable reference points for the application of IoT, DT, and ML technologies in the proactive preservation and sustainable management of cultural heritage sites.

This approach utilizes historical data and sensor readings to train models that can predict potential issues, allowing for timely interventions and preservation efforts. It represents a proactive shift in heritage conservation, blending technology and tradition to safeguard cultural treasures for future generations, which will be discussed in this subsection.

3.6.1. Restitution of Damaged Heritage

The development of comprehensive machine learning (ML) models to effectively utilize data for predicting scenarios like material deterioration or structural damage in heritage buildings represents a significant advancement in the field of heritage conservation [139].

Key to the success of these models is the integration of diverse data types, including time-series data from environmental sensors, visual data from drones, laser scanners, or robotic inspections, and textual data from historical and conservation records [140]. Advanced techniques in data preprocessing and feature engineering are crucial to preparing this heterogeneous data for analysis [141]. Deep learning models, especially those utilizing convolutional neural networks (CNNs) for image analysis and recurrent neural networks (RNNs) for time-series forecasting, are at the forefront of this research [142]. However, the challenge extends beyond model selection and training; it includes ensuring that the models are interpretable by conservation experts and adaptable to the evolving conditions of heritage sites [143].

Parallel to predicting material and structural issues, ML, particularly generative adversarial networks (GANs), offers novel possibilities in the restitution of damaged heritage structures [144]. GANs, which consist of two neural networks—the generator and the discriminator—working in tandem, can be trained on images of undamaged sections of buildings or sculptures to generate realistic reconstructions of missing or damaged parts [145]. This aids in the virtual restoration of cultural heritage for educational as well as research purposes and provides invaluable insights for physical restoration projects [146]. The accuracy and realism of the reconstructions generated by GANs depend on the quality and extent of the training data, as well as the model's ability to understand and replicate complex historical styles and construction techniques [147].

The development and refinement of these ML models require a multidisciplinary approach, combining expertise in machine learning, computer vision, conservation science, and architectural history [148]. Challenges such as data scarcity, especially high-quality images of damaged or destroyed heritage sites, and the need for models to appreciate the context and historical significance of the artifacts they are reconstructing must be addressed [149]. Additionally, ethical considerations around the use of AI in altering images or creating reconstructions of cultural heritage need careful deliberation to ensure that the digital restoration respects the integrity and authenticity of the original works [150].

Table 7 provides a comprehensive summary of recent studies focusing on the application of machine learning techniques in the conservation of heritage buildings. It showcases the innovative use of these technologies across various aspects of heritage conservation, including structural health monitoring, predictive maintenance, automated damage assessment, and the reconstruction of historical buildings.

Table 7. Overview of recent studies on machine learning applications in heritage buildings conservation.

Reference	Main Findings
[139]	Reviews various ML techniques for assessing the health condition of heritage buildings, including predictive models for damage scenarios and mechanical properties of materials.
[144]	Uses conditional generative adversarial networks to predict missing/damaged parts of historical buildings.
[151]	Demonstrates the effectiveness of CNN and SVM models in classifying damage severity levels in heritage buildings.
[152]	Proposes SVM for automatically recognizing elements in existing buildings to create semantic information models from point cloud data.
[153]	Uses deep learning methods, including transfer learning with pre-trained networks, for the classification and localization of defects in cultural heritage buildings in Iran.
[154]	Develops learning models to analyze data from the digital documentation of heritage structures, proposing an ontology for heritage buildings and damage due to disasters.
[155]	Discusses the development and application of machine learning in the fields of energy conservation and indoor environment, including predictive modeling for indoor culturable fungi concentration.
[156]	Proposes a method to support preventive conservation programs through the analysis of maintenance requests using LSTM neural networks, achieving a prediction accuracy of 96.6%.
[157]	Describes the use of machine learning algorithms for analyzing BIM data to improve decision-making in energy renovation projects.
[158]	Surveys the application of machine learning to cultural heritage, analyzing the adoption and adaptation of ML algorithms for various CH applications.
[159]	Discusses the potential of parametric modeling techniques in the restoration and reconstruction processes of heritage buildings through a BIM software plug-in.

3.6.2. Ontology-Based Conservation

Creating ontology-based ML frameworks for the information and knowledge management in architectural heritage conservation offers a sophisticated approach to preserving cultural landmarks [144]. Such frameworks provide ontologies as structured systems that define relationships between various concepts and entities relevant to heritage conservation [160]. Conservationists can significantly improve the decision-making process, informed by a deep understanding of each site's unique characteristics and conservation needs, by integrating these ontologies with ML algorithms [161]. This integration aids in organizing and accessing a vast array of knowledge, from physical elements and conservation techniques to historical significance and environmental impacts, in a clear, hierarchical manner [162].

