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Review article

A systematic review of utilizing extended reality technologies for historical site preservation and visualization

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ABSTRACT

The integration of extended reality (XR) has fundamentally transformed historical site preservation and visualization. This systematic review examines the rapid evolution of these technologies between 2015 and 2025. Following a PRISMA-guided selection process, 115 high-fidelity empirical studies were rigorously analyzed from an initial pool of 798 records. The research is structured around four core areas: immersive platforms, data capture methodologies, software pipelines, and geographic preservation challenges. Key findings reveal a major methodological paradigm shift: while historical workflows relied heavily on single-method photogrammetry (e.g., Agisoft-to-Blender-to-Unity), modern preservation relies on hybrid workflows that merge terrestrial laser scanning (TLS) for structural accuracy with photogrammetry for textural fidelity. Furthermore, modern software pipelines increasingly favor RealityCapture and Unreal Engine 5, utilizing virtualized micro-polygon geometry and progressive rendering to eliminate traditional mesh decimation bottlenecks. While VR headsets remain dominant for providing true architectural scale, the integration of consumer-grade LiDAR is actively driving the rise of accessible mobile AR. Geographically, 73% of digitized projects remain concentrated in Europe, highlighting a critical need for global inclusivity. By defining the functional necessities of hybrid capture and advanced XR pipelines, this review provides a strategic framework for crowdsourcing and optimizing digital twins, ensuring historical accuracy and democratizing global access to cultural heritage.

1. Introduction

The preservation of heritage sites is faced with fresh and acute threats from environmental deterioration, urbanization, and human-induced conflict. Conventional methods, such as physical and documentation, fail to record the fullness and progression of cultural heritage at times. Emerging technologies like virtual reality (VR), augmented reality (AR), mixed reality (MR), and extended reality (XR) have transformed how we record, recreate, and experience heritage sites. For example, VR enables people to visit places that they cannot reach in person, such as the Roman underwater wreck of Cala Minnola [1]. Whereas AR overlays images of structures that have been destroyed, like the Roman Theatre of Palmyra [2], onto their ruins. Both technologies bring heritage to everyone, connecting the past and present [3]. Immersive spectrum is defined as the following: (1) virtual reality (VR): VR creates a completely synthetic, computer-generated environment that users experience through head-mounted displays or similar hardware. In VR, participants are fully immersed in a computer-generated environment where computer-generated sensory inputs (visual, auditory, and sometimes haptic) replace real-world stimulation (e.g., HMD (Head-mounted display) studies of the Seokguram Grotto, [4]). (2) augmented reality (AR): AR overlays virtual content, images, videos, or information onto the real world. AR demonstrates how humans perceive reality by overlaying virtual objects on real-time camera images. People can accomplish this through devices like smartphones, tablets, or AR glasses. (e.g., visualizing underground artifacts at Chan Chan through smartphone apps, [5]), (3) mixed reality (MR): MR goes one step further and merges the real and virtual worlds, allowing digital objects not only to be superimposed onto the real world but also to interact with it in real time. MR technology (for instance, Microsoft HoloLens) enables virtual objects to be manipulated as if they were real (for example, HoloLens reconstructions of the Al Zubarah Fortress, [6]), (4) extended reality (XR): XR is an overarching term for VR, AR, MR, and all other immersive technologies that blend the real and virtual worlds. XR captures all types of experiences, from real to virtual, and focuses on how immersive technologies cooperate and evolve [7].

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The significance of applying these technologies is anchored in three primary areas. First, they provide robust **digital archiving** solutions, utilizing advanced geomatics to create high-fidelity 3D digital twins that permanently safeguard structural and cultural data against physical loss. Second, they directly address **heritage deterioration** by enabling non-invasive structural monitoring and offering virtual tourism alternatives that drastically reduce the physical footprint and wear-and-tear on fragile archaeological sites. Third, they profoundly **enhance educational experiences** by transforming passive observation into interactive, immersive storytelling, thereby democratizing access for global audiences and mobility-impaired individuals who cannot physically visit the sites (e.g., the Roman underwater wreck of Cala Minnola [1]).

Recent advancements in photogrammetry (e.g., Agisoft Metashape) and laser scanning enable high-fidelity reconstructions, as seen in the 3D modeling of the Portes Mordelaises gate [8]. However, the field remains fragmented, with disparities in geographic focus, methodological rigor, and equitable access to preservation tools. Traditional preservation struggles to address dynamic degradation, while immersive technologies face critical barriers: (1) Interoperability gaps between software tools (e.g., photogrammetry-to-modeling workflows) hinder scalable workflows; (2) the rapid evolution of mobile AR (e.g., integrating smartphone LiDAR and progressive rendering) is actively challenging the historical dominance of HMD-driven VR; (3) inconsistent documentation of reconstruction hypotheses risks historical accuracy.

Despite these identified barriers, existing literature predominantly offers descriptive catalogs of individual software tools or high-level socio-technical overviews. There remains a critical research gap: the absence of a unified, actionable engineering framework that dictates exactly *how* to overcome these interoperability and rendering bottlenecks. To address this gap and advance the current literature, the main objective of this research is to systematically review the specific applications of extended reality technologies in historical site preservation, and to synthesize these empirical findings into a novel theoretical model: the **Modular XR Engineering Framework (MXEF)**. To elevate the discourse beyond a descriptive catalog of software tools, this framework categorizes the underlying engineering mechanics into four fundamental layers: Geometric Data Fusion, Algorithmic Optimization, Real-Time Rendering Mechanics, and Immersive Deployment. The research theme is explicitly defined along three main lines: the **value** of immersive applications, the **engineering methodology** of generating digital twins, and the computational **challenges** inherent in heritage preservation. These lines are investigated through four core Research Questions (RQs):

- **RQ1 (Applications & Platforms):** What are the specific applications of immersive platforms (VR, AR, MR, XR) in the digital preservation and visualization of historical sites?
- **RQ2 (Methodologies):** What data capture methodologies (e.g., hybrid photogrammetry and laser scanning) optimize fidelity and scalability for generating digital twins?
- **RQ3 (Pipelines):** What software ecosystems and pipelines are utilized to transition from 3D documentation to optimized, interactive immersive applications?
- **RQ4 (Challenges & Future):** What are the primary methodological challenges, geographic disparities, and future prospects in applying these technologies to heritage preservation?

2. Literature review

Digital reconstruction has evolved significantly from static 3D models to dynamic, interactive systems integrating multidisciplinary datasets. While prior seminal reviews, such as Suh and Prophet's [9] analysis of immersive research and Gaugne et al.'s [10] exploration of XR in cultural heritage, have successfully mapped the broader socio-technical impacts and structural challenges of immersive platforms over the last decade, there remains a critical gap. These high-level frameworks effectively highlight macro-level shifts toward mobile platforms and markerless tracking [11], yet they often lack an analysis of the specific, underlying engineering mechanics. Our review explicitly synthesizes and builds upon these foundational frameworks by focusing on the rigorous engineering workflows, categorized in our proposed Modular XR Engineering Framework, required to actually implement these socio-technical goals in modern digital environments. Early empirical approaches prioritized precision in geometric documentation through techniques such as Historic Building Information Modeling (HBIM), terrestrial laser scanning, and photogrammetry; for instance, the HBIM workflow for Cesis Medieval Castle [12] exemplifies this trend, leveraging laser scanning and photogrammetry to create highly detailed architectural reconstructions. Similarly, the Portes Mordelaises reconstruction [8] demonstrated the use of photogrammetric models (751,600 faces) as visual documentation for excavation reports while also facilitating public engagement through VR installations that attracted over 45,000 visitors.

Despite these advances, balancing accuracy with interpretative flexibility remains a key challenge, particularly for sites with fragmented remains. The Dacian Embossed Disk [13] highlights this issue, where a hybrid workflow combining photogrammetry and laser scanning was necessary to reconstruct a highly deteriorated artifact. Such hybrid methodologies are increasingly being adopted to address missing or damaged elements in historical reconstructions.

Another persistent challenge is interoperability across different reconstruction platforms. The scan-to-HBIM-to-VR workflow for the Battiferro Lock [14] required integrating point clouds from laser scanning, UAV (unmanned Aerial Vehicle) photogrammetry, and parametric modeling within Autodesk Revit. However, the project underscored ongoing issues in seamless data exchange between HBIM environments and immersive VR applications, emphasizing the need for standardized workflows.

