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Review

A State-of-the-Art Review and Bibliometric Analysis on the Smart Preservation of Heritages

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Abstract: The preservation of heritage buildings is a crucial endeavour for countries worldwide. This study presents a comprehensive bibliometric analysis of the latest trends in smart applications for heritage building preservation within the context of Industry 4.0 and Industry 5.0, covering the period of 2020–2024. A total of 216 peer-reviewed journal articles obtained from the Scopus database were subjected to analysis using RStudio and VOSviewer. The methodology was based on a dual analysis, including surface-level examination and in-depth exploration. Consequently, a new conceptual framework is presented for achieving smart preservation of heritages. It is structured based on two pillars: the physical methods pillar, including smart devices and smart processes, and the digital methods pillar, involving smart technologies and environments. Also, the results revealed that the dominant portion of literature publications (61%) emphasize specific topics such as interoperability, monitoring, data management, and documentation. However, training and community engagement represent an insufficient fraction (2–6%), and more research is needed in the future. This paper concludes by discussing a future innovative vision for policy and industry through urging policymakers to promote interoperability standards; address data security; and fund innovative, low-cost technologies, as well as advocating the industry sectors for public engagement, sustainable preservation, and prioritizing skill development programs and workforce.

Keywords: heritage preservation; smart heritage; industrial revolution; AI; H-BIM/DTs; VR/AR; UAVs

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1. Introduction

Cultural heritage is essential for the historic values of a nation and for future generations [1–4]. Interventions are necessary to prevent losses, guarantee integrity, and ensure energy efficiency and environmental sustainability in historic buildings [5–7]. Safeguarding heritage through preservation, rehabilitation, retrofitting, restoration, or adaptation methods contributes to sustainability because they provide ways to limit the consumption of materials and energy, together with waste generation [8,9]. This is a mission with multiple duties and various stakeholders to ensure its preservation and protection, aligning with the 11th goal of the United Nations' Sustainable Development Goals (SDGs). As called for in the 2030 Agenda, efforts to protect and safeguard the world's cultural and natural heritage are to be strengthened [10,11].

Cultural heritage should be treated holistically, but national and local authorities, all stakeholders, and users need to act together [12,13]. The preservation of heritage buildings captures a wide range of challenges, from construction materials and asset management to structural health monitoring, deterioration detection, energy, and thermal performance, while seeking a reduction in environmental impacts [14,15]. A whole building approach (WBA) is necessary for keeping low-energy retrofitting in balance with heritage values, as suggested by the Whole Building Design Guide (WBDG) Historic Preservation Subcommittee; there are five basic steps in the preservation process: identify, investigate, develop, execute, and educate [16,17]. These need to be integrated with other project goals, entailing close coordination on the part of preservationists and design disciplines as a multidisciplinary process [18,19].

Smart cities leverage technology to efficiently collect, collate, and disseminate significant amounts of information to the growing population, thereby improving the functioning of cities, sustaining the environment, and earning it the title of a 'smart' city [20–22]. Smart cities evolved as a discipline towards the end of the 20th century, integrating technology along with infrastructure and architecture to solve problems of a social, economic, and environmental nature [23,24]. Cultural heritage can be integrated into smart city strategic areas, offering numerous goals and potential applications if treated as an exploited asset through the integration between cultural heritage preservation and smart city applications. Smart cities have prompted the integration of technology in monitoring as well as in the predictive maintenance of cultural heritage buildings [20]. This kind of integration will further raise awareness of artistic and cultural heritage monitoring, allowing for better-planned interventions and timing [25]. By leveraging advanced technologies, smart cities can improve the holistic preservation processes, including planning, coordination, prevention, maintenance, restoration, preventive intervention, and limiting risk situations [13,26].

In addition, smart technologies, including high-resolution imaging, 3D scanning, and photogrammetry, greatly help in the digitization and preservation of historic artifacts and sites [27–30]. Data management solutions such as databases and cloud-based information circles further aid in both the storage and distribution of heritage information. Smart heritage has been an emerging concept for the past decade; it connotes urban conservation and restoration [31]. Smart heritage is a fusion of smart technology and heritage disciplines. It refers to the use of state-of-the-art technologies in the management of heritage issues or digitalized historic buildings through 3D modeling technologies [32–34]. Smart heritage utilizes advanced technologies to manage heritage-related issues, contributing to heritage preservation and restoration, a new discourse on both technological and heritage aspects [29,31,35]. Heritage forms a crucial element in the development of the Smart heritage discipline, of which the United Nations Educational, Scientific and Cultural Organization (UNESCO) describes heritage as the cultural and natural significance that transcends national boundaries and whose safeguarding is of common importance to the present and future generations. In the context of UNESCO, digital heritage belongs to a new category of human knowledge and expression created digitally or converted into digital form from existing analog resources [31].

Academic literature has been increasingly witnessing a mention of Smart Heritage over the past decade, pointing at its potential to be a frontier where smart technology converges with heritage disciplines [36,37]. Researchers largely delved into smart heritage, a subject focusing on digital technologies automatically and autonomously engaging the functions of the cities [38,39]. Digital technologies involve such advanced techniques for support to restoration and protection as satellite technologies, architectural studies, knowledge of ancient materials, cataloging strategies, and the collection of semantic and survey data [40–42]. Digital preservation has three characteristics: non destructiveness, convenient operation, and the characteristic of authenticity [26]. Recently, technological advancements have transformed the preservation processes of cultural heritage to be documented and restored. This transformation leads to enhancements in precision, efficiency, and sustainability of preservation practices. These smart technologies can be building information modeling (BIM), digital twins (DTs), 3D scanning, artificial intelligence (AI), the Internet of Things (IoT), virtual reality (VR), etc.

Artificial intelligence (AI) techniques are continuously improving the preservation process of heritages, transforming the whole process [37,43]. Beginning with the optimization of the diagnosis and documentation step through AI, machine learning (ML) in this step may be useful in analyzing the data to determine the status and forecast requirements [44]. This can assist in improving decision making, decreasing possible damage, and enhancing preservation vision [45]. Then, the processing of data from the Scan-to-BIM can be aided by deep learning (DL) for enriching heritage understanding [46–49]. Also, convolutional neural networks (CNNs) may be used to analyze and process complicated data, providing a complete evaluation of structural demolition, material, and characteristics [50]. After that, computer vision (CV) facilitates remote access, enhances virtual restoration, and helps create precise 3D models that result in careful virtual reconstructions [49]. Finally, AI-based systems, including environmental monitoring systems that can track different parameters like humidity, temperature, and light exposure, can also provide real-time data for preventive maintenance and decrease degradation of cultural heritage [51].

Recent scientific research has focused on the adoption of multiple smart technologies in cultural heritage preservation. Examples are the discussing of the adoption of IoT, BIM, and DTs in cultural heritage preservation for intelligent monitoring, predictive maintenance, and decision making, such as studies by Casillo M. et al., 2024, and Cecere L. et al., 2024 [25,52]. Also, the usage of AI, DL, or ML in cultural heritage preservation is discussed in multiple research papers, which highlights the synergy among AI, drones, and IoT technologies for visual inspections [53–55]. Additionally, several studies have pointed out the adoption of VR, augmented reality (AR), and the Metaverse, demonstrating their beneficial role in enhancing the experience through visual representation of heritage assets [56–60]. Furthermore, to avoid compromising the heritage values using advanced technologies, the latest research calls for stakeholders' involvement and the development of standardized protocols for the preservation processes [2,61–63]. Moreover, previous studies discussed the enhancement of efficiency in surveying techniques when cooperating with BIM, such as a study by Borkowski et al. (2024) that discusses the integration of laser scanning, digital photogrammetry, and BIM for the preservation and conservation of historic buildings [64].

The combination of technologies can achieve multiple goals, as each technology achieves a specific role and objective, for instance, the combination of IoT, AR/VR/Metaverse, and BIM [65,66]. It will help in each stage of the preservation of heritage assets by starting with achieving the goal of IoT sensors that are used for real-time data collection accurately [67–69], then the adoption of BIM in order to create a 3D representation of those heritage buildings, suggesting scenarios, and reaching the optimum decision [8,11,12]. Finally, the usage of virtual technologies such as AR, VR, and the Metaverse can help in each stage of the preservation process, including pre-conservation based on visualization, reliable monitoring, and maintenance procedures, which allows for the choice between retrofits, as well as construction and conservation through digitalization of the construction sites, which offer labor safety and quality control [70–72]. Also, virtual technologies can be used post-conservation to enhance the visitors' experience in the heritage sites [70,73].

While these studies result in significant insights and conclusions, gaps remain in implementing the full potential of synergy among smart technologies through a holistic perspective. Therefore, this study developed several research questions to build a broad foundation of existing literature regarding the adoption of smart technologies for heritage preservation. These questions are shaping the structure of the study, starting with the first question, which is "What are the main smart technologies that can be used in cultural heritage preservation?". Then, "How can the mainstream trends of relevant research be analyzed?". After that, "What are the main trends of smart technologies for heritage preservation?". Finally, "What are the key challenges, benefits, and future research priorities for smart heritage preservation?" So, this research aims to answer each question sequentially, covering background, methods, results, and discussion to shape a holistic vision of academic knowledge and professional practice relating to heritage preservation.

This study aimed to understand how previous literature attempted to enhance the heritage preservation process using various smart technologies. Figure 1 represents the structure of this research. Consequently, this study is organized as follows: Section 2 reviews the background of smart applications in heritage preservation. Next, in Section 3, the methodology for understanding the mainstream trend in relevant research is outlined. Section 4 presents the results of the relevant literature based on a bibliometric approach, including (a) surface-level analysis and (b) in-depth analysis. Section 5 then discusses a future innovative vision through a proposed framework for the smart preservation of heritage and demonstrates the key benefits, challenges, and future research. Finally, conclusions are drawn in Section 6.

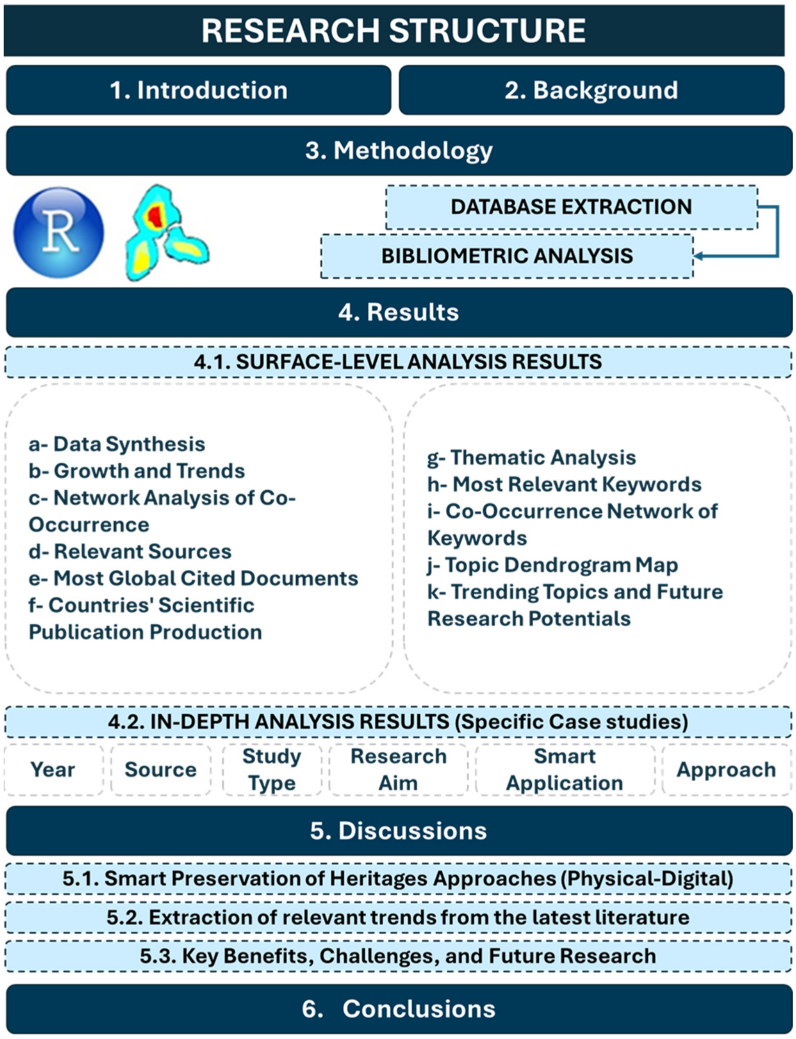

Figure 1. Visualization of the research structure. Source: the authors.