The development of these frameworks involves creating detailed ontologies that encompass the broad spectrum of factors in architectural heritage conservation [163]. This includes categorizing building materials, structural components, decorative features, and conservation methods, as well as considering historical, legal, and environmental aspects [164]. Such comprehensive ontologies serve as powerful tools for managing conservation-related knowledge, facilitating the automated analysis of data through ML algorithms [165]. This allows for the identification of patterns and trends that may not be evident to human analysts, such as predicting the effectiveness of conservation techniques under specific conditions or identifying risks from changing legal frameworks [166]. However, challenges arise in the development and application of ontology-based ML frameworks, primarily due to the interdisciplinary expertise required and the extensive process of data collection and digitization [167]. These challenges underscore the need for collaboration among experts in ontology development, ML, architectural history, and conservation science [168]. Additionally, the frameworks must accommodate the complexity of architectural heritage conservation, processing data from diverse sources like textual documents, architectural plans, and sensor readings, thereby enabling collaborative knowledge sharing among various stakeholders [169].

In addressing the integration of qualitative and quantitative data for the conservation of cultural heritage, an ontological model for 3D semantic annotation aims to bridge the gap between data acquisition and expert knowledge interpretation [170]. This multidisciplinary approach integrates semantic, spatial, and morphological dimensions to describe conservation states comprehensively [171]. For example, using reality-based 3D annotations to incorporate expert analyses directly into a heritage structure's 3D representation allows for dynamic monitoring of conservation states over time [172]. The integration of semantic annotation with CIDOC-CRM and the use of image-based modeling and 3D point clouds enrich the documentation process, enabling a detailed analysis that combines diverse data types and expert insights [173].

3.7. Enriching Heritage Experience with AR and VR

3.7.1. Underwater Archeological Sites

Exploring underwater archeological sites through virtual reality (VR) and augmented reality (AR) technologies marks an important shift in research and public engagement with submerged cultural heritage [174]. These technologies afford immersive experiences that dramatically improve access to and comprehension of historical sites located beneath water bodies, traditionally restricted to the public and specialists due to the harsh conditions and advanced equipment needed for exploration [175]. VR offers the opportunity to develop detailed, interactive simulations based on 3D models from underwater photogrammetry, sonar imaging, and archeological discoveries, allowing users to virtually experience these sites with a realism that emulates diving, minus the risks or need for certifications [176]. AR enhances this further by integrating digital reconstructions with the real world, enriching visits to museums or actual sites with historical narratives and comparisons through smartphone apps or AR glasses [177].

However, the development of VR and AR applications for this purpose is not without its challenges [178]. It necessitates collaborative efforts across disciplines, including archeology, marine science, and technology development, combining accurate archeological data with advanced 3D modeling and user-centric designs to create compelling educational tools [179]. Technical hurdles such as creating high-resolution, realistic yet computationally efficient 3D models for real-time rendering on VR and AR platforms pose significant obstacles [180]. Additionally, there is the task of overlaying digital information accurately onto the physical world in AR applications, which requires precise geo-location and image recognition technologies to offer a seamless integration of past and present states of archeological sites [181].

Despite these challenges, the potential of VR and AR technologies to enhance visibility, accessibility, and understanding of underwater cultural heritage is immense [182]. For instance, the virtual reconstruction of the Antikythera shipwreck in Greece using VR allows users worldwide to explore the site in detail, offering insights into ancient maritime history that were previously limited to a select few divers and researchers [183]. Similarly, AR applications can transform a visit to the British Museum by superimposing digital images of the original form of artifacts over their current states, providing a more contextual understanding of their historical significance [184]. Beyond public education and engagement, these technologies serve as vital tools for the conservation and preservation of submerged sites, reducing physical impact on these delicate environments and enabling precise monitoring over time to safeguard them for future generations [185].

3.7.2. Engineering-Grade Devices

Developing robust AR and VR devices capable of withstanding the complex conditions prevalent at construction and heritage sites marks a significant challenge in the field of immersive technology [186]. These environments often present harsh conditions, including dust, moisture, vibration, and extreme temperatures, necessitating the creation of engineering-grade devices that are not only technologically advanced but also durable and reliable [187]. The key to engineering these devices lies in designing for ruggedness from the ground up [188]. This includes the use of durable materials capable of protecting sensitive electronic components from physical impact, water ingress, and particulate matter [189].

For example, high-grade plastics, metals, and rubberized seals can be employed to achieve a durable exterior, while internal components may require shock-absorbing materials to protect against vibration and impacts commonly encountered on construction sites.

In addition to physical durability, these devices must possess high-performance computing capabilities to render complex AR/VR experiences in real-time [190]. This requires efficient thermal management systems to dissipate heat generated by processors, especially in outdoor environments where temperatures can significantly fluctuate. Advanced cooling techniques, such as heat pipes and thermal conduction materials, become critical in maintaining optimal device performance without compromising the integrity of the hardware [191]. Battery life is another critical consideration, as these devices need to operate for extended periods without access to charging facilities [192]. Implementing energy-efficient processors and displays, alongside larger capacity batteries and potentially energy harvesting technologies, can help extend the operational life of AR/VR devices in the field [193]. Furthermore, the user interface and experience must be tailored to the needs of construction and heritage site workers, who may have limited experience with AR/VR technology and who often wear protective gear [178]. Devices should feature intuitive controls that can be easily manipulated with gloves, and displays must be readable in a wide range of lighting conditions, including direct sunlight [194]. Voice recognition and gesture-based interfaces offer promising alternatives for hands-free operation, enhancing usability in environments where manual interaction is limited [195].