In addition to technical challenges, digital reconstructions also raise ethical considerations in heritage conservation. A notable example is the speculative reconstruction of Palmyra's Roman Theatre, where spherical photogrammetry and manual modeling were employed to restore a site largely destroyed by conflict digitally. While such reconstructions offer invaluable cultural insights, they also prompt debates about historical fidelity, authenticity, and the implications of reconstructing lost heritage with speculative data [2].

These case studies illustrate the evolving methodologies in digital reconstruction, emphasizing the importance of hybrid workflows, data interoperability, and ethical considerations.

2.1. Extended reality (XR) applications

XR technologies go well beyond simply displaying 3D models; they serve as a psychological bridge to the past. A central theme in modern HMD-based research is the critical distinction between user perception constructs, specifically *immersion* and *presence*. Immersion generally refers to the objective technical fidelity of the hardware (e.g., visual resolution, tracking latency), whereas presence is the subjective, psychological sensation of actually "being there" within the historical space. As Dincelli [15] emphasizes, achieving this deep sense of presence requires careful, multi-method evaluation of how users interact with virtual environments by design.

Furthermore, Dincelli and Yayla [16] point out that from a technology affordance perspective, the hybrid-narrative structures found in emerging Metaverse platforms fundamentally change how users engage with virtual spaces. Consequently, achieving high psychological presence requires more than just generating high-resolution meshes; it demands deliberate emotional design. As Lin et al. [17] note, fostering deep emotional connections to lost or degraded heritage sites is heavily dependent on how effectively XR spaces evoke empathy and historical context.

To accommodate the full spectrum of XR, recent applications leverage different levels of immersion. While VR isolates the user to maximize presence within fully reconstructed environments, such as the Madre de Deus Monastery project [18], which allowed users to explore imagined architectural histories, Augmented Reality (AR) and Mixed Reality (MR) anchor the digital past directly into the user's physical surroundings. AR applications effectively overlay digital reconstructions onto physical ruins, making tools highly accessible for on-site tourists [5]. MR goes a step further by mapping the spatial depth of a room, allowing users to physically walk around and manipulate holographic artifacts as if they were physically present in the laboratory or classroom. Crowdsourcing has further expanded these applications; for example, 3D models of the Temple of Bel were developed from social media images, though subsequent issues with image quality underscored the ongoing need for rigorous data verification [19].

Ultimately, immersive visualization tools across the XR spectrum help solve critical accessibility challenges. The Ulaca Virtual Tour utilizes interactive 360-degree panoramic viewers to offer site access to mobility-impaired individuals [20], while the Pleito Cave VR system enables Native American groups to view sensitive rock art without physical contact [21]. Moreover, as demonstrated by the Corsano Castle VR experience, which integrated audio narratives from local factory workers, these platforms are uniquely equipped to preserve intangible cultural memories right alongside the physical architecture [22].

2.2. Hardware and software

The democratization of immersive technologies relies heavily on the rapid evolution of both hardware and software. On the hardware front, while consumer-level HMDs (e.g., Oculus Quest 2) initially lowered the barrier to entry for VR [23,24], the landscape has shifted significantly toward mobile accessibility. Recent advancements utilize built-in smartphone LiDAR and low-cost mobile scanning systems (e.g., Pix4Dcatch, RealityScan) to generate highly accurate spatial models directly from mobile devices, circumventing the need for expensive terrestrial scanners in smaller contexts.

Simultaneously, software pipelines have underg1 a major paradigm shift. While early literature heavily favored Agisoft Metashape for photogrammetry and Unity for visualization [25], current workflows are increasingly dominated by RealityCapture due to its superior handling of hybrid datasets (laser scanning combined with photogrammetry). Furthermore, rendering pipelines are actively migrating toward Unreal Engine 5; specifically, its Nanite virtualized geometry system allows for the real-time rendering of cinematic-quality, non-decimated point clouds and meshes (such as the high-fidelity rendering of the Balzi Rossi cliffs [26]), solving historical bottlenecks in VR/AR asset optimization.

Hybrid workflows are becoming more common during the last decades, scan-to-HBIM-to-XR workflow for the Claudius Anio Novus aqueduct [27] combined UAV photogrammetry and laser scanning to achieve cost and accuracy constraints. Interoperability is still a problem, as seen in the Al-Quaraouiyine Mosque project [7], where the combination of HBIM, beacon sensors, and MongoDB needed custom coding to harmonize the data meanings.

2.3. Educational and cultural impact

Immersive technologies have reshaped heritage education by fostering experiential learning. The Ajanta Caves VR project [28] reported heightened visitor engagement through LiDAR-scanned models, while the Seokguram Grotto study [29] linked immersive visualization to increased perceived cultural significance. Educational applications, such as the AI-driven avatars at the Temple of Demeter [30], enabled natural language interactions, blending storytelling with technical data.

Community-centric projects emphasize inclusivity. The Chan Chan AR app [5,31] empowered Peruvian visitors to uncover hidden artifacts, fostering local pride, while the Alistrati Cave VR tour [32] addressed over-tourism by offering sustainable virtual alternatives. However, geographical bias remains: 73% of studies focused on European sites (e.g., Italy, Greece, Spain), with limited representation from regions like Sub-Saharan Africa or South America. Emerging tools like blockchain for metadata traceability and AI for automated reconstructions [30] remain underexplored, signaling opportunities for future research.

3. Methodology

To ensure scientific rigor and reproducibility, we conducted a systematic literature review adhering to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. Our search strategy targeted specific applications of immersive technologies in historical site preservation. We utilized Google Scholar as our primary academic search engine, as it comprehensively indexes peer-reviewed literature across major databases, including Scopus, Web of Science, IEEE Xplore, and the ACM Digital Library. To capture the most recent and relevant technological advancements while maintaining strict empirical integrity, the time range for publication selection was strictly defined to encompass fully completed calendar years, spanning from January 1, 2015, to December 31, 2025. This specific 10-year temporal boundary was deliberately selected to provide an adequate historical baseline to observe distinct technological trends, while ensuring the data remains highly relevant given the exceptionally rapid development pace of modern immersive hardware. Furthermore, to ensure granularity in our data extraction, the search strategy was deliberately designed to target the specific, underlying modalities of the immersive spectrum (VR, AR, MR) rather than the overarching umbrella term "Extended Reality" (XR). This forced the query to capture empirical case studies that explicitly defined their technological platforms, thereby inherently covering the XR domain from the ground up while naturally minimizing the retrieval of broad, theoretical discourse that merely uses "XR" as a high-level buzzword. We utilized the following Boolean search query:

- ("historical site*" OR "heritage site*" OR "archaeological site*" OR "architectur*")
- AND ("mixed reality" OR "MR" OR "augmented reality" OR "AR" OR "virtual reality" OR "VR")
- AND ("head-mounted display" OR "HMD" OR "headset" OR "glasses" OR "immersive display")
- AND ("laser scanning" OR "photogrammetry" OR "HBIM")
- AND ("3D reconstruction" OR "digital reconstruction" OR "virtual reconstruction")
- AND ("implementation" OR "case study" OR "prototype")
- NOT ("museum" OR "tourism" OR "education" OR "literature review")

The selection conditions were tightly controlled. Studies were included if they focused on historical site reconstruction using immersive technologies, employed specific reality-capture techniques (laser scanning, photogrammetry, or HBIM), involved an empirical case study or prototype, and explicitly specified the software ecosystems used. The exclusion of domains such as "museum," "tourism," and "education" was a deliberate methodological choice to filter out front-end pedagogical applications that lacked the rigorous backend geomatics and 3D prototyping data necessary for our engineering analysis. Theoretical discussions, studies lacking a palpable prototype or real-world application, and studies that failed to explicitly state the specific reality-capture techniques and software pipelines used during prototype development were excluded Table 1.

As shown in Fig. 1, this updated query returned 798 records after applying the 2015-2025 date range filter. The PRISMA flow diagram (Fig. 1) illustrates our study selection process:

Identification (n = 798): We retrieved 798 records using the specified search string and removed duplicates and non-peer-reviewed entries (e.g., book abstracts).

Screening (n = 483): After discarding 315 duplicates and non-relevant records, 483 studies proceeded to the rigorous evaluation stage.