2. Background: Smart Applications in Heritage Preservation

The industrial revolution affected heritage preservation processes [74]. It began with Industry 1.0, which appeared in the form of physical restoration and preservation through manual efforts, and Industry 2.0, through enhanced restoration with better-quality materials and more efficient processes [75]. As for Industry 3.0, it brought about development with the emergence of digital archives and databases, computer-aided design (CAD) software 3.0, and non-invasive imaging technologies (infrared and 3D scanning), resulting in precise restoration tasks with automated machinery and detailed analysis without damage to artifacts [76]. Industry 4.0, which is related to cyber-physical systems and smart technologies, came as a turning point with the emergence of advanced tools and technology such as IoT sensors, AI, VR, AR DTs, blockchain, drones, robotics, and BIM, which helped in real-time monitoring [77]. With IoT came big data analytics, VR/AR for immersive experiences, predictive maintenance with AI, creation of digital twins, blockchain for provenance tracking, detailed 3D models, maps, and digital reconstructions [78,79]. It moved to greatly enhance community engagement through extensive digital accessibility, virtual tours, and community engagement through technology [80,81].

As for the emergence of Industry 5.0, which is related to human-centric and sustainable technologies, heritage preservation operations were strengthened through human–robot collaboration, personalized AI, biotechnology, sustainable practices, digital twins, smart materials, additive manufacturing, and laser cleaning techniques [82,83]. With advanced AI respecting cultural codes, this led to biotechnology for bio-cleaning, sustainable materials, data analytics, pattern recognition, secure blockchain record-keeping, collaboration between humans and robots for precise work, eco-friendly methods and materials, innovative materials, accurate documentation, physical exhibitions and replicas, greater stakeholders' involvement, personalized experiences, and virtual heritage experiences [84,85]. Overall, the smart evolution in heritage preservation was only possible had there not been the advancement of technologies to Industry 4.0 and later Industry 5.0. The fact that digital technology allows for optimization of restoration strategies multiplies the efficiency of digital cultural heritage conservation [86–88]. Figure 2 illustrates how industrial technology advancements have improved heritage preservation actions, as well as the evolution of accessibility and stakeholders' involvement in the heritage preservation process.

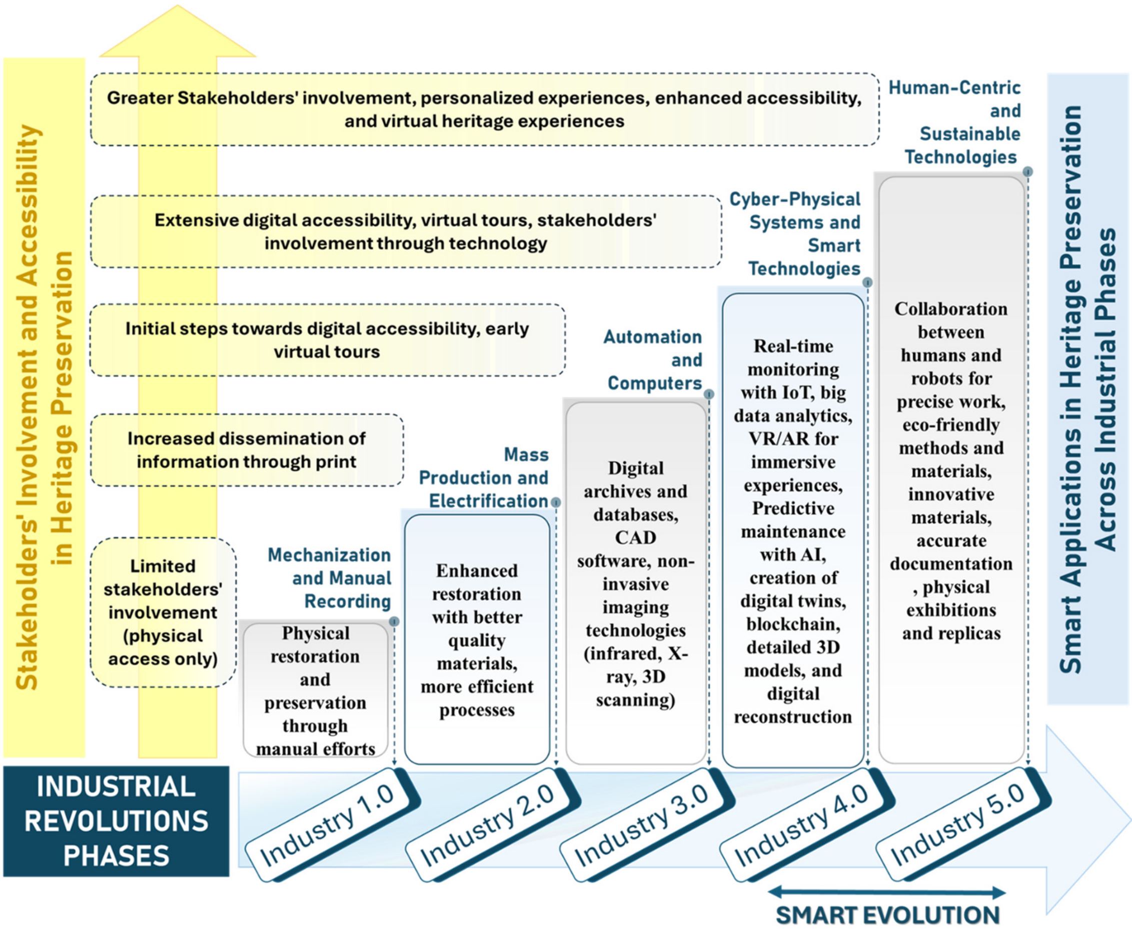

Figure 2. Industrial revolution impact on heritage preservation processes. Source: the authors.

3. Materials and Methods

Figure 3 shows the methodological structure of the research and database extraction. This section describes how information about publications that relate to heritage preservation and smart technology was gathered, as well as the software used in conducting the bibliometric analysis. Database selection is the most significant step for conducting scientific reviews because it has a direct impact on the results' quality and demonstrates the research's uniqueness and gaps in this field [89,90]. There are several sources to retrieve data, including Scopus, Medline, Web of Science, and Google Scholar. However, Scopus is the most widely used database in bibliometric analysis, covering the full mapping of trends, contributions to research, and the development of publishing in subjects, thus being highly useful for gaining insight into their evolution and impact [91,92].

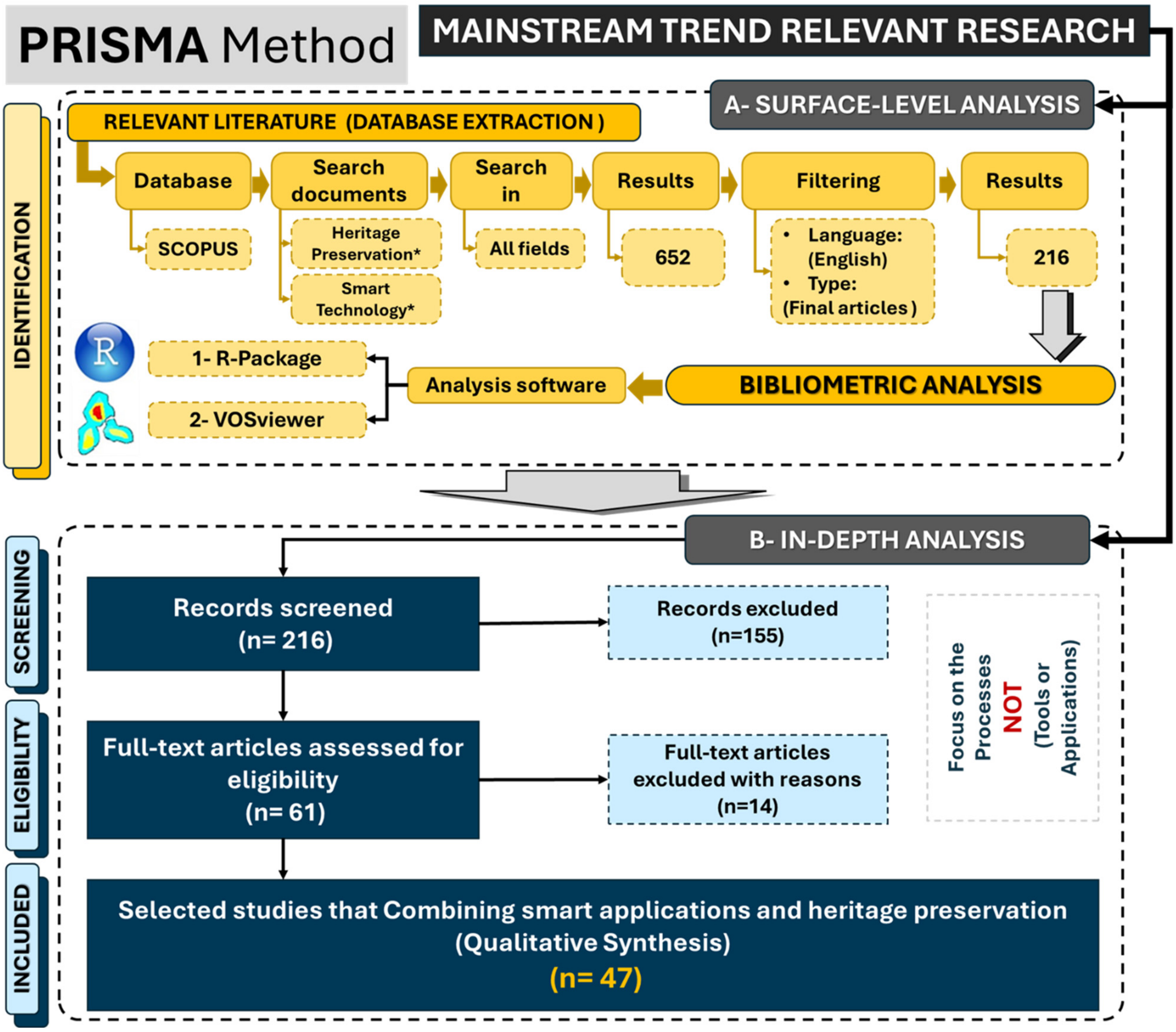

Figure 3. Visualization of the research methodology. In Scopus, (*) is used as a wildcard to allow variations of a word to be retrieved in a keyword search. Source: the authors.

3.1. Database Extraction

A preliminary search was conducted for documents related to "heritage preservation" and "smart technology" in Scopus, searching in all fields, including searching by the following (heritage AND preservation) AND ALL (digital AND heritage) AND ALL (smart AND city) OR ALL (smart AND heritage) AND (buildings) AND (technology), searching limited to the Engineering subject, and in the time frame from 2020 to 2024 to reach the latest relevant trends. This search returned 652 documents on 5 July 2024. Publications in languages other than English were excluded, and the selected documents were limited to final articles. As a result, 216 documents were found to meet the initial criteria. Table 1 summarizes the database extraction parameters with inclusion and exclusion criteria.

Table 1. Database extraction parameters with inclusion and exclusion criteria. Source: the authors.

Parameter	Details	Inclusion Criteria	Exclusion Criteria
Database	Scopus	-	-
Keywords	"heritage AND preservation" AND ALL ("digital AND heritage") AND ALL ("smart AND city") OR ("smart AND heritage") AND ("buildings") AND ("technology")	Keywords aligned with heritage preservation and smart technologies	-
Fields	All fields	-	-
Subject area	Engineering	Engineering-related topics	Topics outside engineering
Time frame	2020–2024	Publications from 2020 onwards	Publications before 2020
Language	English only	English language only	Non-English publications
Document type	Final articles only	Peer-reviewed journal articles	Non-final articles (e.g., conference abstracts, reviews)
Initial search results	652 documents (as of 5 July 2024)	-	-
Documents after filters	216 documents	Relevant documents on smart technology in heritage preservation	Irrelevant documents or duplicates

3.2. Bibliometric Analysis

This selected database is used for understanding the mainstream trend relevant research through two types of analyses: surface-level analysis and bibliometric analysis, with the help of two main forms of software: RStudio version 4.3.2 and VOSviewer version 1.6.19. The quantitative method of document description using bibliometric analysis has become a well-established component of information research. Any topic matters and the majority of issues about written communication can be addressed with it. Broadly speaking, bibliometrics may be defined as the statistical or quantitative analysis of literature. Based on visual analysis, the bibliometric analysis used in this study combines mathematical and statistical techniques with the distribution of literature to show quantitative relationships, internal research structure, disciplinary features, and the evolution of a particular subject [93].