Interoperability with existing digital tools and systems used in construction and heritage conservation is also essential [196]. This requires the development of open standards and APIs that facilitate seamless integration with software for project management, 3D modeling, and data analysis, ensuring that AR/VR devices can be effectively incorporated into the existing technological ecosystem of these industries [197]. The development of engineering-grade AR/VR devices for construction and heritage sites represents an intersection of advanced materials science, electronics, and user-centered design [198]. Achieving this blend of durability, performance, and usability will not only revolutionize the way professionals interact with complex sites but also open new possibilities for the application of immersive technologies in various industrial settings, enhancing efficiency, safety, and the preservation of cultural heritage [199].

3.7.3. Digital Preservation of Cultural Elements

Applying AR and VR for digital preservation marks a transformative approach to conserving cultural elements, enabling vivid contextual recall and comparison of old scenes at heritage sites [200]. This innovative use of technology allows not only for the preservation of physical structures but also for the capture and recreation of the intangible aspects that give these sites their unique cultural and historical significance [201]. AR technology can overlay historical images, videos, or 3D reconstructions onto the current view of a site, allowing visitors to see how it has changed over time [202]. This immediate contextual comparison helps in understanding the evolution of the site, highlighting the conservation efforts and changes due to natural or human factors. For instance, visitors equipped with AR devices or smartphones can point their cameras at different parts of a heritage site and see overlays of historical photographs or artistic recreations of past events associated with that location [203]. This enhances the visitor experience by making history come alive and serves an educational purpose, providing deeper insights into the cultural and historical context of the site.

VR takes this one step further by creating completely immersive environments that can transport users to different time periods [204]. Through detailed 3D modeling and rendering, VR can reconstruct heritage sites in their historical context, allowing users to explore them as they once were [205]. This is particularly valuable for sites that have been damaged or lost due to natural disasters, conflict, or neglect. VR enables the preservation of these sites in digital form, ensuring that their cultural and historical value is accessible to future generations [206]. Users can navigate through these virtual reconstructions, experiencing the spatial and architectural elements of the past firsthand, which is invaluable for educational, research, and preservation purposes [207]. Moreover, these technologies offer significant benefits for the preservation of intangible cultural heritage, such as rituals, languages, and traditional crafts.

3.8. Bridging Disciplines

3.8.1. Ethical Frameworks for Digital Replication

Ethical Principles for Digital Workflows

Developing ethical principles or codes of ethics for heritage recording specialists is critical to addressing the moral and ethical implications of digital technologies in the conservation of heritage buildings [208]. As digital workflows become increasingly integral to the documentation, analysis, and preservation of heritage sites, the need for a guiding ethical framework becomes paramount [209]. Such principles should address issues like data accuracy, representation, accessibility, and the long-term preservation of digital records [210]. They must ensure that digital documentation and analysis methods respect the integrity and authenticity of heritage sites, preventing the distortion or loss of historical and cultural significance [211].

Furthermore, ethical guidelines should consider the impact of digital technologies on privacy and the rights of communities associated with heritage sites [212]. The use of digital tools in heritage conservation often involves capturing detailed information about sites that may have cultural sensitivities or require protection from exploitation [87]. Ensuring that communities are engaged in the decision-making process and that their rights are protected in the digital representation of heritage sites is essential [213]. This includes acknowledging intangible cultural heritage and ensuring that digital reproductions do not misinterpret or misrepresent cultural practices and values [214].

Ethics by Design

Ethics by Design is a fundamental approach for framing a code of ethics in the digital age, ensuring that digital and leading-edge technologies align with data protection and ethical standards [215]. This approach mandates the integration of ethical considerations into the very fabric of technology development and deployment processes, focusing on protecting individual privacy, ensuring data security, and promoting fairness and inclusivity [216].

The Ethics by Design methodology emphasizes transparency, accountability, and user empowerment in the development of digital technologies [217]. It requires developers and organizations to not only adhere to existing legal frameworks and data protection laws but also to exceed these standards by fostering an ethical culture that prioritizes the well-being of individuals and communities [217]. This involves conducting thorough impact assessments to understand and address the societal implications of technologies, engaging with diverse stakeholders to gain a broad perspective on potential ethical issues, and committing to continuous ethical evaluation and improvement of technologies post-deployment [218]. Implementing Ethics by Design also involves addressing the challenges of technological innovation, such as artificial intelligence (AI) and big data analytics, where ethical risks can be complex and unpredictable [219].

An example of Ethics by Design in heritage conservation could be the development of an AR mobile application for visitors to engage with a historic cathedral, ensuring ethical considerations must be integrated throughout the design and implementation process [220]. This includes obtaining user consent for data collection, securing user data, and providing transparent documentation of information sources. Stakeholder engagement guarantees accuracy and authenticity, while user empowerment must be prioritized through customizable features catering to diverse interests [221]. Continuous evaluation and improvement of the application post-deployment ensure ongoing alignment with ethical standards, enhancing visitors' understanding and appreciation of the cathedral's cultural heritage while respecting privacy and promoting inclusivity [222].