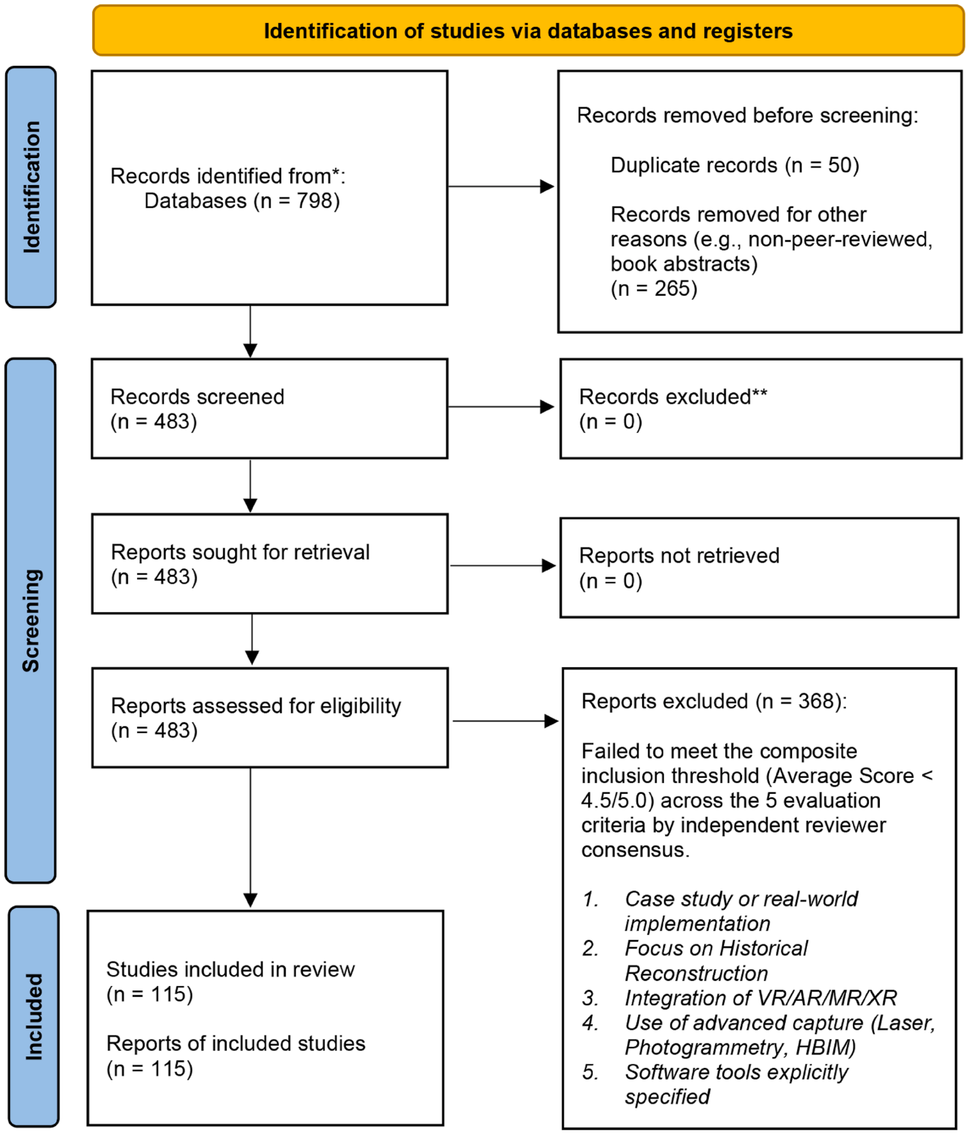

Fig. 1. PRISMA flow diagram.

Table 1
Evaluation questions and metrics for filtering.

No	Question	Motivation
Q1	Does the study involve a case study, prototype, or real-world implementation?	Ensure practical insights or empirical data.
Q2	Does the study focus on Historical Reconstruction?	Focus on reconstruction as a preservation method.
Q3	Does the study use VR, AR, MR, or XR?	Capture the use of immersive technologies.
Q4	Are laser scanning, photogrammetry, or HBIM techniques employed?	Identify advanced 3D reconstruction techniques.
Q5	Are software tools for modeling or rendering specified?	Analyze software trends and best practices.

Eligibility (n = 115): To ensure high analytical quality and eliminate selection bias, we applied a strict evaluation metric. This step mathematically enforced our explicit exclusion criteria: verifying the presence of a palpable prototype (Q1) and the explicit documentation of the hardware sensors and software pipelines used to build it (Q4, Q5). Each study was independently and blindly assessed by three researchers from our team. The following evaluation questions were scored as 1 (yes) or 0 (no):

After the independent blind reviews were completed, the scores for each article were aggregated. Articles achieving a combined average score of higher than 4.5 (out of 5.0) were considered eligible. This rigorous filtering step excluded 368 studies that failed to meet this composite threshold, leaving a final dataset of 115 high-fidelity case studies for comprehensive quantitative and qualitative synthesis. To ensure the findings extended beyond a descriptive narrative review, the subsequent data extraction phase focused on a clearly defined set of engineering variables mapped directly to our Research Questions: the immersive deployment hardware (RQ1), the geometric capture modalities (RQ2), and the software rendering pipelines (RQ3). By systematically analyzing the technical relationships between these variables across the 115 studies, specifically how certain capture inputs dictate distinct rendering constraints, we synthesized the empirical data to construct the Modular XR Engineering Framework (MXEF), thereby ensuring the analytical depth required of a systematic review.

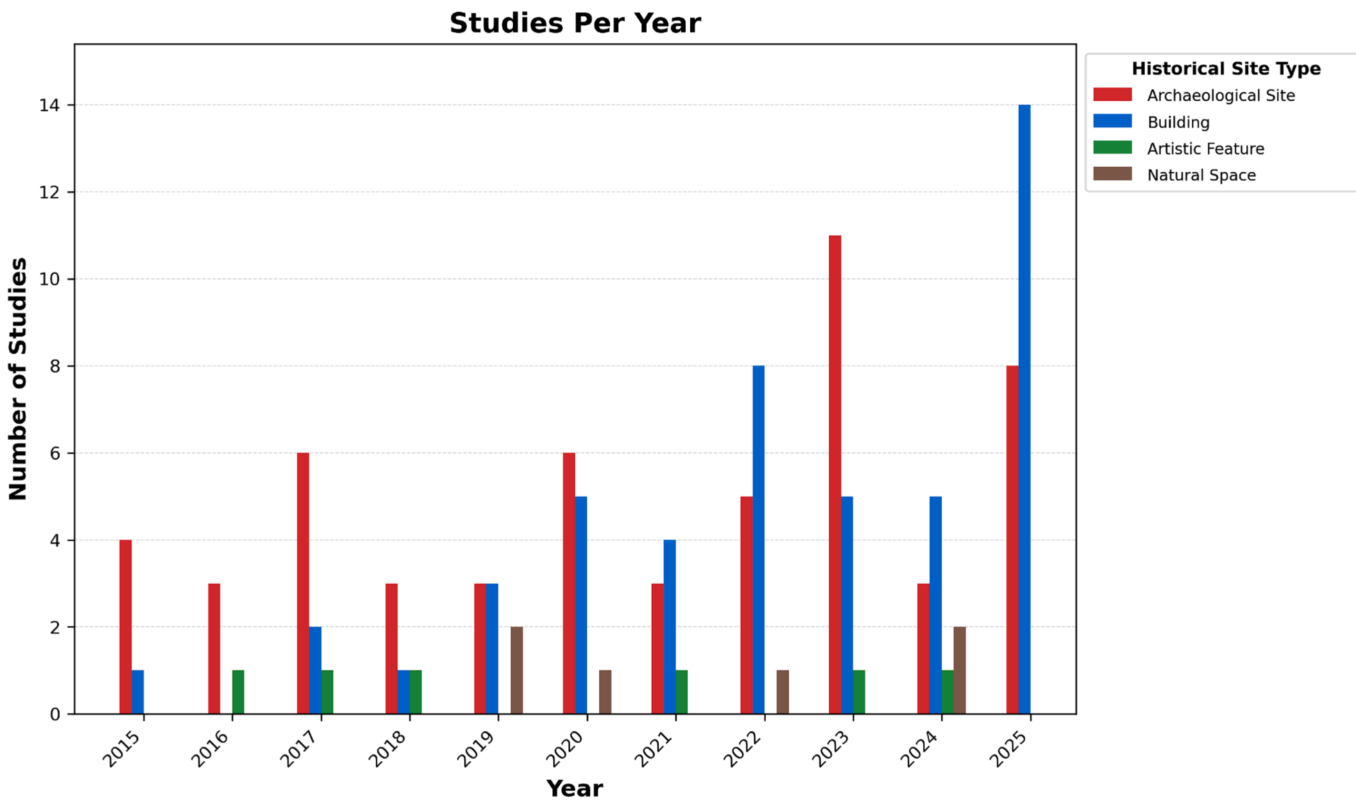

Fig. 2. Timeline of publications by historical site categories.