RStudio includes tools for bibliometric data analysis, including Bibliometrix and biblioshiny packages for quantitative research through ML [93]. Bibliometrix is an open-source tool for conducting quantitative research in scientometrics and bibliometrics. It is based on the integration of all key bibliometric analytical techniques, supporting the application programming interfaces (APIs). Moreover, by adding Biblioshiny to the programming code, it can appear as an easy web interface for data gathering, filtering, analytics, and generating insightful plots across various metrics [94]. Additionally, VOSviewer specializes in network analysis and visualization, using algorithms to cluster data based on similarities [95]. Both use text mining and natural language processing (NLP) techniques to extract significant terms from titles and abstracts, assigning relevance scores [96].

This research paper uses a mixed method approach, which includes macro-quantitative analysis by examining a large number of relevant studies in the SCOPUS database using a bibliometric approach (216 documents). It also involves micro-qualitative analysis by conducting an in-depth analysis of the relationship between heritage preservation and smart technology. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method was employed to narrow the scope and filter the data in relevant research to determine trends, key benefits, challenges, and future research. The final data sample for the in-depth analysis consisted of (47 documents), selected based on two criteria:

1. The articles discussed content on heritage preservation and the use of other smart innovations to improve these projects.
2. The choice of the articles was based on their potential applications within the heritage preservation processes, which aligned with the main research trend.

This macro-quantitative analysis aims to reach out to the following: data synthesis, growth and trends, network analysis of co-occurrence, relevant sources, most global cited documents, countries' scientific publication production, thematic analysis, most relevant keywords, co-occurrence network of keywords, dendrogram map, trending topics, and future research potentials. Then, the second type of analysis is an in-depth analysis to select studies that combine smart applications and heritage preservation for qualitative synthesis. At this level, the analysis was deeply scoped to identify the source; type of study (literature review, analytical study, or applied study); and what the research aim, smart application, and approach were (either physically or digitally).

4. Results

This section presents a bibliometric approach that includes (a) surface-level analysis and (b) in-depth analysis; it discusses the findings to reflect the growth and trends of research on the smart preservation of heritages, scholars, countries, and social networks; the hierarchical clustering of relevant topics; and the trending topics and future research potentials of the smart preservation of heritages.

4.1. Surface-Level Analysis

The surface-level analysis results from the state-of-the-art, up-to-date prospects for smartness and heritage preservation research. The document encapsulates the data synthesis, growth and trends, the co-occurrence network analysis with relevant sources, as well as the most globally cited documents. The document surveys the scientific publication production at the country level and provides a thematic analysis of the field pertaining to smartness and heritage. It identifies the most relevant keywords, together with a co-occurrence network of those terms, which is supported by a topic dendrogram map. In this manner, it contributes to the literature on what has been trending in the field and possible future lines of research.

4.1.1. Data Synthesis

The dataset focuses on recent studies, specifically from 2020 to 2024. The scope of the study is smart heritage preservation, with more emphasis on Industry 4.0 and Industry 5.0. This implies that the subject is emerging and significant. In this study, with the previous inclusion and exclusion criteria, it can be seen that scientific contributions came from a substantial quantity of 216 documents; the dataset provides a solid foundation for the study. The notable yearly growth rate of 18.24% and documented average age of 1.66 years demonstrate how rapidly the issue is gaining scholarly attention. In keeping with the rapid rise that has been seen, the majority of the study is recent. Each paper has garnered 13.28 citations on average, indicating a moderate effect on the academic community. The dataset includes 1424 keywords plus, and 891 author's keywords for 793 authors with a global interest and cross-border cooperation of 25.46%. All of these patterns indicate a rapidly developing, multidisciplinary field of active study. Table 2 summarizes the research on smart preservation of heritages that have been published. The table reveals the main information of the collected data.

Table 2. Data synthesis with an overview of the dataset and main data. Source: the authors, based on RStudio software.

Description	Results
Main information about data	
Timespan	2020:2024
Documents	216
Annual growth rate %	18.24
Document average age	1.66
Average citations per doc	13.28
References	14,852
Document contents	
Keywords plus (id)	1424
Author's keywords (de)	891
Authors	
Authors	793
Authors of single-authored docs	8
Author collaboration	
Single-authored docs	8
Co-authors per doc	4.09
International co-authorships %	25.46
Document types	
Article	216

4.1.2. Growth and Trends

In this section, the annual scientific production of articles in the field of the study of smart preservation of heritages is presented. Figure 4 shows the annual scientific growth of the smart preservation of heritages study field computed by RStudio software. The search for the smart preservation of heritages began in 2013, with only two documents recorded that year, which were entitled Software for Storage and Management of Microclimatic Data for Preventive Conservation of Cultural Heritage, authored by Fernández-Navajas et al. (2013), and Historic Building Information Modelling: Adding intelligence to laser and image-based surveys of European classical architecture, presented by Murphy et al. (2013) [97,98]. Then, the publications remained comparatively low and steady, and they had little growth. After that, there has been a discernible rise in the number of published articles since approximately 2018. Between 2020 and 2023, the growth accelerated especially. Finally, publications related to this field increased significantly with the technological progress in the construction industry, reaching now in 2023 a total of 103 publications. This implies that there has been a notable increase in interest and research in this area in recent times.

4.1.3. Network Analysis of Co-Occurrence

Keyword co-occurrence analysis can also be performed to identify research frontiers and hotspots [99,100]. Therefore, the most popular keywords for this study related to previous publications are shown in Figure 5 and Table 3. The word cloud is a visual representation of the keyword metadata analysis. It reflects the most relevant terms depending on the collected database, and the size of the word varies according to the frequency. In the previous figure, the most frequent word is historic preservation; on the other hand, the keywords related to using cutting-edge technologies, such as computer vision and learning systems, are still less discussed in the research.

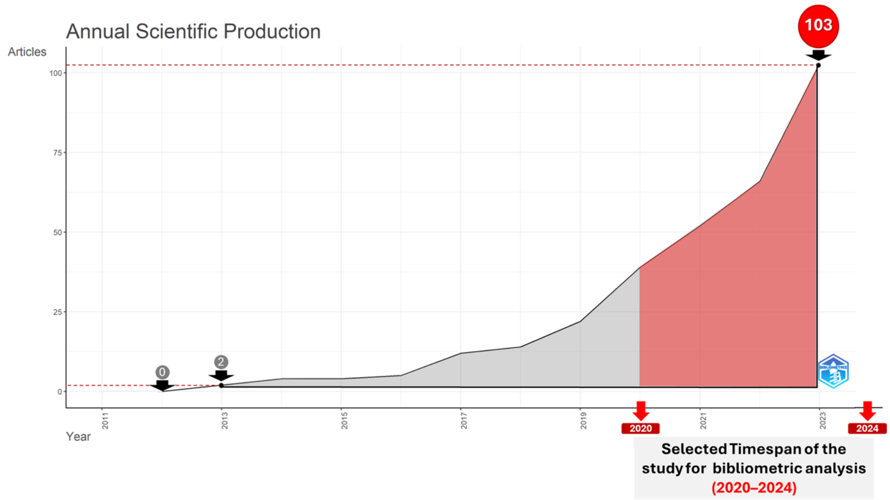

Figure 4. Annual scientific production. Source: the authors, by RStudio software.

Figure 5. A visualized word cloud of the research keywords. Source: the authors, by RStudio software.

Table 3. Top ten most frequent words. Source: the authors, based on RStudio software.

N	Terms	Frequency
1	historic preservation	43
2	architectural design	32
3	heritage buildings	21
4	building information modelling	20
5	cultural heritages	15
6	photogrammetry	14
7	virtual reality	14
8	deep learning	13
9	sustainable development	13
10	buildings	12

4.1.4. Relevant Sources

Table 4 and Figure 6 elaborate on the sources of relevant studies in the smart preservation of heritages, underlining the number of published documents. "*Buildings*" is the most prolific source, with 28 published documents that initially approach building science, engineering, and architecture. *Applied Sciences* is the second one, with 23 documents in applied natural sciences strongly advocating for interdisciplinary methodologies for heritage preservation and restoration. Additionally, "*Sensors*" concerns the part of sensing technologies in the assessment and preservation of the structural and environmental dimensions that characterize heritage buildings; it has issued 11 documents. "*Building and Environment*" contributed eight documents, focusing on providing sustainable technologies for heritage buildings, and "*Energies*" has issued eight documents concerning energy efficiency and integration of renewable energy. Moreover, "*Heritage Science*" contributed eight documents on themes of how digital technologies adoption has the potential to fight destruction. "*IEEE Access*" confirmed the applicability of IoT, AI, and big data technologies in heritage site conservation and management by publishing eight documents. Moreover, the "*International Journal of Architectural Heritage*" contributed eight documents on themes of innovative conservation techniques, "*The Journal of Building Engineering*" contributed another six documents on advanced engineering solutions, and finally "*Sustainability*" contributed six documents on sustainable management and preservation of cultural heritage.

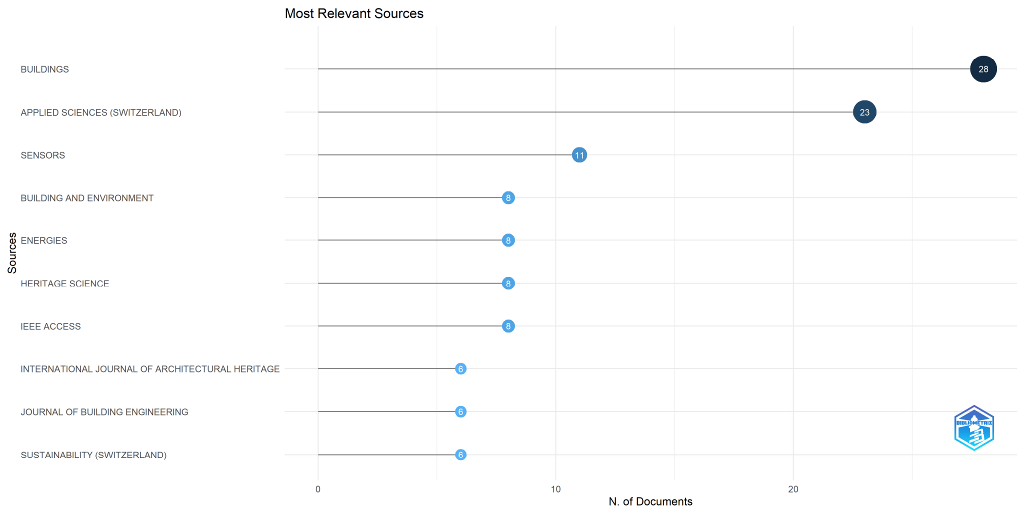

Figure 6. Relevant sources and documents in the smart preservation of heritages. Source: the authors, by RStudio.

Table 4. The top ten most relevant sources (journals). Source: the authors, based on RStudio software version 4.3.2.

N	Sources	Articles
1	*Buildings*	28
2	*Applied Sciences*	23
3	*Sensors*	11
4	*Building and Environment*	8
5	*Energies*	8
6	*Heritage Science*	8
7	*IEEE Access*	8
8	*International Journal of Architectural Heritage*	6

Table 4. *Cont.*

N	Sources	Articles
9	*Journal of Building Engineering*	6
10	*Sustainability*	6

4.1.5. Most Globally Cited Documents

The most widely referenced pertinent publications that influenced other research are crucial for figuring out how the area of study has developed. Table 5 displays documents that were the most referenced. Taking these studies into account had a significant impact, according to the citations annually. The study by Vargas et al. in 2020 [101] entitled Survey: Using augmented reality to improve learning motivation in cultural heritage studies was an important study with the highest value (47 total citations, 9.40 total citations per year, and 1.49 normalized total citations).

Table 5. Top ten most cited references based on the number of global citations from the collected dataset. Source: the authors, by RStudio software.