3.8.2. The Convergence of Multidisciplinary Expertise

Multidisciplinary Decision-Making Methods

Multidisciplinary decision-making methods, particularly multi-criteria decision-making (MCDM), play a crucial role in navigating the complexities of heritage building conservation [223]. These methods enable the integration of various perspectives, including architectural, historical, environmental, and socio-economic factors [224], into a cohesive decision-making framework [225]. MCDM offers a structured approach to evaluate multiple criteria that are often conflicting, making it possible to arrive at decisions that balance preservation needs with modernization demands [226]. However, the application of these methods in the context of heritage buildings is fraught with challenges [227]. These include the subjective nature of valuing historical significance, the difficulty in quantifying esthetic and cultural factors, and the need for stakeholder engagement in the decision-making process [227].

Despite the potential of MCDM to enhance decision-making in heritage building conservation, there remains a significant gap in research concerning its practical application and effectiveness [223]. Current studies often focus on theoretical frameworks and methodological developments without sufficiently addressing the real-world complexities and the dynamic nature of heritage conservation [228]. There is a particular need for empirical research that explores how these methods are applied in practice, including the integration of stakeholder preferences, the handling of uncertain and incomplete information, and the assessment of long-term sustainability impacts [229]. Addressing this gap is essential for developing more robust and adaptable decision-making tools that can meet the unique challenges of conserving heritage buildings [230].

Non-Destructive Techniques for Conservation

The development of non-destructive and non-contact techniques for conservation assessment marks a significant advancement in preserving heritage buildings [231]. These techniques, which include methods like ground-penetrating radar, ultrasonic testing, and digital photogrammetry, allow for the detailed analysis of a structure's condition without causing harm to the building's fabric [232]. This approach preserves the integrity of historical sites and provides a wealth of information about hidden or inaccessible features [231]. Interdisciplinary expertise is crucial in this area, combining knowledge from civil engineering, materials science, computer science, and conservation science to innovate and refine these technologies [232].

However, there is a gap in the interdisciplinary application and integration of these techniques into standard conservation practices [233]. Many conservation professionals may not be fully aware of the capabilities and limitations of these technologies, leading to underutilization in the field. Furthermore, there is a need for comprehensive frameworks that guide the selection and application of appropriate non-destructive techniques based on the specific requirements of each heritage site [234]. Bridging this gap requires focused research on the practical implementation of these technologies, including case studies demonstrating their effectiveness in various conservation scenarios and guidelines for their integration into conservation strategies [235].

3.9. Case Study

In this detailed exploration through this review paper, the research investigates the potential of emerging technologies in the conservation and restoration of heritage buildings [236–239], through a compelling case study from Saudi Arabia.

The research explored four distinct historical sites, each presenting unique challenges and opportunities for the application of digital twin (DT) technologies, including building information modeling (BIM), laser scanning, machine learning (ML), and the Internet of Things (IoT). The aim is to demonstrate novel contributions to the field by specifying equipment and methods and providing examples of how these technologies can be implemented to preserve the cultural legacy of these sites.

Saudi Arabia is chosen as a focal point for this exploration due to its rich cultural tapestry and the government's progressive stance on heritage preservation [240–242], as exemplified by Vision 2030. The country's rapid modernization, juxtaposed with its deep historical roots [240,243,244], provides a unique backdrop for the implementation of DT technologies. The three historical sites selected—At-Turaif District, Bujairi Quarter, Buwaib Village, and Rughabah Village, as can be seen in Table 8—represent a cross-section of the kingdom's diverse heritage, from urban landscapes (242–245) to agricultural terrains and abandoned rural settlements. Table 8 succinctly summarizes the interventions undertaken at each site, illustrating the varied methodologies employed and their corresponding impacts. This table not only serves as a reference for specific interventions but also emphasizes the overarching strategies of conservation, such as the importance of maintaining the traditional atmosphere while adapting to modern needs. The diversity of use cases, from tourist attractions to museums, underscores the multifaceted approach needed for sustainable heritage preservation.

Table 8. Summary of sustainable heritage reuse interventions in Saudi Arabia. Case studies of Ushaiger Village, At-Turaif District, Rawdat Sudair Village, and Rughabah Village based on [245].

Heritage Site	Location	Conservation Date and Institutions	Methodologies and Interventions	Use
Ushaiger Village	Najd region, near Shaqra. History of 1500 years as a pilgrim rest spot.	Rehabilitated in 2017 by the Saudi Commission for Tourism and National Heritage. Received the Prince Sultan bin Salman Award.	One hundred houses restored with modern amenities. Strategy to preserve traditional atmosphere.	Evolved to a tourist attraction with a restaurant, market, and private museums.
At-Turaif District	The first capital of the Al Saud dynasty, northwest of Riyadh. UNESCO World Heritage site.	Conservation was segmented into periods before 2010, 2010–2017, and after 2017. Managed by Diriyah Gate Development Authority.	Focus on non-intrusiveness, reversibility, and original materials. Some anastylosis.	Open-air museum with buildings open to the public, showcasing the area's history.
Rawdat Sudair	In Sudair region, Najd province. Historically significant for agriculture.	Restored between 2005 and 2015 by the Saudi Commission for Tourism and Antiquities.	Conservation aimed at reusing Al-Dakhlah Mosque. Used local materials, minimal anastylosis.	Commercial activities, like a museum, promote tourism with a focus on traditional values.
Rughabah Village	Northwest of Riyadh in Najd, urban development from 1669.	Tower restored in 1974, 1996, and 2018 by various patrons and the Saudi Commission for Tourism and National Heritage.	Traditional materials and techniques for restoration. Minimal legibility and reversibility.	Abandoned village known for the restored tower and nearby castle remains functions as an open-air museum.