4. Results

The results of this research are categorized into quantitative and qualitative findings, which have been structured to directly address the four Research Questions (RQs) established in Section 1. The quantitative results (Section 4.1) provide data-driven insights into publication trends, platform adoption (RQ1), technique usage (RQ2), and software preferences (RQ3). Meanwhile, the qualitative analysis (Section 4.2) interprets these metrics, highlighting representative case applications, methodological challenges, and geographic disparities (RQ4).

4.1. Quantitative results

This section focuses on the analysis of the collected data quantitatively based on the research results and technologies that have been used by previous researchers, as follows.

4.1.1. Summaries of publication trends

The annual number of publications from 2015 to 2025, divided into four main site categories as shown in Fig. 2, which are Building, Archaeological Site, Artistic Feature, and Natural Space. Overall, publications on archaeological sites show the highest frequency, peaking at 11 publications in 2023. This surge indicates a strong research focus on excavated or partially unearthed locations that benefit from digital documentation and preservation.

The building category also demonstrates a marked increase over the years, especially peaks in 2025 by 14 studies. This consistent growth reflects ongoing interest in architectural reconstructions, such as temples, monuments, and historically significant urban structures.

In comparison, artistic features and natural spaces register fewer publications overall. Nevertheless, both categories exhibit a gradual upward trend. Artistic features (e.g., murals, sculptures) remain a niche area, yet they show growth since 2017. Natural spaces (e.g., cultural landscapes or heritage parks) display a similar pattern, indicating that while less prevalent than built heritage, they are gaining recognition in literature.

Notably, the lowest publication counts appear in the earlier years (2015-2016), underscoring how digital heritage research has gained momentum over the past decade. By 2025, archaeological site publications achieve their highest recorded number, highlighting the field's expanding interest in systematic and precise reconstruction methods for excavation sites. This trend, coupled with the sustained rise in building-related studies, served as a key motivator for our systematic review to identify and standardize effective reconstruction techniques that address the growing complexity of heritage preservation projects.

To further illustrate the specific composition of these categories within the 115 reviewed studies, Fig. 3 presents a hierarchical sunburst chart of the historical site types. The inner ring confirms the dominance of Archaeological Sites and Buildings, which collectively represent the vast majority of digital preservation efforts. The outer ring provides a granular breakdown of these broad categories, revealing specific subtypes such as religious buildings, fortifications, underwater wrecks, and open-air ruins. This visualization highlights that while structural and excavated heritage receive extensive technical focus, artistic features (e.g., isolated murals or sculptures) and natural cultural landscapes remain comparatively underrepresented in the current XR literature.

4.1.2. Platform trends (RQ1)

The number of publications associated with four immersive platforms, VR, AR, MR, and XR, broken down by device type (HMD, PC, Mobile, and Immersive Display). Each platform's bar group is subdivided to indicate how many publications leverage a particular device setup presented in Fig. 4.

VR demonstrates the highest overall count, with a notable preference for HMD-based solutions (69 publications), followed by Mobile (22) and PC-based (18) implementations. Immersive displays (4) are comparatively rare for VR but still present, indicating some usage of large-scale projection environments (e.g., CAVE systems). AR ranks second in total

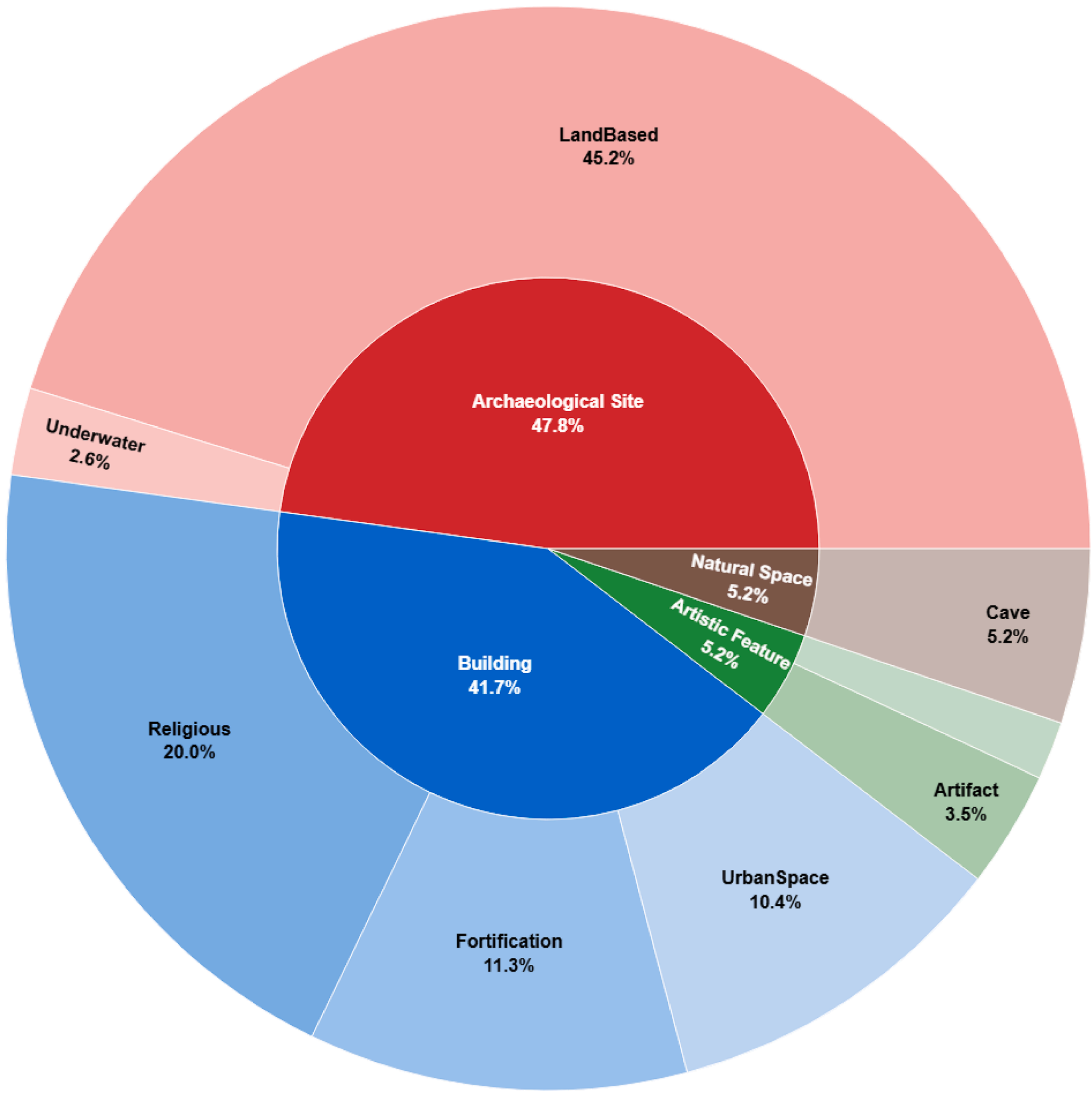

Fig. 3. Hierarchical distribution of historical site types.

publications, with HMD-based AR (18) and Mobile AR (13) leading the device types and reflecting the growing accessibility of smartphone or tablet-based solutions. In contrast, PC-based AR (5) and Immersive Display AR (3) appear less frequently but still represent valuable tools in specialized or laboratory contexts.

MR shows modest adoption overall, primarily reliant on Mobile (3) and PC-based (1) approaches. XR, although limited in total publications, exhibits a small but distinct presence, with Immersive Displays (3) and PC-based XR (1) suggesting ongoing experimentation in fully integrated mixed-environment systems. Overall, these data reveal that VR, especially through head-mounted displays, dominates the immersive technology landscape, followed by steadily growing AR usage. Meanwhile, MR and XR remain in earlier stages of adoption but exhibit incremental research interest, signaling a broader diversification of device ecosystems in digital heritage and reconstruction contexts.