N	Ref	Authors	Title	Year	Source Title	Total Citations	TC per Year	Normalized TC
1	[101]	Vargas J.C.G.; Fabregat R.; Carrillo-Ramos A.; Jové T.	Survey: Using augmented reality to improve learning motivation in cultural heritage studies	2020	*Applied Sciences*	47	9.40	1.49
2	[102]	Angulo-Fornos R.; Castellano-Román M.	HBIM as support of preventive conservation actions in heritage architecture. experience of the renaissance quadrant facade of the cathedral of seville	2020	*Applied Sciences*	44	8.80	1.39
3	[57]	Zhang X.; Yang D.; Yow C.H.; Huang L.; Wu X.; Huang X.; Guo J.; Zhou S.; Cai Y.	Metaverse for Cultural Heritages	2022	*Electronics*	42	14.00	1.38
4	[68]	Bacco M.; Barsocchi P.; Cassara P.; Germanese D.; Gotta A.; Leone G.R.; Moroni D.; Pascali M.A.; Tampucci M.	Monitoring Ancient Buildings: Real Deployment of an IoT System Enhanced by UAVs and Virtual Reality	2020	*IEEE Access*	40	8.00	1.27
5	[103]	Moyano J.; Gil-Arizón I.; Nieto-Julián J.E.; Marín-García D.	Analysis and management of structural deformations through parametric models and HBIM workflow in architectural heritage	2022	*Journal of Building Engineering*	38	12.67	1.25

Table 5. *Cont.*

N	Ref	Authors	Title	Year	Source Title	Total Citations	TC per Year	Normalized TC
6	[104]	Skrzypczak I.; Oleniacz G.; Leśniak A.; Zima K.; Mrówczyńska M.; Kazak J.K.	Scan-to-BIM method in construction: assessment of the 3D buildings model accuracy in terms inventory measurements	2022	*Building Research and Information*	38	12.67	1.25
7	[105]	Ma Y.-P.	Extending 3D-GIS District Models and BIM-Based Building Models into Computer Gaming Environment for Better Workflow of Cultural Heritage Conservation	2021	*Applied Sciences*	37	9.25	2.70
8	[106]	Templin T.; Popielarczyk D.	The Use of Low-Cost Unmanned Aerial Vehicles in the Process of Building Models for Cultural Tourism, 3D Web and Augmented/Mixed Reality Applications	2020	*Sensors*	36	7.20	1.14
9	[107]	Palomar I.J.; García Valldecabres J.L.; Tzortzopoulos P.; Pellicer E.	An online platform to unify and synchronise heritage architecture information	2020	*Automation in Construction*	36	7.20	1.14
10	[108]	Marra A.; Gerbino S.; Greco A.; Fabbrocino G.	Combining Integrated Informative System and Historical Digital Twin for Maintenance and Preservation of Artistic Assets	2021	*Sensors*	35	8.75	2.55

4.1.6. Countries' Scientific Publication Production

The study also evaluated the scientific output, which is the number of publications in the field of studying the smart preservation of heritages across the countries. Table 6 and Figure 7 show the top 10 countries that have significantly contributed to research related to the study of the smart preservation of heritages. The reason these countries attach high importance to smart heritage preservation is due to a mixture of historical reasons, financial gains, national identity, and governmental and international support. The result demonstrates that China has the largest number of publications, reaching 185 publications, perhaps because it has a rich cultural heritage with quick development and technological progress, contributing to the huge number of initiatives and investments in smartness and heritage preservation [29,109]. Figure 8 represents the density of publications in each country.

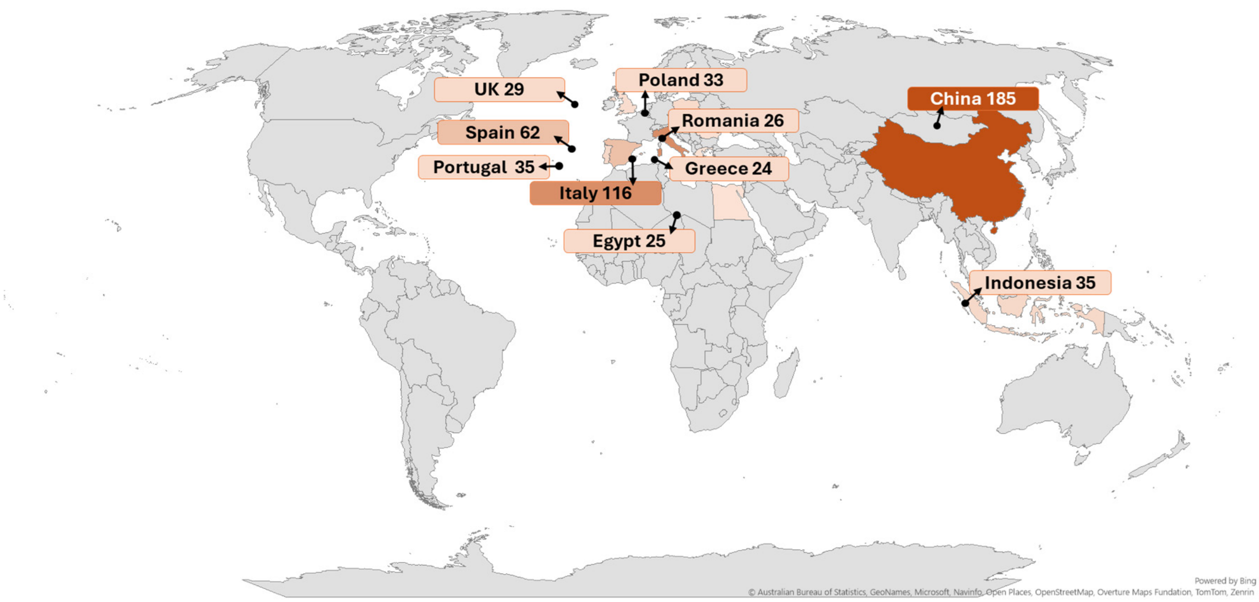

Figure 7. The top ten countries in the scientific production of the field of study. Source: the authors.

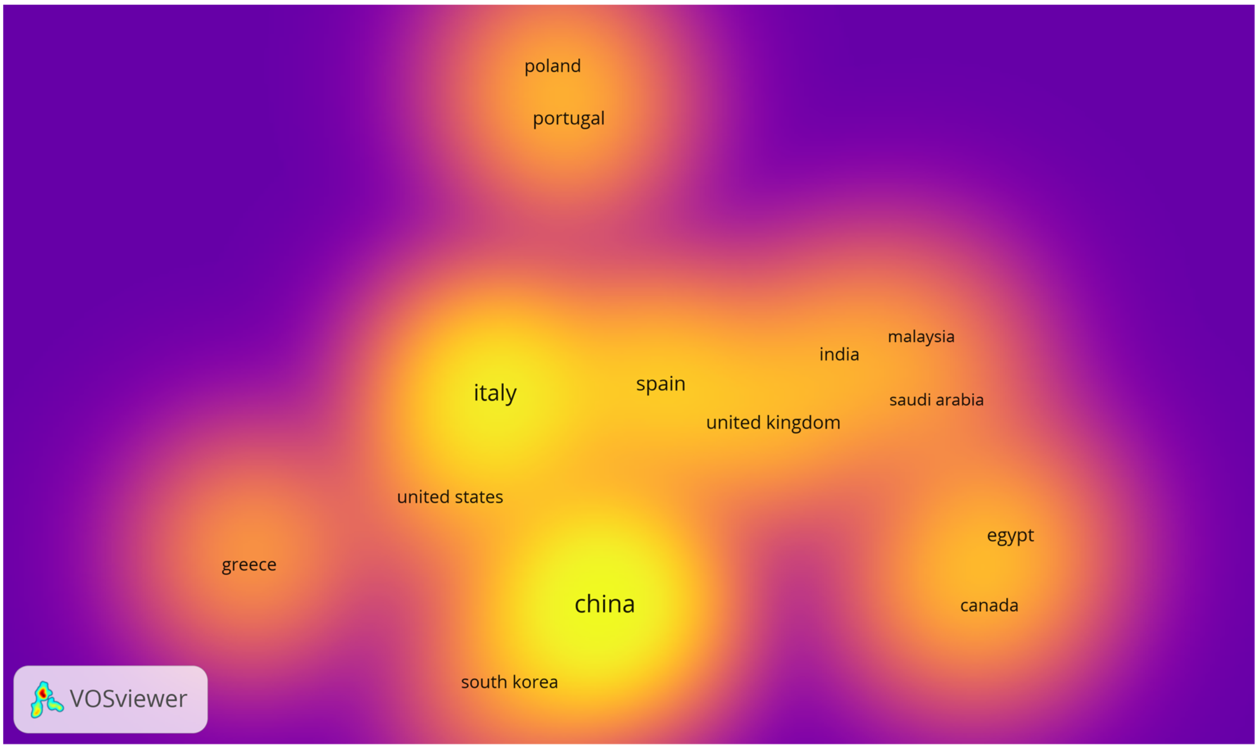

Figure 8. Countries' scientific publication production density, yellow regions indicate higher numbers of documents, while purple areas indicate lower numbers of documents. Source: the authors, by VOSviewer.

4.1.7. Thematic Analysis

A three-field plot generated in the field of smartness and heritage preservation illustrates the research on the correlation between common themes or keywords (on the left) combining multiple themes such as heritage generally, BIM and DT, surveying practices, automation processes, virtual environments, and the Metaverse. Also included are sources (in the middle) and authors' countries (on the right), as seen in Figure 9. Furthermore, Figure 10 illustrates the thematic map of the field for studying smartness and heritage preservation, which is mainly divided into four quadrants: Q1 to Q4. The fundamental themes are shown in the bottom right quadrant (Q4), whereas the motor themes are represented in the top right quadrant (Q1). However, specialized topics are found in the upper left quadrant (Q2), whereas developing or declining themes are found in the bottom left quadrant (Q3). Topics such as "heritage preservation", "heritage buildings", "cultural heritage", "BIM", and "photogrammetry" were introduced in Q4, which are fundamental for the development of the field. On the other hand, innovative themes were made by the second quadrant Q2 subjects, such as "digital transformation", "Metaverse", and "interdisciplinary approach", which offer potential topics in need of future study.

Table 6. The top ten countries in the scientific production of the field of study. Source: the authors, by RStudio software.

N	Country	Number of Publications
1	China	185
2	Italy	116
3	Spain	62
4	Indonesia	35
5	Portugal	35
6	Poland	33
7	UK	29
8	Romania	26
9	Egypt	25
10	Greece	24

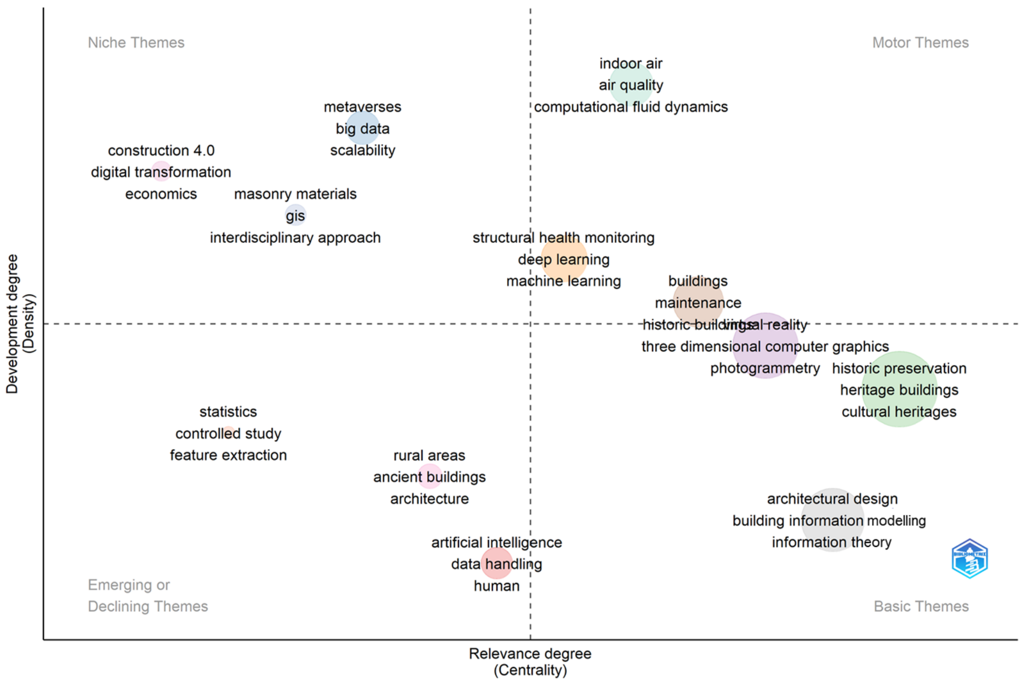

Figure 9. Three-field plot diagram using RStudio software for the relationship between keywords (left), source (middle), and authors' countries (right).