In addition, Figure 19 provides a quantified evaluation of various conservation interventions across the four heritage sites mentioned above. This figure visually encapsulates the comparative effectiveness of different conservation methods, revealing insightful patterns in how each site's interventions align with key criteria such as legibility, reversibility, and alteration. For instance, the high score for reversibility at Ushaiqer Village suggests a successful strategy in maintaining the integrity of the site while allowing for necessary adaptations. Conversely, the lower scores for Rughabah Village in legibility indicate areas where further attention may be needed to enhance visitor understanding and engagement. This visual representation not only aids in assessing the success of interventions but also highlights areas for future research and practice, aligning conservation efforts with standardized criteria for intervention success. The assessment considers criteria such as legibility, reversibility, overstanding, alteration, replacement, and analysis and ruins. This visual representation aids in understanding the effectiveness of different conservation methods applied to each site. It becomes clear that while some sites like Ushaiqer Village score high in terms of reversibility, others like Rughabah Village are better evaluated for legibility. These data are invaluable for directing future conservation efforts, ensuring that strategies employed not only respect the inherent value of the cultural heritage but are also measured against standardized criteria for intervention success. Integrating these assessment values into the DT framework enhances decision-making processes by providing a metric-based approach to evaluate and refine conservation techniques.

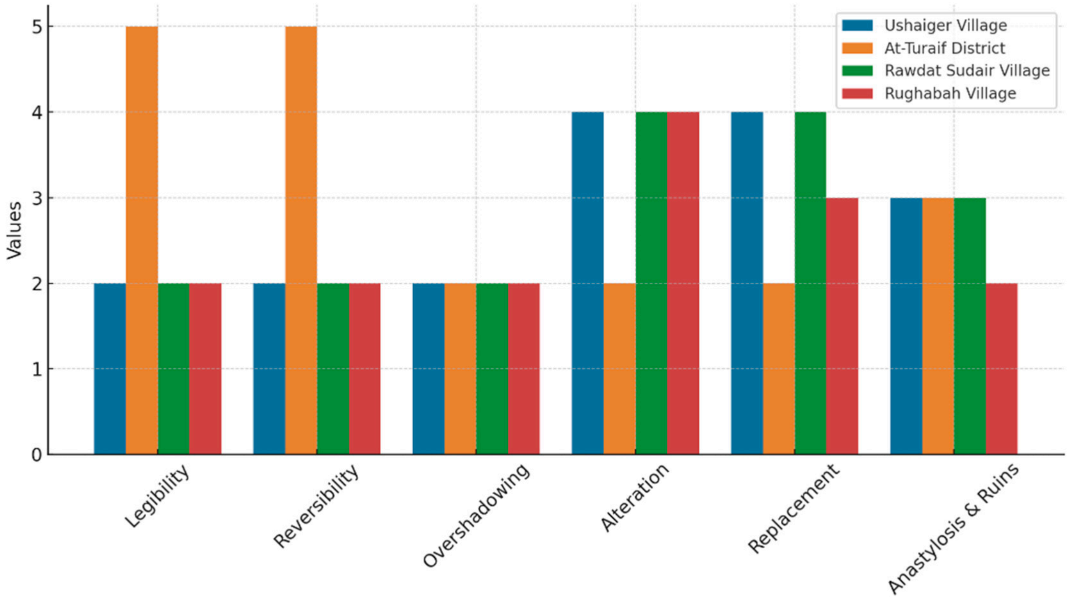

Figure 19. Assessment values for the specified urban heritage intervention parameters based on [245].

3.9.1. At-Turaif District

At-Turaif District, with its historical significance, offers fertile ground for DT technology. Here, BIM acts as the cornerstone of digital preservation. Utilizing the advanced capabilities of Autodesk Revit, it is possible to construct a precise virtual model of the district. Integrating this with HBIM, specialized in heritage buildings, allows for the layering of historical data, enabling the tracing of architectural evolution over time. For example, the implementation of Trimble's TX8 laser scanner would produce detailed 3D models of the district's unique Najdi architectural features, aiding in the accurate restoration of damaged structures. These models are instrumental for physical restoration and serve educational and research purposes, as they enable historians and architects to analyze the site's historical construction techniques within a virtual environment. This digital approach enhances preservation accuracy and paves the way for innovative virtual tourism experiences, extending the site's reach without endangering its physical state.

3.9.2. Bujairi Quarter

At the Bujairi Quarter, the DT model becomes a nexus between agricultural heritage and architectural conservation. IoT technology can be extensively employed to monitor the microclimate that affects both the crops and earthen structures. A network of sensors, such as the Decagon 5TM Water Content and Temperature sensors, could be strategically placed to relay real-time data on soil moisture levels and ambient temperatures. These data, fed into an AI platform like IBM's Watson IoT, enables predictive analytics to safeguard heritage structures from adverse weather effects by forecasting potential risks and automating preventive measures. Furthermore, ML, through platforms like TensorFlow, can process this environmental data alongside historical conservation records to predict structural vulnerabilities, guiding timely maintenance while preserving the site's agricultural narrative.