In Fig. 5, the annual distribution of publications referencing four immersive platforms, VR, AR, MR, and XR, between 2015 and 2025 is illustrated. VR appears as the dominant platform, exhibiting consistent growth from 2015 onward, peaking around 2022-2023 before a slight decline in 2024. AR follows a more variable trajectory, showing moderate use in the early years but occasionally surpassing VR in specific intervals (e.g., 2019) and continuing a gradual ascent thereafter. MR and XR remain comparatively lower throughout the timeline yet display incremental increases, signaling emergent interest in more integrated or mixed-environment experiences. Collectively, the data suggests that VR secured an early lead as the immersive technology of choice, while AR has steadily caught up, and MR/XR is beginning to gain traction in digital heritage research. This overall diversification reflects a broader trend toward employing multiple immersive modalities to capture, visualize, and reconstruct historical sites.

4.1.3. Technique trends (RQ2)

The hierarchical view of the techniques employed in digital heritage research, with the inner ring illustrating broad categories (e.g., Image-Based Techniques, 3D Scanning, Modeling & Reconstruction, Geospatial Techniques) and the outer ring detailing specific sub-techniques

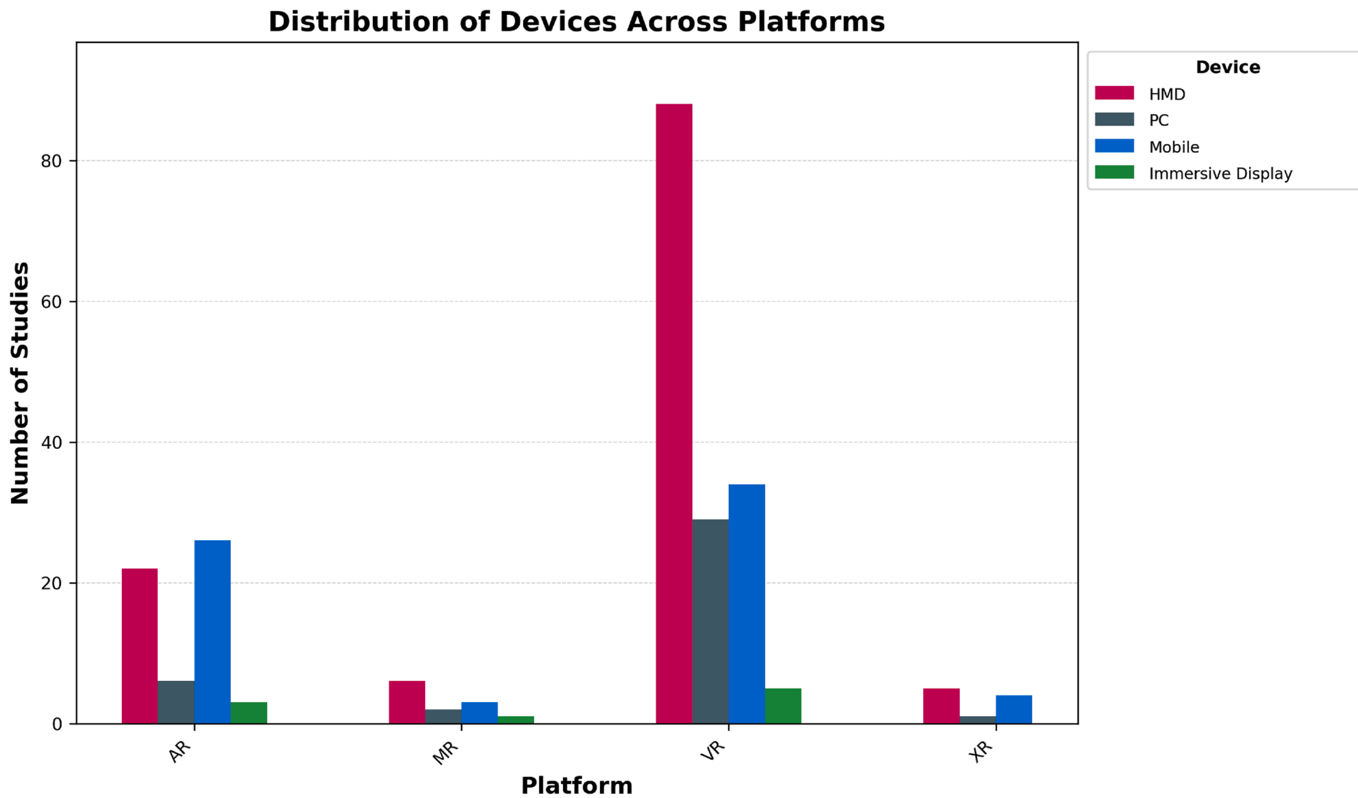

Fig. 4. Distribution of devices across platforms.

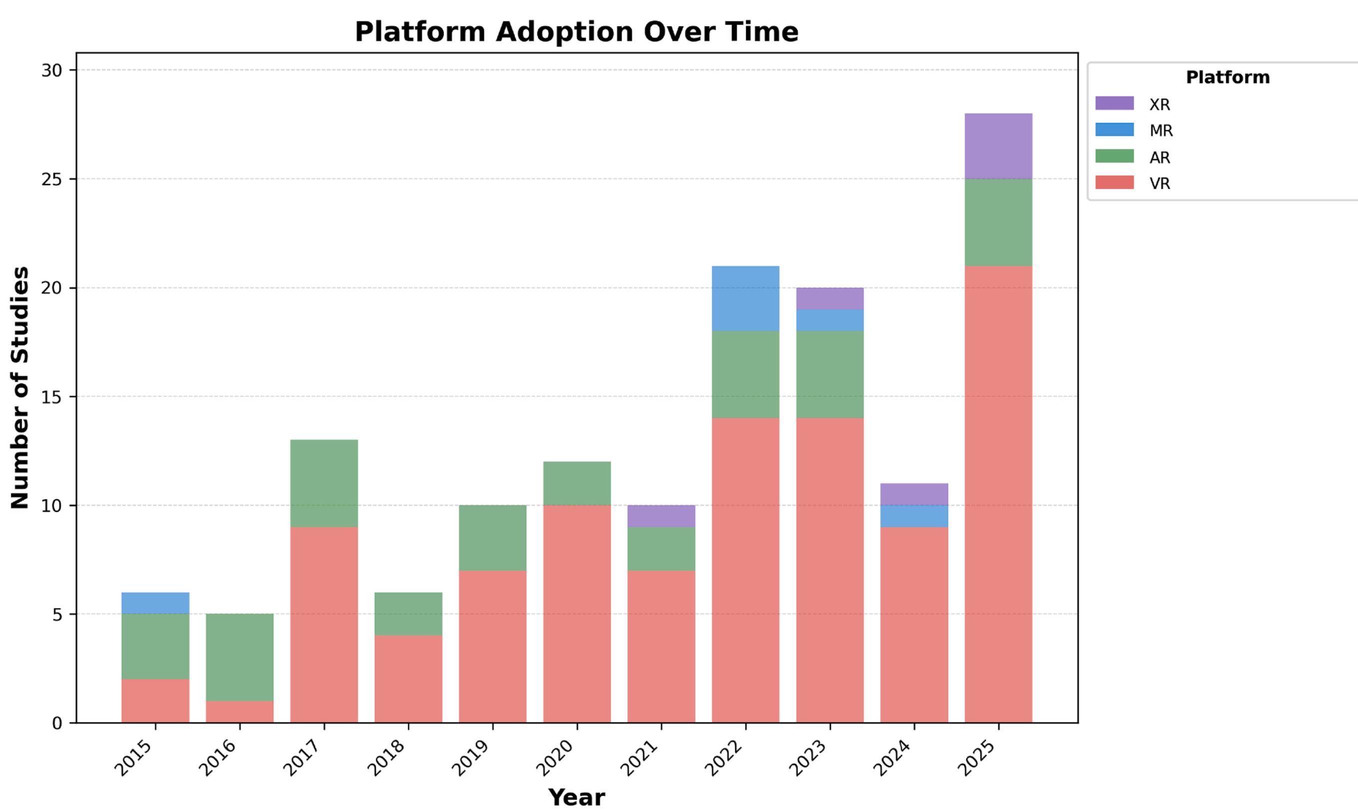

Fig. 5. Platform adoption over time.