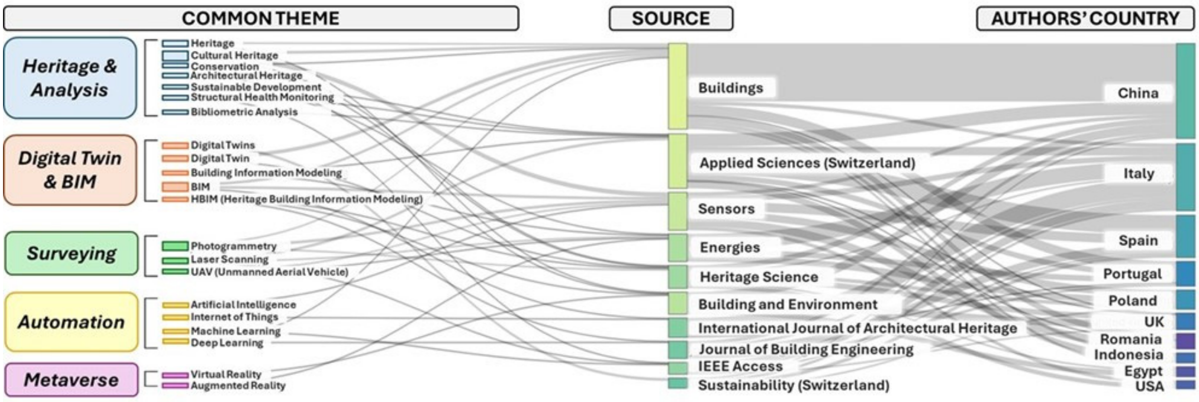

Figure 10. Thematic map of the most frequent keywords. Source: the authors, by RStudio software.

4.1.8. Most Relevant Keywords

The most frequent keyword analysis is crucial for the bibliographic analysis that makes it easier to identify important areas of study for various specializations [110,111]. By revealing the cross-correlations between research topics and subtopics within the domain, networks built using keyword analysis offer a comprehensive understanding of the research domain [112,113]. From the collected database, as shown in Figure 11, “historic preservation”, with 43 occurrences, is the most frequent keyword; then, “architectural design” with 32 occurrences; and after that, “heritage buildings” with 21 occurrences, and “building information modelling” with 20 occurrences. The remaining keywords such as “cultural heritages”, “photogrammetry”, “virtual reality”, “deep learning”, “sustainable development”, and “buildings” seem to be less frequent, occurring between 12 and 15 times.

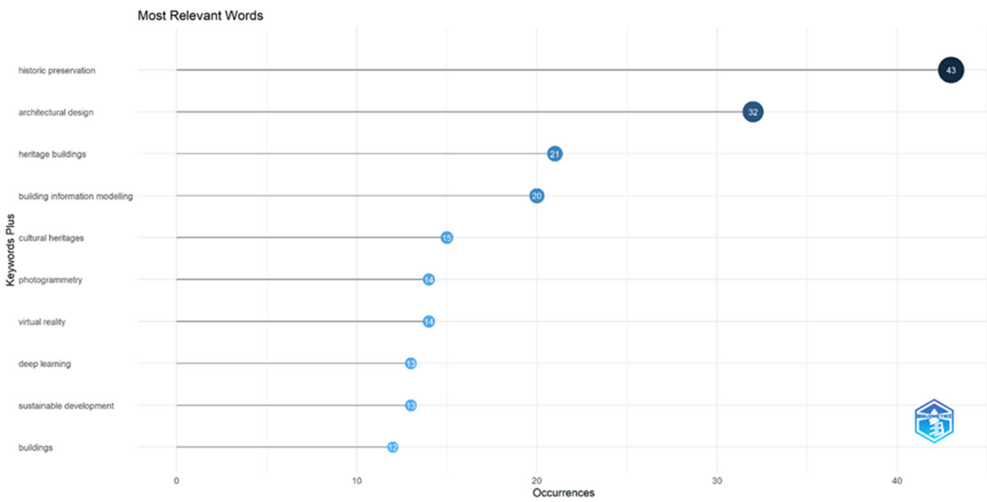

Figure 11. Top 10 most frequent keywords. Source: the authors, by RStudio software.

4.1.9. Co-Occurrence Network of Keywords

The co-occurrence keywords network has been generated in VOSviewer. Table 7 summarizes the filters and keywords used in VOSviewer for the study. Considering authors’ keywords, the size will express their popularity, colored lines identify different clusters, and their proximity indicates how similar they are. The co-occurrence network of the author’s keywords contains 891 keywords. The co-occurrence filtering was 98 with at least a minimum occurrence of two times. Six research clusters were identified based on the most popular keywords, as shown in Figure 12. These clusters were (cluster 1) “Historic preservation and maintenance”, (cluster 2) “BIM and H-BIM”, (cluster 3) “decision-making and data handling”, (cluster 4) “energy efficiency and environmental management”, (cluster 5)

"AI and Metaverse", and finally (cluster 6) "laser scanning and photogrammetry". Some of these keywords in the clusters have been more intensively researched than others, which identifies possible research gaps that should be studied by researchers. Additionally, Figure 13 shows the density of keywords representing the six clusters.

Table 7. Overview of the filters and keywords used in VOSviewer for the study. Source: the authors.

Aspect	Details
Keywords used	Authors' keywords explicitly provided in the publications.
Total keywords	891 keywords.
Co-occurrence filter	Minimum co-occurrence threshold: 2 occurrences. Keywords appearing less frequently were excluded.
Keyword frequency (top keywords)	- 1. Historic Preservation: 43 occurrences. - 2. Architectural Design: 32 occurrences. - 3. Heritage Buildings: 21 occurrences. - 4. Building Information Modeling (BIM): 20 occurrences. - 5. Other Frequent Keywords: cultural heritage, photogrammetry, virtual reality, deep learning, sustainable development, buildings (12–15 occurrences).

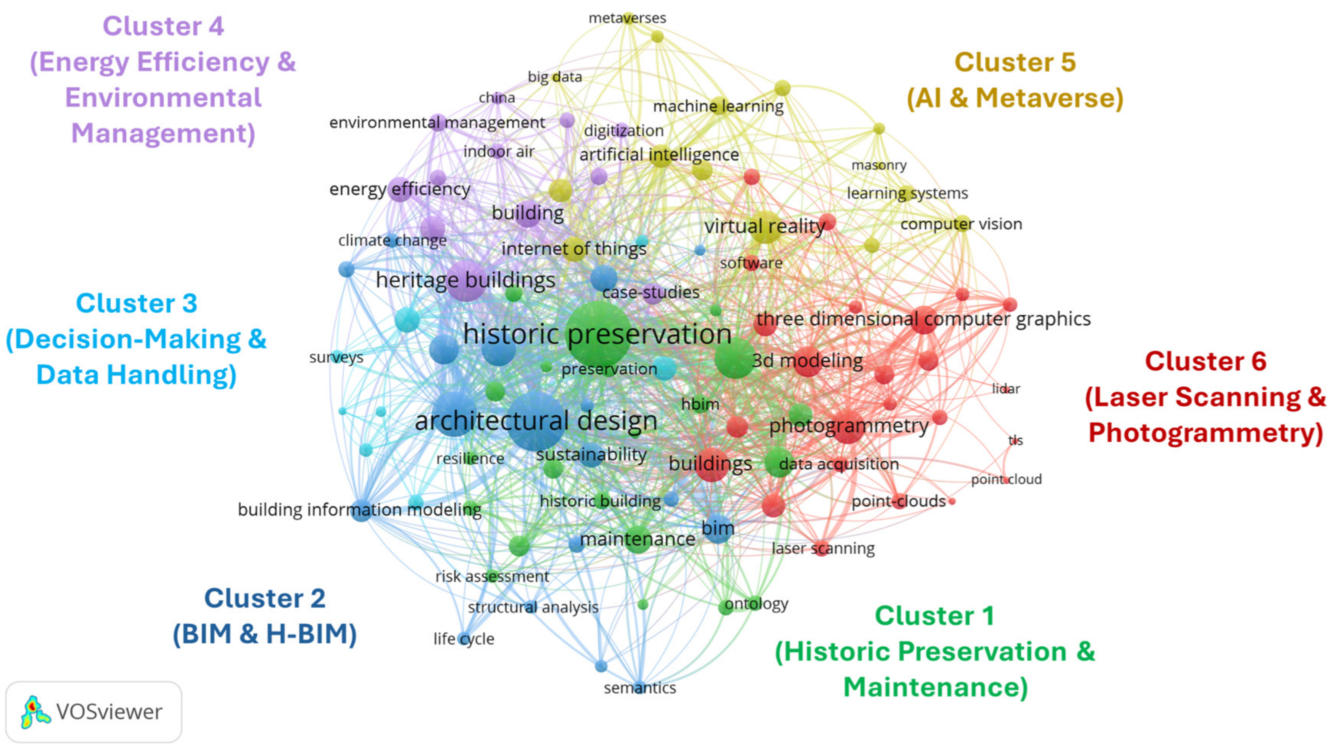

Figure 12. Co-occurrence keywords network. Source: the authors, by VOSviewer.

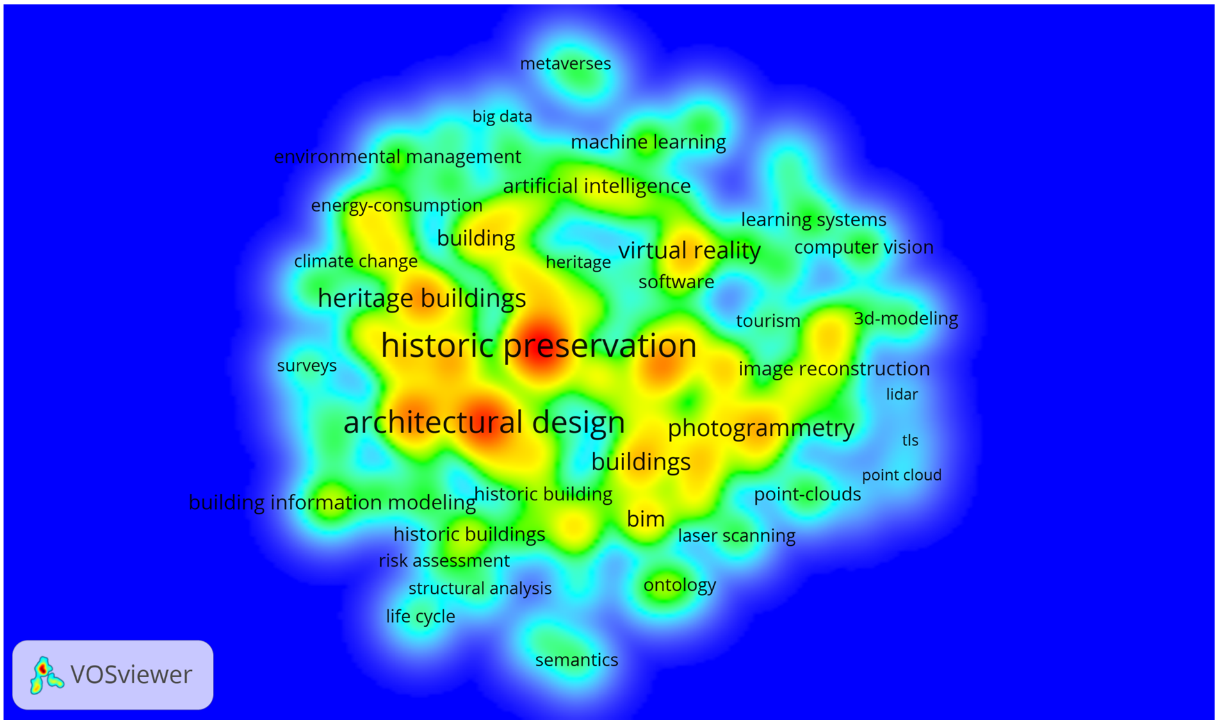

Figure 13. Co-occurrence keywords density network, red/yellow (high density) to green/blue (low density). Source: the authors, by VOSviewer.