3.9.3. Buwaib Village

For Buwaib Village, the combination of laser scanning and BIM facilitates the resurrection of a forgotten past. High-definition scanners, such as the FARO Focus3D, can digitally capture the village's current state, allowing for the creation of an exact virtual replica. This digital reconstruction serves as a blueprint for restoration and as a foundation for the virtual museum experience. In this DT environment, IoT sensors can be installed to manage the site's microclimate and visitor interactions. For instance, integrating Bosch's Connected Building Solutions can help in preserving the structures and enhance the visitor experience through interactive guides and augmented reality tours, bringing the vibrant history of the village to life.

3.9.4. Rughabah Village

Rughabah Village, positioned northwest of Riyadh, stands as a testament to the endurance of traditional construction techniques amidst urban development since 1669. The village's restoration efforts, particularly of its historic tower, have been periodic and respectful of the original building methods. Here, DT can provide a cohesive platform for managing future restorations and enhancing the site's role as an open-air museum. Laser scanning, using high-precision equipment like the Artec Leo 3D scanner, could capture the texture and form of the tower and nearby castle remains, creating a detailed digital archive. BIM, through platforms such as Bentley Systems' MicroStation, could integrate these scans with historical data, allowing conservators to plan restoration with an emphasis on material authenticity and traditional techniques. Furthermore, the integration of ML could analyze patterns from past restorations to ensure that any future interventions maintain minimal legibility and reversibility—a key aspect of sustainable heritage conservation. For example, employing Google's AutoML Vision could help in identifying the most durable materials and construction techniques that align with traditional methods. This predictive analysis would also support the planning of maintenance schedules, optimizing resource allocation.

The implementation of IoT can contribute significantly to the village's upkeep and visitor experience. Environmental monitoring systems, such as the Onset HOBO data loggers, can continuously assess conditions that may affect the structural integrity of the site. Simultaneously, IoT-enabled wearables could offer visitors an interactive exploration of the village, providing historical context and stories behind each structure, narrated through synchronized mobile applications.

The interplay of BIM, laser scanning, ML, and IoT in these case studies from Saudi Arabia illustrates a transformative approach to heritage conservation. Through incorporating specific devices and platforms, such as Autodesk Revit for BIM, Trimble TX8 and FARO Focus3D for laser scanning, IBM Watson and TensorFlow for ML, and an array of IoT sensors, the research paved the way for novel solutions that respect the authenticity of heritage sites while embracing modernity. These technologies collectively form a comprehensive DT framework, as can be seen in Figure 20, ensuring the longevity and accessibility of cultural heritage for future generations. This flowchart encapsulates the integrative approach necessary for effective heritage conservation, illustrating how various technologies intersect and complement each other. By depicting the relationships between BIM, laser scanning, ML, and IoT, Figure 20 clarifies the process of creating a digital twin, which acts as a dynamic repository of knowledge for ongoing conservation efforts. Such a framework not only supports the preservation of physical structures but also enhances public engagement through immersive experiences. The visual clarity of this figure aids stakeholders in understanding the potential of these technologies to transform traditional practices, promoting a collaborative framework that respects both innovation and heritage. Through such innovative implementations, DT conserves history and redefines the narrative of heritage preservation.

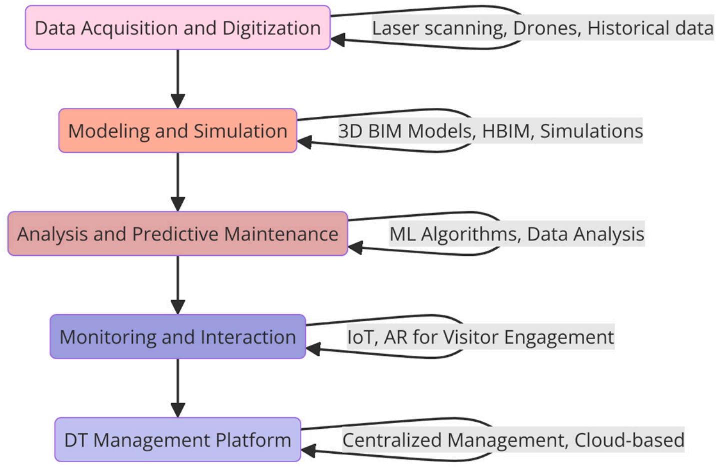

Figure 20. Flowchart depicting the integrative framework of digital twin technology for the preservation of heritage buildings in the case study.

4. Discussion

The integration of emerging technologies such as digital twins (DTs), building information modeling (BIM), 3D laser scanning, machine learning (ML), and the Internet of Things (IoT) in the conservation of heritage buildings marks a significant shift towards more informed and precise preservation practices. Expert interviews conducted as part of this study underscore the value of these technologies in enhancing structural analysis and restoration planning. The consensus among professionals in the architecture, engineering, and construction (AEC) sector is clear; detailed digital representations and predictive analytics can significantly improve the identification of vulnerabilities and the formulation of conservation strategies. Nonetheless, the interviews revealed a gap in the widespread adoption and understanding of these technologies, highlighting the necessity for focused training and knowledge sharing within the conservation community.