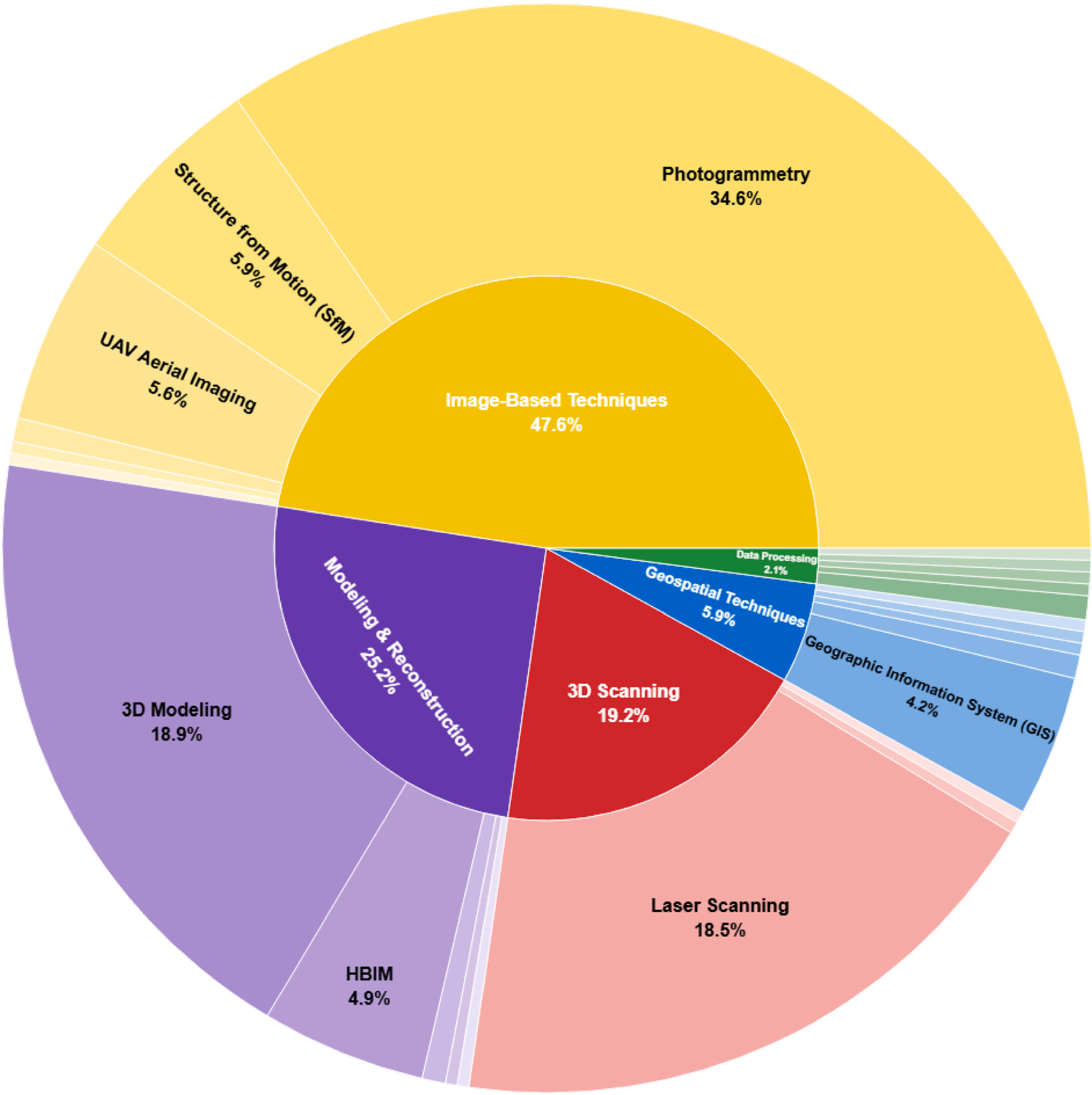

Fig. 6. Technique & sub-technique distribution.

(e.g., photogrammetry, laser scanning, UAV imaging) as shown in Fig. 6. Image-Based Techniques comprise nearly half of the dataset (47.6%), underscoring the popularity of methods like photogrammetry, which alone accounts for 34.6%. This dominance reflects a preference for photogrammetry's relatively low cost and high fidelity in capturing architectural and archaeological details. Meanwhile, 3D Scanning represents 19.2% of the techniques used, including laser scanning and structured-light scanning approaches that support precise geometric documentation. Modeling & Reconstruction follows at 25.2%, emphasizing the importance of post-capture workflows for generating accurate 3D representations. Additional segments, such as Geospatial Techniques (5.9%) and Data Processing (2.1%), illustrate the broader ecosystem of tools needed for site analysis, metadata management, and alignment across multiple data sources. Overall, the chart reveals a strong inclination toward photogrammetry and scanning-based workflows, while also highlighting an emerging trend toward integrating geospatial and data-processing solutions to address the growing complexity of heritage reconstruction projects.

To further clarify the specific applications of these technologies, Fig. 7 presents a Sankey diagram illustrating the flow between the study focus (Reconstruction vs. Visualization), the specific historical site type, and the chosen geomatics technique. This visualization demonstrates that archaeological sites and buildings heavily rely on hybrid workflows combining image-based techniques and 3D scanning to achieve the necessary fidelity for digital preservation.

Fig. 8 presents a heatmap depicting the frequency of five key techniques, 3D Scanning, Data Processing, Geospatial Techniques, Image-Based Techniques, and Modeling & Reconstruction, across four histor-

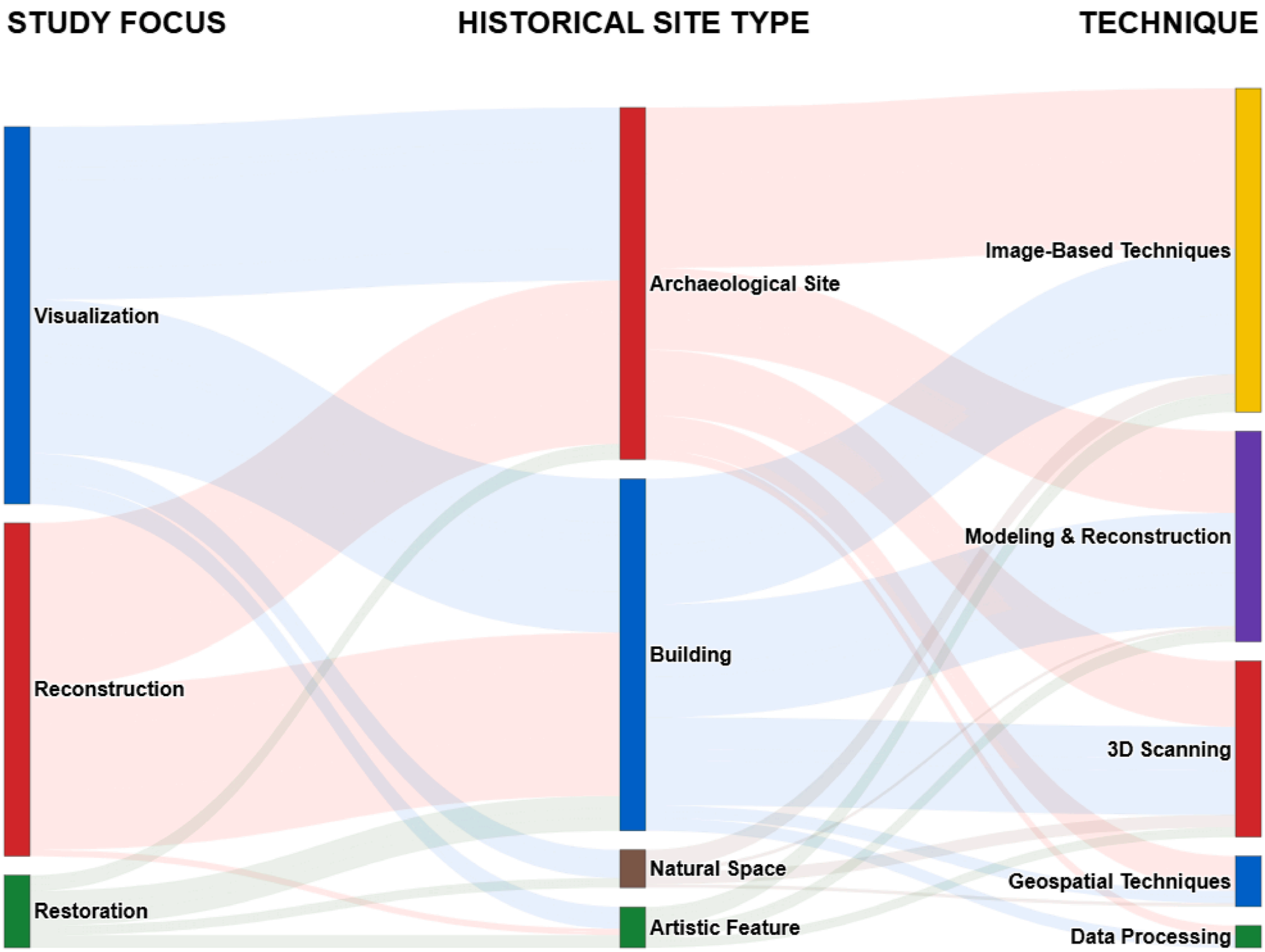

Fig. 7. Mapping of study focus, historical site types, and employed techniques.