4.1.10. Topic Dendrogram Map

A dendrogram map is a data representation tool designed for hierarchical organization in big dataset exploration for machine learning; it also harnesses a hierarchical cluster structure learned from high-dimensional representations of multi-level dataset distribution exploration and drill-down to areas of interest [114–116]. The topic dendrogram map, as shown in Figure 14, has hierarchical clustering of the topics under "SMART HERITAGE" into five major groups: automation, surveying, optimization, modeling, and potentials. Under the automation cluster are topics on augmented reality, e-learning, artificial intelligence, and many others relating to automated and intelligent heritage management. Surveying, on the other hand, tests advanced imaging and surveying techniques such as 3D computer graphics and unmanned aerial vehicles (UAVs).

Since heritage preservation has affiliated disciplines related to both environmental and energy efficiency, computational fluid dynamics, and climate change, optimization must belong to them. Modeling refers to making digital models of heritage buildings regarding subjects such as building information modeling and sustainability. Therefore, some of the significant potentials include a large variety of future applications and interdisciplinary approaches to virtual reality, structural health monitoring, and the Internet of Things. The dendrogram's hierarchical structure indicates the relationships among these topics and shows which ones are more related to one another. The height of the branches comes to represent the distance—or dissimilarity—amongst topics, so that the lower the branch, the more similar the topics are to one another. This is a visualization for identifying key focuses and interdisciplinary linkages toward strengthening heritage preservation and management.

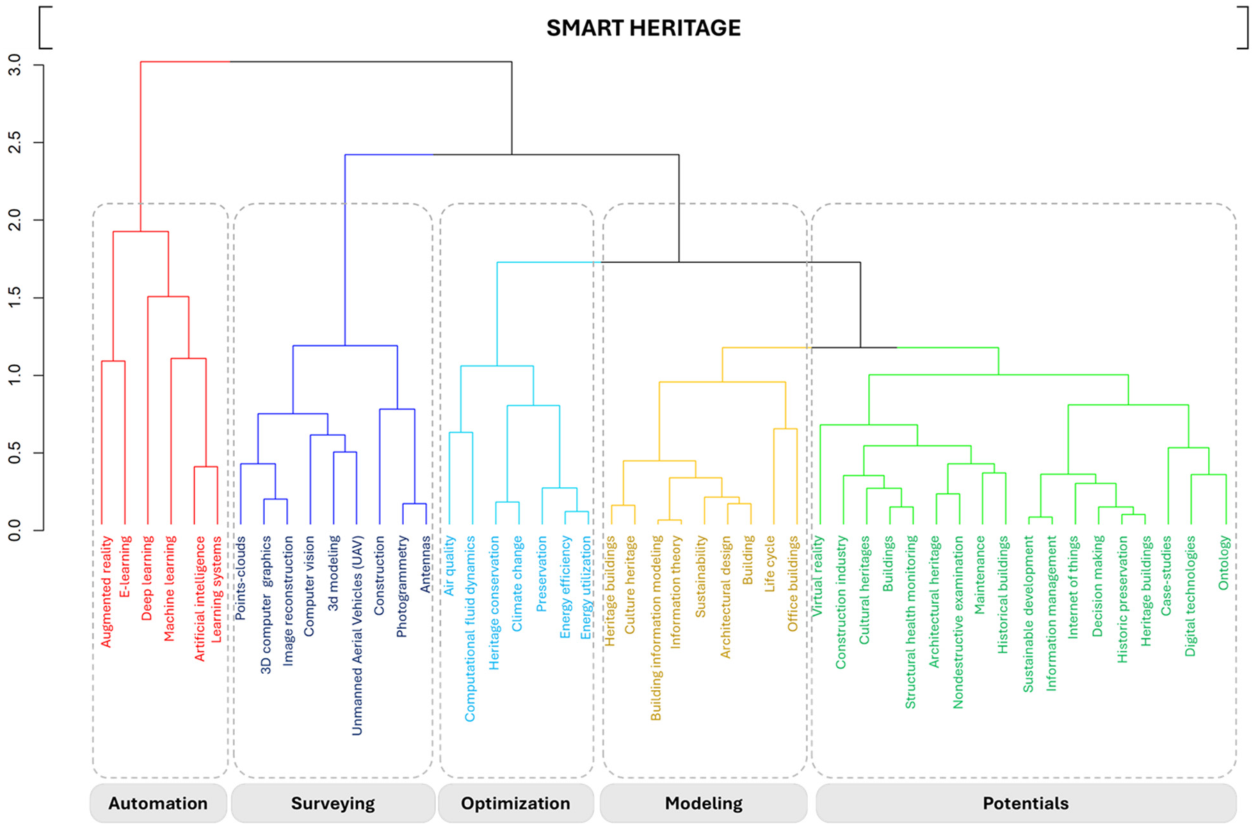

Figure 14. The topic dendrogram with the associated keywords and five clusters using hierarchical clustering and hierarchical order. Source: the authors, by RStudio software.

4.1.11. Trending Topics and Future Research Potentials

Figure 15 represents the latest trends in relevant literature; there are three main findings. The first cluster is emerging trends in the use of Metaverses, big data, AI, VR, and IoT in enhancing the construction industry, and the second cluster is focused on heritage preservation through DTs and BIM, through much attention on using AI and digital technologies for the automation of managing and preserving heritage buildings. Finally, the third cluster shows how technologies such as UAVs, BIM, and computer vision have been used to extend the construction industry.

4.2. In-Depth Analysis

Table 8 below offers an in-depth analysis of relevant case studies. It includes 47 references from various journals representing review, analytical, and applied research. The table underlines interdisciplinary efforts and technological developments that keep pushing the preservation of heritage forward. It also indicates smart applications in heritage preservation, including H-BIM, AR, IOT, VR, and DTs, among other state-of-the-art technologies. These technologies are then applied to the management, monitoring, and conservation of cultural heritage through both digital and physical approaches. Additionally, the objectives of the research range from energy refurbishment and structural health monitoring to improving education and tourism experiences related to heritage buildings.

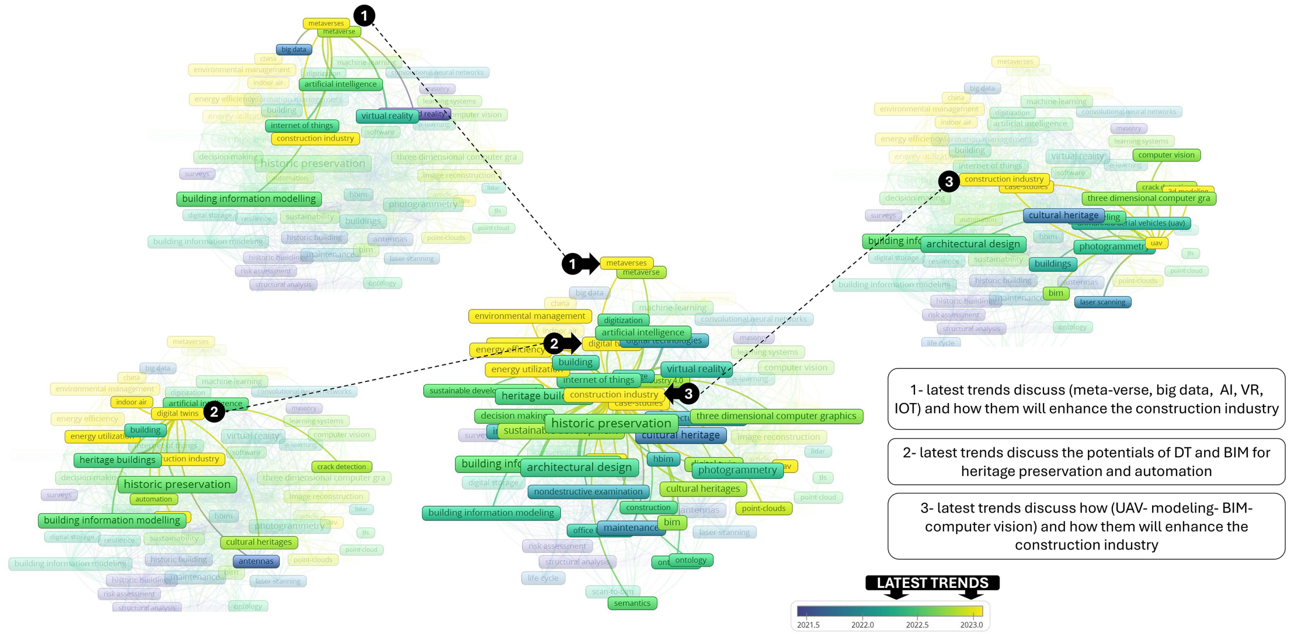

Figure 15. Trending topics and future research potentials. Source: the authors, by VOSviewer.

Table 8. In-depth analysis of the relevant studies. Source: the authors.

Ref.	Year	Source	Study Type	Research Aim	Smart Application	Approach
[117]	2020	*Energies*	applied study	To use H-BIM to implement system for energy refurbishment.	H-BIM	Digitally
[118]	2020	*Engineering, Construction and Architectural Management*	analytical study	To explore the adoption of historic building information modeling (HBIM) in managing built heritage.	H-BIM	Digitally
[119]	2020	*Smart Infrastructure and Construction*	applied study	To explore the use of resource description framework literals in a built heritage context.	H-BIM	Digitally
[102]	2020	*Applied Sciences*	applied study	To explore the use of H-BIM for managing heritage information for cultural asset preservation.	H-BIM	Digitally
[101]	2020	*Applied Sciences*	analytical study	To explore the use of augmented reality (AR) in cultural heritage education to enhance the learning experience.	AR	Digitally
[68]	2020	*IEEE Access*	applied study	To propose an IoT architecture with virtual reality for a remote monitoring system for historical buildings.	IOT, VR	Digitally

Table 8. *Cont.*

Ref.	Year	Source	Study Type	Research Aim	Smart Application	Approach
[120]	2020	*Building Research and Information*	literature review + analytical study	To present a piece of literature on structural health monitoring (SHM) for historic building preservation and new structure design.	N/A	Physically
[106]	2020	*Sensors*	analytical study + applied study	To present a universal methodology for inventorying historical buildings using UAVs and the potential of 3D models focusing on Web/AR/MR/VR technology.	UAV, Web/AR/MR/VR technology	Digitally and physically
[121]	2020	*Sensors*	applied study	To use infrared thermography to automatically monitor cultural heritage elements and detect thermal footprints.	Infrared thermography	Physically
[105]	2021	*Applied Sciences*	applied study	To investigate the application of game technology in incorporating historical building models and 3D-GIS to attribute data into a virtual reality simulation for heritage conservation.	3D-GIS, gamification, VR	Digitally
[122]	2021	*Applied Geomatics*	applied study	To present a new methodology for digitizing cultural heritage through H-BIM.	H-BIM	Digitally
[123]	2021	*Developments in the Built Environment*	applied study	To use H-BIM and big data and smart sensing for monitoring and visualization.	H-BIM	Digitally
[108]	2021	*Sensors*	applied study	To present a comprehensive digital approach to the preservation and protection of artistic and cultural heritage.	DT	Digitally
[124]	2021	*Drones*	applied study	To present a case study of the development of a hyper-realistic 3D model of heritage building, using unmanned aerial vehicles (UAV).	UAV	Physically

Table 8. *Cont.*

Ref.	Year	Source	Study Type	Research Aim	Smart Application	Approach
[125]	2021	*Engineering Structures*	applied study	To investigates retrofitting irregular steel joints in traditional Chinese buildings to enhance strength while preserving historical architectural heritage.	Smart materials	Physically
[126]	2021	*Studies in Conservation*	applied study	To explore the use of conservators' unique materials and heritage experience for heritage preservation, focusing on cleaning and repair rather than replacement.	Laser cleaning	Physically
[127]	2022	*Smart and Sustainable Built Environment*	literature review	To review 354 articles on BIM and provide key priorities for future research.	BIM and digital technologies	Digitally
[128]	2022	*Buildings*	applied study	To present a method for using digital twin, ensuring consistency and avoiding information loss and dispersion issues.	DT	Digitally
[129]	2022	*Journal of Information Technology in Construction*	analytical study + applied study	To improve the digital transformation of the construction sector by integrating cultural and architectural heritage conservation management.	DT, VR	Digitally
[130]	2022	*Journal of Imaging*	applied study	To assess the use of low-cost sensors in the photogrammetric field for digitizing cultural heritage.	Spherical camera photogrammetry, sensors	Physically
[131]	2023	*IoT*	analytical study	To establish a method for long-term storage of digital twins	DT	Digitally
[132]	2023	*Buildings*	analytical study	To integrate BIM with heritage preservation	BIM	Digitally
[133]	2023	*Buildings*	applied study	To present an IoT BIM-based solution for real-time monitoring of built cultural heritage using low-cost sensors.	IOT, BIM	Digitally
[134]	2023	*Buildings*	literature review	To drive sustainable design and development using BIM	BIM	Digitally
[135]	2023	*Sensors*	applied study	To propose a 3D model-associated informative tool and a priority index.	BIM and H-BIM	Digitally
[136]	2023	*Automation in Construction*	literature review	To explore the application of digital twins in heritage construction.	DT, H-BIM, IOT	Digitally