To deepen the discussion on the integration of emerging technologies in heritage conservation, it is essential to explore the complex potentials and challenges associated with these advancements. The insights gleaned from expert interviews and bibliometric analysis indicate a transformative impact on preservation practices, yet a more nuanced examination is necessary. For instance, digital twins (DTs) have demonstrated significant potential in real-time monitoring and predictive maintenance, allowing for proactive conservation strategies. However, the implementation of DTs also faces challenges, such as the need for extensive initial data collection and the integration of various data sources, which can be resource-intensive. Case studies, such as the application of BIM in the restoration of historic buildings, reveal both successes—like enhanced collaboration among stakeholders and improved decision-making—and challenges, including difficulties in standardizing data formats and ensuring interoperability. By incorporating specific examples of these technologies in action, the discussion can provide clearer insights into how they can revolutionize heritage conservation while addressing the practical hurdles that must be overcome. This approach will enrich the manuscript's academic and practical value, offering a comprehensive understanding of the landscape of digital innovation in heritage preservation.

The bibliometric analysis of literature from 1996 to 2024 reveals an increasing academic and professional interest in the application of technology in heritage conservation. This growing attention underscores the recognition of digital innovations as vital tools in the preservation of cultural heritage. However, the analysis also points to a notable imbalance, with a considerable focus on technological advancements at the expense of practical applications and interdisciplinary methodologies. This imbalance suggests that while technological innovation is progressing rapidly, its integration into heritage conservation practices remains an area ripe for further exploration and development.

Identified research gaps through this paper illuminate several critical areas needing attention. Among these, the absence of standardized protocols for integrating laser scanning data with DTs presents a significant barrier to creating unified digital representations of heritage sites. Furthermore, the demand for detailed finite element models that accurately reflect the structural characteristics of heritage buildings emphasizes the need for enhanced data processing and modeling techniques. Challenges in automating Heritage Building Information Modeling (HBIM) processes and integrating 360° photography further underscore the technological and methodological advancements required to advance the field of heritage conservation.

In combining the insights from expert interviews, bibliometric analysis, and identified research gaps, this discussion underscores the transformative potential of emerging technologies in heritage building conservation. While challenges remain, particularly in the realms of technology adoption, interdisciplinary collaboration, and ethical considerations, the path forward is clear. The ongoing restoration efforts at Notre Dame and similar high-profile projects illustrate the practical application of digital technologies in heritage conservation [246]. For instance, the use of 3D laser scanning and building information modeling (BIM) [247] has been instrumental in creating detailed digital models that guide restoration strategies, ensuring the preservation of both the physical and intangible aspects of the structure. Additionally, recent studies have focused on the integration of digital twins into heritage conservation practices, highlighting efforts to organize heritage data for effective conservation planning [102]. These initiatives emphasize the necessity of adapting current standards for heritage documentation to incorporate advanced digital tools, facilitating a more comprehensive approach to conservation that respects historical integrity while leveraging technological advancements. By acknowledging such case studies, the manuscript underscores the importance of practical applications of technology in enhancing heritage conservation efforts. Bridging the identified gaps necessitates a concerted effort from technologists, conservationists, and policymakers to foster the development and application of digital innovations in a manner that respects both the material and intangible aspects of cultural heritage. Addressing these challenges through multidisciplinary research and practice will enhance the effectiveness of conservation efforts and ensure the sustainable preservation of heritage buildings for future generations.

5. Future Directions

The exploration of emerging technologies in the conservation of heritage buildings has unveiled promising avenues for future research. As highlighted in the discussion, the integration of DT, BIM, 3D laser scanning, ML, and the IoT offers transformative potential for heritage conservation. However, to fully harness these technologies, several key areas require further exploration and development.

Additionally, future research will involve selecting a specific case study in Saudi Arabia to focus on the detailed potential of applying emerging technologies in heritage conservation. This targeted exploration aims to illustrate how these technologies, including digital twin (DT), building information modeling (BIM), and 3D laser scanning, can be effectively utilized to preserve and restore cultural heritage. By concentrating on a specific site, this research will provide comprehensive insights into the impact and applications of these technologies, thereby enriching the overall discourse on digital innovations in heritage preservation.

Firstly, future research should focus on developing standardized information protocols for integrating diverse data sources, such as laser scanning and IoT sensor data, with DT and BIM frameworks. To address the noted gap regarding standardization in the integration of digital tools in heritage conservation, it is essential to provide specific, actionable recommendations for practitioners. A dedicated section will be included that outlines detailed standardization protocols, including data protocols for the integration of diverse digital tools, interoperability standards to ensure seamless data exchange, and guidelines for effectively utilizing various technologies in conservation practices. These recommendations will enhance the practical utility of the manuscript and position it as a pivotal resource for professionals in the field, facilitating the successful adoption and implementation of digital innovations in heritage preservation. Standardization would facilitate seamless data exchange and interoperability among different technological platforms, enhancing the accuracy and efficiency of digital conservation efforts. Investigating methodologies for automating the conversion of raw data into actionable insights within Heritage Building Information Modeling (HBIM) processes could significantly streamline conservation workflows.