ical site categories: Archaeological Site, Artistic Feature, Building, and Natural Space. The usage frequency is visualized through a color gradient, ranging from light green (low usage, 0) to dark green (high usage, up to 50), with numerical values providing precise insights. Image-Based Techniques emerge as the most dominant method, particularly in Archaeological Sites (51 uses) and Buildings (40 uses), where the darkest shades reflect their extensive application. This prevalence likely stems from the accessibility and cost-effectiveness of methods like photogrammetry for detailed documentation. In contrast, Data Processing and Geospatial Techniques exhibit minimal usage, with values of 0 and 4, respectively, across all categories, as indicated by the lightest shades, notably in Artistic Features and Natural Spaces. Archaeological Sites and Buildings show moderate reliance on 3D Scanning (21 and 28 uses) and Modeling & Reconstruction (26 and 36 uses), marked by mid-range green shades, suggesting a preference for high-fidelity digital preservation in these contexts. Natural Spaces, however, demonstrate the lowest overall engagement, with all techniques ranging from 0 to 6 uses, highlighting a potential underrepresentation in digital heritage efforts. These findings underscore methodological preferences in heritage preservation and inform this review's focus on selecting studies that leverage advanced, scalable techniques for accurate site reconstruction.

4.1.4. *Software analysis (RQ3)*

In the horizontal bar chart illustrated in Fig. 9, the usage frequency of software tools across three distinct categories, which are Data Processing, 3D Modeling, and Rendering, is derived from a systematic review of software applications in heritage-related studies. The chart employs a color-coded scheme to distinguish the categories: blue for Data Processing, green for 3D Modeling, and red for Rendering. The x-axis quantifies the usage count, ranging from 0 to 61, while the y-axis lists the software tools grouped by category. The length of each bar corresponds to the usage frequency, providing a clear visual representation of software adoption within the reviewed studies.

In the Data Processing category, Agisoft Metashape emerges as the most frequently utilized tool, with a usage count of 60, its blue bar extending to the chart's maximum value. This is followed by Autodesk ReCap (15), Leica Cyclone (14), Reality Capture (10), and both ArcGIS and QGIS tied at 5 each. Agisoft Metashape's dominance suggests its critical role in photogrammetry and 3D data generation, processes foundational to creating accurate digital representations of heritage sites. The relatively lower usage of other tools, such as ArcGIS and QGIS, may indicate their more specialized applications, such as geospatial analysis, which are less universally required in the workflows examined.

The 3D Modeling category is led by Blender, which records a usage count of 38, its green bar markedly longer than those of its counterparts: , Autodesk Revit (16), Autodesk 3ds Max (15), Autodesk AutoCAD (13), and both Rhinoceros and ZBrush at 6 each. Blender's prominence can likely be attributed to its open-source availability, robust feature set, and adaptability for detailed geometric refinement, making it a favored tool for modeling tasks in digital heritage projects. The moderate usage of Autodesk products reflects their established presence in professional settings, though their lower counts compared to Blender suggest a preference for cost-effective or flexible solutions among the reviewed studies.

In the Rendering category, Unity stands out with a usage count of 61, its red bar approaching the chart's upper limit, followed by Unreal

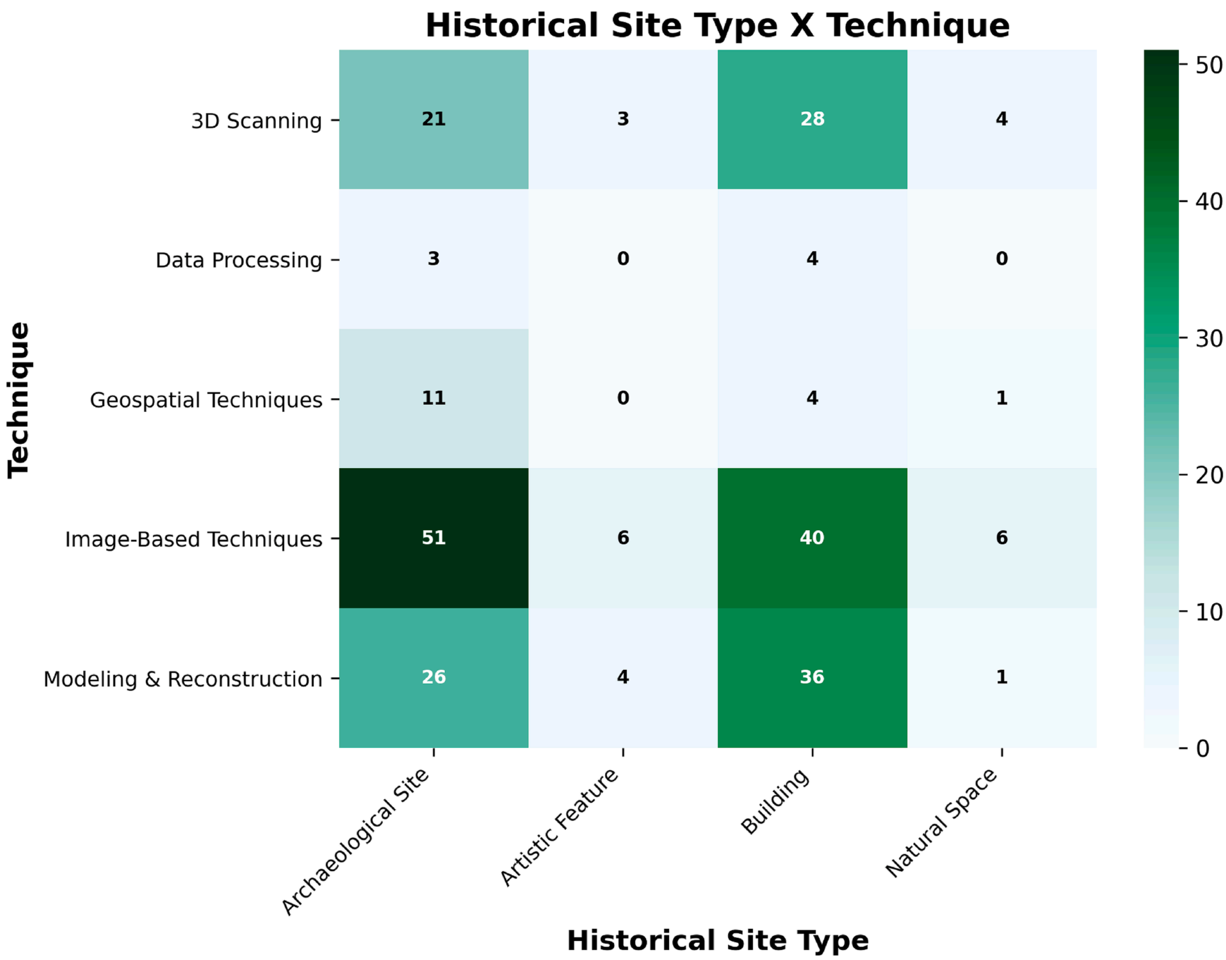

Fig. 8. Technique usage across historical site types.

Engine at 26. Unity's high usage underscores its significance in producing real-time, interactive visualizations, a growing priority for making heritage sites accessible through virtual platforms. Unreal Engine, while less frequently adopted, remains notable for its capacity to deliver high-fidelity renders, likely catering to projects requiring photorealistic outputs.