Table 8. *Cont.*

Ref.	Year	Source	Study Type	Research Aim	Smart Application	Approach
[137]	2023	*Buildings*	applied study	To explore the implementation of BIM in a complex renovation project.	BIM	Digitally
[80]	2023	*International Journal of Architectural Heritage*	applied study	To explore the benefits of multi-scale digitization for architectural renovation and energy upgrades.	H-BIM	Digitally
[138]	2023	*Italian Journal of Planning Practice*	applied study	To utilize BIM and GIS technologies to preserve historic districts through field surveys, digital mapping, and GIS integration.	BIM, GIS	Digitally
[139]	2023	*Automation in Construction*	applied study	To present a method for health monitoring of historic structures using photogrammetry technologies and point cloud processing algorithms, as well as virtual models.	DT, photogrammetry	Digitally and physically
[140]	2023	*Buildings*	applied study	To use explainable artificial intelligence (XAI) to create accurate models of ancient architecture and lacquer art.	XAI	Digitally
[141]	2023	*Energies*	applied study	To present research on machine learning applications for remote monitoring of historic buildings and create an online HBIM platform for urban monitoring.	ML, HBIM	Digitally
[30]	2023	*Applied Sciences (Switzerland)*	applied study	To define the role of the three-dimensional scanning and 3D printing in cultural heritage preservation.	3D scanning, 3D printing	Physically
[142]	2023	*Buildings*	applied study	To document vernacular heritage buildings in 3D using photogrammetry and laser scanner technology.	Photogrammetry and laser scanner	Physically
[143]	2023	*Buildings*	applied study	To establish a virtual model for the conservation through efficient sensors.	Sensor, DT	Digitally and physically
[144]	2023	*Advances in Science and Technology Research Journal*	applied study	To showcase the potential of advanced geodetic techniques for research, preservation, and heritage documentation.	Photogrammetry, digital cameras, sensors	Physically

Table 8. *Cont.*

Ref.	Year	Source	Study Type	Research Aim	Smart Application	Approach
[145]	2023	*Journal of the International Measurement Confederation*	applied study	To propose a new methodology using a smartphone and LiDAR terrestrial laser scanners to examine wall cracks and displacement.	Smartphone, terrestrial laser scanners (LiDAR scanners)	Physically
[146]	2023	*Drones*	applied study	To use scan-to-HBIM-to-XR process and UAV photogrammetry to enhance the depiction of archaeological ruins and enhance opportunities.	UAV photogrammetry, H-BIM, XR	Digitally and physically
[133]	2023	*Buildings*	applied study	To present an IoT BIM-based solution for real-time monitoring of built cultural heritage using low-cost sensors.	Sensors	Physically
[147]	2023	*Construction and Building Materials*	applied study	To present an experimental investigation of smart intervention materials for historic masonry structures.	Smart materials	Physically
[148]	2023	*Applied Physics A*	analytical study	To explore femtosecond laser cleaning for historic monument materials, while preserving substrate integrity.	Laser cleaning	Physically
[149]	2024	*Construction Innovation*	analytical study + applied study	To assess and simulate renovation scenarios in terms of duration, cost, effort, and disruptive potential.	BIM	Digitally
[150]	2024	*Applied Mathematics and Nonlinear Sciences*	applied study	To explore the impact of virtual reality (VR) on tourism in cultural heritage sites.	VR	Digitally
[151]	2024	*Applied Sciences*	applied study	To explore the integration of game mini-map navigation design elements into online virtual museums for enhancing virtual experiences.	Gamification	Digitally
[152]	2024	*Applied Sciences (Switzerland)*	applied study	To develop a BIM-based system for managing repair history.	BIM	Digitally
[153]	2024	*IEEE Access*	analytical study	To explore the role of blockchain in creating and managing the Metaverse platform.	Blockchain, Metaverse	Digitally

Table 8. *Cont.*

Ref.	Year	Source	Study Type	Research Aim	Smart Application	Approach
[154]	2024	*Journal of Building Engineering*	applied study	To investigate the use of unmanned aerial vehicle photogrammetry for rapid structural inspections of cultural heritage and demonstrate the potential of AI in this process.	UAV photogrammetry, AI	Digitally and physically

In the analyses of the relevant literature in the previous table, it has been found that several studies discuss the smart preservation of heritage, such as [108,127,129,134], which propose a comprehensive digital approach to preserving artistic and cultural heritage, focused on the integration of many technologies such as BIM, digital twins, and machine learning for a holistic solution to heritage conservation. Many studies, such [80,102,117–119,122,123,135], attached great importance to the utilization of H-BIM for the digital preservation and management of heritage buildings. These studies have tended to prove the capabilities of H-BIM in digitally documenting and refurbishing historical structures, hence developing efficient heritage management. For example, Piselli et al. (2020) provide an example of applying H-BIM in energy refurbishment [117], and Charlton et al. (2021) show its adoption in the framework of built heritage management [118]. Several studies focus on digital twins and IoT technologies for monitoring and real-time visualization of heritage structures [108,128,129,131,133,139,143]. These are technologies that enable the continuous feed of the data and do not allow the loss of information [128]. The use of IoT for real-time monitoring provides details on how modern sensing technologies can be combined with traditional efforts at preservation [133].

Meanwhile, recently, various smart virtual techniques have been researched to enable better experiences of cultural heritage preservation digitally. Recent trends discuss the incorporation of digital technologies like BIM and DTs into higher education for AEC disciplines [155]. Additionally, in the previous analysis and particularly in heritage preservation, cooperation with AR and virtual technologies will be beneficial in enhancing AEC heritage education. Vargas et al. (2020) discussed the usage of AR in education and improving learning experiences [101], while Li et al. (2024) examined the impact of VR on heritage-linked tourism [150]. Also, the integration of emerging technologies into heritage conversation efforts is also being made in aspects of blockchain, AI, and gamification [27,140,153,156–158]. Elsadig et al. (2024) present the role that blockchain can play in the management of Metaverse platforms [153], while some studies demonstrate the use of AI and gamification in the enhancement of virtual experiences and heritage documentation [151,158]. Several benefits of multi-scale digitization and its integration physically with heritage assets are discussed in [106,139,143,154], such as BIM and GIS technologies for the preservation of historic districts [138]. Also, UAVs have been increasingly considered for the physical and digital documentation of heritage sites [68]. Works show that UAVs can contribute to photogrammetry, producing 3D models for structure inspection and documentation [159,160]. These applications demonstrate how UAVs can be used to capture highly detailed and accurate data, which is very important in heritage preservation [161]. In addition, among the physical preservation techniques related to direct intervention in the maintenance and restoration of heritage structures are laser cleaning [126,148,162] and smart materials' application [125,147], evidencing the significance of monitoring and management intervention in both physical and digital terms [123,139].

5. Discussion

Previous studies have a strong trend of leveraging smart technologies for digital and physical heritage building preservation efforts. H-BIM, digital twins, IoT, AR, VR, UAVs, and other new technologies provide exciting, innovative solutions for cultural heritage management and conservation. These technological developments improve not only efficiency and accuracy of heritage documentation but also the different aspects of engagement and educational knowledge associated with cultural heritage sites.

5.1. Smart Preservation of Heritage Approaches (Physical-Digital)

The concept of smartness dealing with heritage physically focuses on the conservation, maintenance, and physical representation of heritages. It includes several innovative examples: Laser scanners can carefully capture 3D information about heritage structures, thereby providing a chance for detailed documentation and analysis [159,163–165]. Additionally, UAVs or drones are used for aerial imagery and 3D mapping in order to conduct site surveys and structural inspections that are hard to attend [160,161,166,167]. Environmental conditions, such as temperature and humidity, around and inside cultural heritage sites are measured with the help of a range of sensors, which provide very critical data for heritage preservation efforts [168–170]. Moreover, additive manufacturing via 3D printing technology is utilized to create replicas and produce components for replacing specific parts or even architectural elements [171–173]. Smart materials are being tailored for specific requirements critical to heritage conservation [147,174]. Finally, laser cleaning techniques make it entirely possible to remove debris, pollution, and biological growth without much damage to sensitive heritage surfaces [126,162].

Furthermore, the smartness concept of dealing with heritage digitally means heritage information presentation, documentation, and management, focusing on the digital representation, documentation, and management of heritage information [175–177]. It includes several digital 3D-based techniques: BIM and DT, which establish detailed models of historical structures aimed at documentation, visualization, and analysis; geographic information systems, as well as global positioning systems for accurate mapping and geolocation of heritage sites [178–183]. It will utilize AI, ML, and DL algorithms in ways such as data analytics, pattern recognition, and restorations through artifact aids [156,184–186]. Experiences in the virtual realm using VR, AR, and MR technologies are developed by letting people see the invented heritage sites virtually [187–190]. Gamification also comes into play in doing this by engaging the public and giving visibility to issues associated with cultural heritage [151,158,191]. At the same time, blockchain secures secure and transparent record-keeping of origin, authentication, and ownership concerning artifacts [27,153,157].

Thus, this smart heritage approach can fall into two broad categories: the use of digital technologies and innovative physical interventions. Implementation complexity varies according to the category, such as the physical approach, involving physical installation and maintenance and requiring integration with existing physical structures. Conversely, the digital approach involves software development and data integration, and it requires digital infrastructure and cybersecurity measures, both revolving around the physical/digital preservation for the effectual maintenance and promotion of cultural heritage. An integrated approach to the physical integrity of the historical structures helps in the preservation and also serves digitally in documenting and promoting cultural heritage for the future generations.

The concept of smartness in dealing with heritage physically can be categorized into two pillars. The first pillar is smart devices, including laser scanners, UAV “drones”, and sensors. The second pillar is smart processes including 3D printing, smart materials, and laser cleaning. These physical approaches will help in expanding the preservation actions to additional actions that involve on-site preservation, environmental control, aerial surveys, surface cleaning, material conservation, innovative materials, and physical exhibitions and replicas in heritage buildings. Also, the concept of smartness dealing with heritages digitally can be categorized into two pillars. The first pillar is smart technologies, including BIM and DTs; geographic information system (GIS) and global positioning system (GPS); and AI, ML, and DL. The second pillar is smart environments, including VR, AR, MR, gamification, and blockchain. Additional actions can be implemented to extend the main preservation actions by utilizing digital methods, including mapping historical sites, creating digital archives, detecting issues, creating virtual replicas for simulation, creating virtual tours, and managing data online. Figure 16 illustrates the proposed framework that promotes the integration of the physical and digital methods for achieving smart preservation of heritages.