Additionally, there is a crucial need for research into the ethical implications of using digital technologies in heritage conservation. Developing ethical guidelines that address issues of authenticity, representation, and accessibility in digital replication and restoration is paramount. This includes considering the impact of these technologies on the perception of historical integrity and exploring how they can be used responsibly to support rather than supplant traditional conservation methods.

Another promising area for future research lies in the application of machine learning algorithms to predict deterioration and guide conservation strategies. Studies could explore the development of predictive models that utilize environmental, structural, and historical data to forecast potential risks and recommend preventative measures. This approach would mark a significant shift towards proactive conservation, leveraging the vast amounts of data generated by IoT sensors and other digital tools to anticipate and mitigate deterioration before it occurs.

Lastly, the potential of augmented reality (AR) and virtual reality (VR) technologies to enrich the heritage experience invites further investigation. Research should explore innovative ways to use AR and VR for educational and engagement purposes, creating immersive experiences that allow the public to connect with heritage sites in new and meaningful ways. Additionally, studies could examine how these technologies can be employed for remote conservation assessments, enabling experts to evaluate and plan conservation interventions without the need for physical presence on site.

6. Limitations

This research, while comprehensive in its scope and analysis, encounters several limitations that are inherent to studies of this nature. Firstly, the reliance on expert interviews, though invaluable for gaining in-depth insights, is subject to the availability and the perspectives of the respondents. Despite efforts to include a diverse range of professionals across the architecture, engineering, and construction (AEC) sector, the views represented may not fully encompass the breadth of opinions and experiences within the field. This limitation suggests a potential bias towards the technologies and methodologies that are currently more visible or accessible to those within certain segments of the conservation community.

Secondly, bibliometric analysis, while offering a robust overview of the academic landscape surrounding the integration of emerging technologies in heritage conservation, may not capture the entirety of relevant research and developments. Given the rapid pace of technological advancement and the interdisciplinary nature of heritage conservation, significant work may be published outside the traditional academic channels or in rapidly evolving fields not thoroughly indexed by the databases utilized for this review.

Furthermore, the identification of research gaps, although comprehensive, is constrained by the scope of the literature reviewed. Innovations and challenges emerging from practice, unpublished works, or those within closely related but distinct fields may not be fully represented. This limitation underscores the necessity for ongoing review and synthesis of literature across a broader spectrum of sources to ensure a holistic understanding of the field.

Additionally, the research primarily focuses on the technological aspects of heritage conservation, potentially underrepresenting the socio-cultural, economic, and ethical dimensions that play crucial roles in the preservation of heritage buildings. The complex interplay between technology and these broader considerations is essential for the development of sustainable, ethical, and effective conservation strategies but may not be fully explored within the confines of this study.

7. Conclusions

The exploration into the integration of emerging technologies such as DTs, BIM, 3D laser scanning, ML, and the IoT within the field of heritage building conservation presents an important shift towards safeguarding cultural heritage with unprecedented precision and foresight. This review paper has integrated expert insights, bibliometric analyses, and identified research gaps to illuminate the vast potential and the challenges inherent in applying these technologies to the conservation of heritage buildings. The consensus among experts and the trends identified through bibliometric analysis underscore a burgeoning interest and optimism in the role of technology in preservation efforts. However, they also highlight a critical need for standardization, ethical considerations, interdisciplinary collaboration, and further research to overcome current limitations and fully realize the potential of these digital tools in conservation practices.

Future research directions, as outlined, aim to bridge the identified gaps through the development of standardized protocols, ethical frameworks, predictive models for conservation, and innovative applications of AR and VR technologies. These efforts promise to enhance the efficiency and effectiveness of conservation strategies as well as to foster a deeper connection between the public and heritage sites, ensuring that these treasures are preserved for future generations to appreciate and learn from.

While the path forward is fraught with challenges, the integration of digital innovations into heritage conservation offers a new paradigm that marries the rich insights of the past with the boundless possibilities of the future. By continuing to explore, refine, and apply these technologies, it will be possible to stand on the cusp of revolutionizing the way to preserve and interact with cultural heritage, ensuring its endurance and relevance in an ever-evolving world.

Funding: This research was funded by Prince Sultan University, RIC Research and Initiative Center, grant number: seed project n. 112, 2022–2023. The APC was funded by the RIC Research and Initiative Center, Prince Sultan University, Riyadh, Saudi Arabia.

Institutional Review Board Statement: Informed consent was obtained from all subjects involved in the study. The study was conducted following the Declaration of Helsinki and approved by the Institutional Review Board of Prince Sultan University RIC Seed Project n. 112, 2022–2023.

Data Availability Statement: Data are available at Prince Sultan University, P.I. Responsible Dr. Silvia Mazzetto.

Acknowledgments: The author gratefully acknowledges Prince Sultan University for covering the article processing charges (APC) and providing financial incentives. Special thanks are also extended to the Prince Sultan College of Architecture and Design, the Department of Architecture, and the Sustainable Architecture Laboratory (SA Lab) for fostering a supportive research environment that contributed to these outcomes.

Conflicts of Interest: The authors declare no conflicts of interest.

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