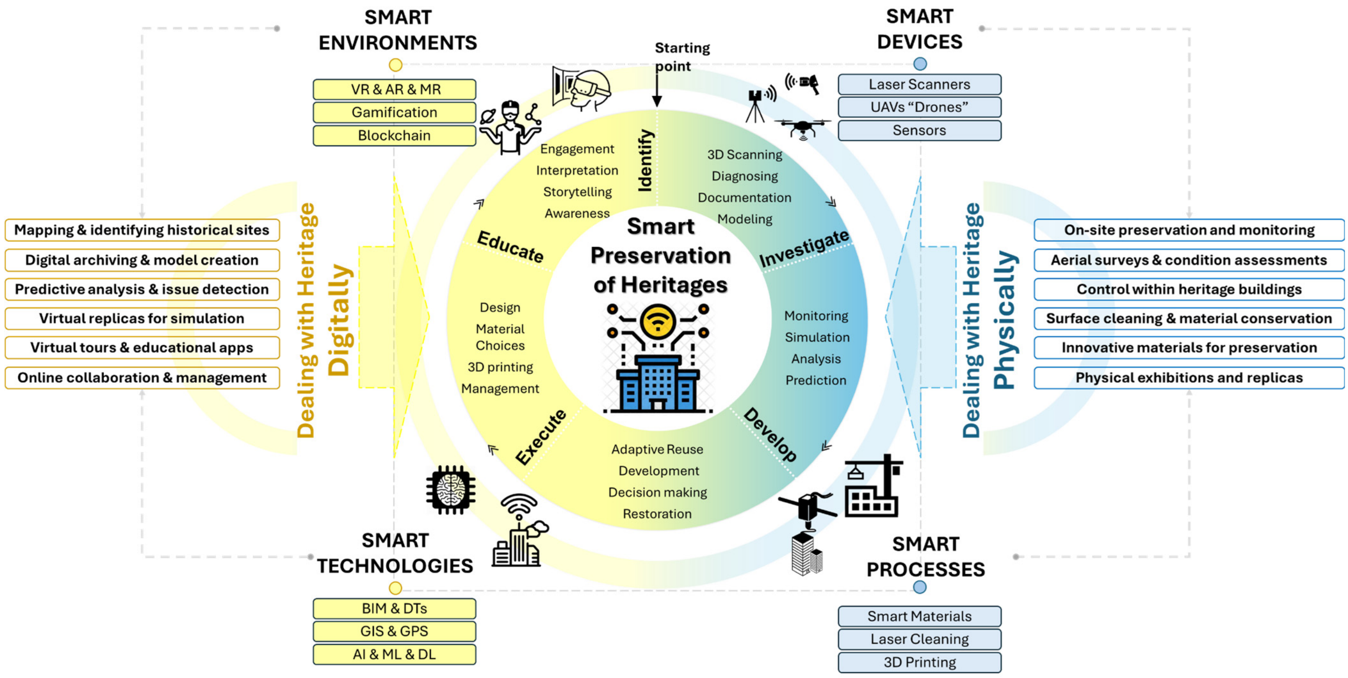

Figure 16. The proposed framework-based integration of the physical and digital methods. Source: the authors.

5.2. Extraction of Relevant Trends from the Latest Literature

Recent smart heritage preservation literature—represented by the 216 documents from the collected database extracted from Scopus—denotes the relevant trends. The first is interoperability and integration, which make up about 21% of the total documents, underlining the need for seamless technology integration. Advanced monitoring and predictive maintenance also constitute an essential part of the literature, at 18%, showing great interest in the enhancement of monitoring systems and preventive care in heritage sites. Data management and cybersecurity are represented by 11% of the studies, pointing to the stringent need for robust data handling and strengthened security measures. Cost reduction and funding models are the themes of 11% of the documents, which witness the continuous efforts toward cost reduction and the development of more affordable preservation technologies.

Enhanced documentation and accessibility are discussed in 8% of the literature, with a view of having better digital records and public engagement. Futureproofing and sustainability, accounting for 7%, concern the long-term relevance and sustainability of preservation practices. Cultural and community engagement, at 6%, underscores the need to involve and respect local communities in preservation projects. The specialized topics that cannot be generalized make up 6% of the studies, dealing with a different and specific objective. Balancing preservation and modernization and resilience to environmental changes each account for 5% of the documents, concerning integrating modern technology without losing authenticity and adapting to climate change impacts, respectively. Finally, skill development and training represent 2% of the literature, thus showing the need for building expertise in smart technologies for heritage preservation. Table 9 summarizes the extraction of relevant trends from the latest international literature.

Table 9. Relevant trends from the latest international literature. Source: the authors.

Research Area (Relevant Trends)	Objective	No. Documents	Percentage
Interoperability and integration	Ensure seamless technology integration	45	21%
Advanced monitoring and predictive maintenance	Improve monitoring and preventive care	40	18%
Data management and cybersecurity	Data management and enhanced security	24	11%
Cost reduction and affordable models	Lower costs and affordable technologies	23	11%
Enhanced documentation and accessibility	Improve digital records and public engagement	18	8%
Futureproofing and sustainability	Ensure long-term relevance and sustainability	15	7%
Cultural and community engagement	Involve and respect local communities	14	6%
Specialized topics that cannot be generalized	Various objectives	12	6%
Balancing preservation and modernization	Integrate modern tech without compromising authenticity	10	5%
Resilience to environmental changes	Adapt to climate change and environmental impacts	10	5%
Skill development and training	Build expertise in smart technologies	5	2%

5.3. Key Benefits, Challenges, and Future Research

As a result of the surface-level analysis and in-depth analysis, Table 10 presents a future innovative vision of smart heritage preservation based on the relevant trends and approaches of the latest international literature to enhance the use of smart technology in heritage preservation. Each research area horizontally includes key benefit challenges addressing potential future research and stakeholders. These matrix strategies range from flexible performance solutions and green retrofitting incentives to digitalization and stakeholder involvement, which permits effective implementation and coordination for heritage preservation and smart technology integration by providing a view that is overarching for the initiatives.

However, this review study discusses the positive impacts of smart technology adoption on cultural heritage preservation by integrating both physical and digital methods. This study has potential limitations that should be addressed to assure wider efficacy and implementation. These limitations can be related to the applicability to the labor market, which can include the acceptance of these technologies by the stakeholders, the existence of qualified and skilled labor, and the high cost of this technology adoption. In addition, there are some limitations related to cybersecurity and complexity, as the smartness concept is mainly based on digitalization, which can be used in heritage preservation for documentation and analytics. So that these concerns can be addressed, the most significant issue emerging is the need for standardized protocols for more scalability and seamless operation.

Table 10. Future innovative vision (key benefits, challenges, and future research). Source: the authors.

Research Area	Key Benefits	Challenges	Future Research	Stakeholders
Interoperability and integration	Smooth technology adoption Reduced technical disruptions	Technical complexity Integration issues	Standardization of IoT communication protocols Modular plug-and-play (PnP) heritage monitoring systems	Technology developers Heritage site managers
Advanced monitoring and predictive maintenance	Proactive preservation Extended lifespan of heritages	Ineffective monitoring High maintenance costs	AI-driven predictive maintenance models Development of advanced sensors for monitoring	AI specialists Heritage conservationists
Data management and cybersecurity	Enhanced data transfer Reduced risk of cyberattacks	Data transfer Cybersecurity risks	AI-driven cybersecurity systems for heritage sites Blockchain for data management in heritage preservation	IT experts Heritage managers
Cost reduction and affordable models	Broader implementation of smart technologies Enhanced financial sustainability	High initial costs	Developing low-cost sensors and IoT devices	Government agencies
Enhanced documentation and accessibility	Comprehensive digital archives Global accessibility Enhanced educational value	Limited documentation Accessibility issues	Advanced 3D scanning projects VR and AR applications for virtual tours of heritages	VR/AR developers Heritage educators
Futureproofing and sustainability	Long-term viability of technology investments Reduced environmental impact	Technological obsolescence, environmental impact	Development of scalable, adaptable tech solutions Sustainable practices in heritages	Environmental experts Technology developers
Cultural and community engagement	Greater community involvement Culture and technology integration	Cultural considerations Community acceptance	Community-led tech integration projects in heritage preservation	Local communities Cultural experts
Balancing preservation and modernization	Synergy of technology and heritage	Preservation vs. modernization balance	Guidelines for integrating smart tech in historic buildings	Heritage conservationists Architects
Resilience to environmental changes	Increased resilience to climate impacts Proactive environmental management	Vulnerability to environmental changes Climate adaptation needs	Climate adaptation heritage strategies Advanced environmental monitoring systems for heritages	Environmental specialists Climate experts
Skill development and training	Increased technical proficiency Efficient use of smart technologies Empowered staff	Skill gaps Training requirements	User-friendly software for heritage preservation	Educational institutions Heritage organizations Technology providers

6. Conclusions

The preservation of heritage buildings is an activity of global importance and requires smart solutions for cultural heritage preservation. The purpose of this review was to highlight the adoption of smart technologies in cultural heritage preservation by integrating physical and digital methods and to see how they have changed the process and are still changing. This paper has targeted, through a bibliometric analysis, recent trends in smart applications for heritage building preservation during the time frame starting from 2020 to 2024 by exploring the latest trends and how technologies from Industry 4.0 and Industry 5.0 can facilitate the process of heritage preservation. Applying the RStudio and VOSviewer on 216 peer-reviewed journal articles from the Scopus database was performed in order to obtain a clear insight into the main trends and interdisciplinary developments related to smart heritage preservation.

This analysis has revealed that smart applications such as H-BIM, AR, IoT, VR, and DTs are currently leading refurbishment, monitoring, and educational efforts in heritage preservation. This also involves smart preservation technologies, including laser scanning for detailed 3D documentation, aerial surveys through UAVs, condition monitoring with environmental sensors, 3D printing to replicates, smart materials tailored for conservation needs, and laser cleaning techniques sensitive to surfaces. These technologies reinforce the preservation effort from environmental control to on-site maintenance and material conservation. Finally, on the side of digital modeling, there are BIM and DTs, and on the side of mapping and geolocation, GIS and GPS technologies. On the side of data analytics, pattern recognition, and artifact restoration, there are AI, ML, and DL algorithms. Finally, on the immersive experience side, there are VR, AR, and MR, while blockchain will guarantee secure and transparent record-keeping of the heritages.

Therefore, the findings of this study suggest a comprehensive framework for heritage preservation evolution through smart technology adoption. This framework categorized the smartness concept into two categories: physical methods and digital methods. The physical approach with physical interventions including laser scanning, UAVs, 3D printing, smart materials, etc. On the other hand, the digital approach with digital representation through BIM, DTs, VR, AR, etc., as well as gamification. This integration ensures the effective maintenance and promotion of cultural heritage preservation. This study successfully indicated that these smart technologies could enhance the preservation and promotion of cultural heritage through detailed documentation, improve engagement, and ensure the sustainability of heritage sites. Also, they can deliver innovative solutions to overcome the traditional preservation challenges like limited accessibility, environmental vulnerability, and cost restrictions.

Recent literature on smart heritage preservation shows several trends: interoperability, advanced monitoring, cost reduction, enhanced documentation, futureproofing, cultural engagement, and skill development. Each trend emphasizes certain benefits, challenges, and areas for further research that, when put together, point to a comprehensive strategy and road map for leveraging smart technologies in heritage conservation. Although this study focused on both physical and digital methods of smartness and their impacts on evolving the heritage preservation processes, these findings may well have needed to consider the way of implementation in the real world. This can be done through the integration of policy and industry.

For this integration, from a policy perspective, governments and policymakers should standardize protocols and frameworks, prioritize funding, provide training programs for local communities and stakeholders, and incorporate cybersecurity to protect heritage data. Also, for industry and labor markets, collaboration is beneficial for proposing cost-effective tools and software. The construction industry can be enhanced through these technologies that offer accurate surveying, digital documentation, and up-to-date monitoring through information technology. Also, the tourism's industry could be more entertaining through the use of virtual technologies for immersive experiences, while environmental and sustainable industries should first evaluate the heritage needs and adopt SDG-based solutions.

Additionally, future research shall be directed at standardizing the communication protocols so that technology can be integrated and have a smooth interface through better stakeholders' interaction, with bias-free models made possible by ethical AI in heritage preservation and enhancing cybersecurity systems; these systems can provide data privacy, algorithmic bias, and the need for transparent and explainable AI systems, creating low-cost, smart devices and being responsive to community involvement in tech integration. Moreover, the focus would be on developing scalable and sustainable technologies that adapt to climate impacts and address the ensuing skill gaps with resultant focused training programs. Of further significance are digital documentation and restoration, immersive experiences, data recognition, structural health monitoring, and real-time monitoring using IoT devices. Applications that use AR, VR, and AI may provide immersive learning environments. When specific thresholds are exceeded, AI systems can automatically notify authorities or trigger preventive steps. Smart sensors are capable of monitoring environmental conditions. AI not only has the potential to improve digital documentation and restoration but also to enhance 3D reconstruction, virtual conservation labs, and the digitalization of cultural material.

Overall, smart preservation of heritage sites is a complex undertaking that incorporates both innovative physical and digital techniques. This research provided the researchers with a clear summarized database of studies and allows them to understand possible future research opportunities. It enables the understanding of current challenges and the exploration of future research avenues in the preservation and promotion of cultural heritage for its accessibility and engagement with future generations.

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