The chart's design, with its clear color differentiation and proportional bar lengths, enables straightforward comparisons across categories. Notably, Agisoft Metashape (Data Processing) and Unity (Rendering) exhibit the highest usage counts overall, at 50 and 47, respectively, highlighting the field's reliance on photogrammetry for initial data capture and game engines for final visualization. In contrast, the 3D Modeling category, while led by Blender (38), shows a more distributed usage pattern, suggesting a diversity of tools tailored to specific modeling needs. The lower usage counts in tools like ArcGIS, QGIS, Rhinoceros, and ZBrush (all at 6) indicate niche applications rather than widespread adoption.

These findings align with the broader research objective of identifying prevalent software tools in heritage reconstruction, reflecting a workflow that prioritizes accurate data acquisition (via Agisoft Metashape), versatile modeling (via Blender), and immersive presentation (via Unity). The distribution suggests that scalable, accessible tools are favored, likely due to their balance of functionality and cost, a critical consideration for heritage preservation efforts often constrained by resources.

This analysis provides a concise, comprehensive visualization overview of software usage trends, offering valuable insights into best practices for digital heritage documentation and visualization as evidenced by the systematic review.

Fig. 10 presents a heatmap that compares how different software tools are utilized across five primary technique categories: 3D scanning, data processing, geospatial techniques, and image-based techniques. Each cell's numeric value and color intensity indicate the frequency a given software technique pairing appears in the surveyed literature, with higher counts reflecting more prevalent usage. Several notable patterns emerge. First, image-based techniques show the strongest affinity with tools like Agisoft Metashape, underscoring their prominence in generating high-fidelity 3D models from photographic data. Blender exhibits a broad distribution across image-based, modeling, and reconstruction tasks, highlighting its flexibility as an open-source platform that can bridge various workflow stages. In contrast, specialized scanning and data-processing software, such as Leica Cyclone, appears concentrated in narrower technique categories, pointing to its niche role in handling point clouds and advanced laser-scan data. Unity and Unreal Engine are primarily associated with modeling and rendering, demonstrating their significance in creating interactive or immersive outputs. Taken together, these observations reveal a tendency toward integrated workflows in which multiple software solutions are combined to optimize data capture, mesh processing, and final visualization. By visualizing these usage frequencies, the heatmap also contributes to the broader systematic review by clarifying where each software tool excels, thereby guiding researchers in selecting compatible, efficient pipelines for historical site reconstruction and VR applications.

Fig. 11 is a heatmap that examines relationships between data processing and modeling software. Rows list data software (Agisoft Metashape, Autodesk ReCap, Leica Cyclone, Reality Capture) from top to bottom, and columns list modeling software (Autodesk 3ds Max, Autodesk AutoCAD, Autodesk Revit, Blender, Rhinoceros, SketchUp)

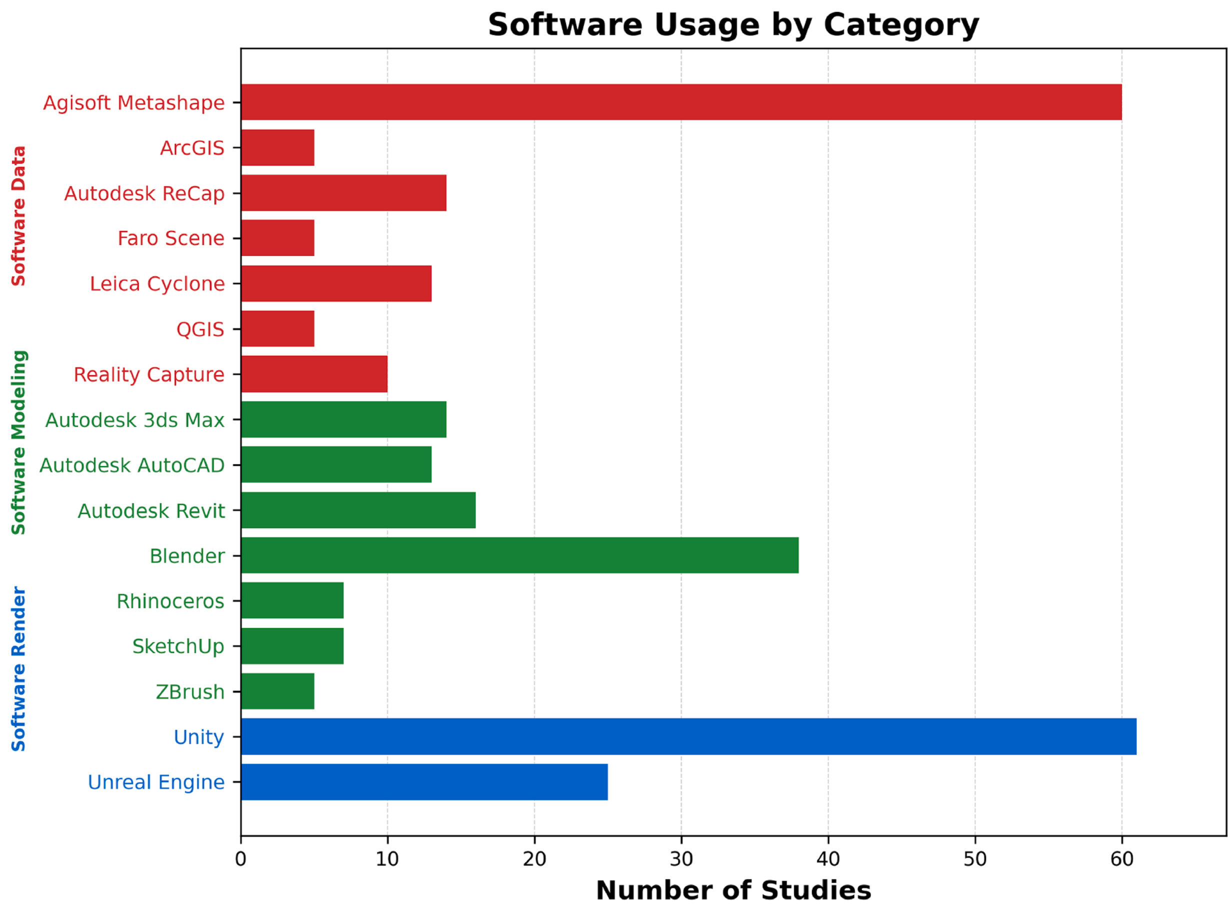

Fig. 9. Software usage by category.

from left to right. A color gradient from light green to dark green indicates relationship strength, with numerical values in each cell. Agisoft Metashape shows the strongest relationship with Blender (25), followed by moderate links with Autodesk AutoCAD (7), Autodesk Revit (6), and Autodesk 3ds Max (5). It has wekaer link with Rhinoceros and SketchUp (3). Autodesk ReCap and Leica Cyclone connect moderately with Autodesk Revit (5, 4), and Autodesk ReCap with Rhinoceros (4). Reality Capture links slightly with Blender (3). Many cells show 0, indicating no combined usage scenarios.

The pronounced Agisoft Metashape and Blender pairing suggests a seamless workflow from photogrammetry to modeling, critical for heritage projects requiring detailed 3D reconstructions. The sparse connections elsewhere highlight specialized or less integrated software pairings.

A heatmap in Fig. 12 explores connectivity between modeling and rendering software. Rows list rendering software (Blender, Enscape, Lumion, Unity, Unreal Engine) from top to bottom, and columns list modeling software (Autodesk 3ds Max, Autodesk AutoCAD, Autodesk Maya, Autodesk Revit, Blender, Meshlab, Rhinoceros, SketchUp, ZBrush) from left to right. A color gradient from light blue (0) to dark green (25) indicates relationship strength. Unity has the strongest link with Blender (25, dark green), followed by Autodesk 3ds Max (10) and Autodesk Revit (7). Unreal Engine connects moderately with Blender (8) and minimally with Autodesk 3ds Max (3) and Autodesk Revit (5). Lumion and Twinmotion show minor connections with Rhinoceros (1, 2) and SketchUp (2, 0), respectively. Many cells are 0 (e.g., Tree.js with most modeling tools), indicating limited integration. The Unity-Blender relationship underscores their synergy in real-time heritage visualization, while the sparse connections elsewhere suggest a focus on specific, high-compatibility workflows.

Fig. 13 depicts a stacked area chart illustrating the annual usage frequency of seven prominent software tools: Agisoft Metashape, Autodesk Recap, Autodesk 3Ds Max, Autodesk Revit, Blender, Unity, and Unreal Engine grouped into three broad categories of data processing, 3D modeling, and rendering from 2015 to 2025. The vertical axis represents the number of studies in which each tool was employed during a given year, while color-coded segments within each stack indicate the share contributed by each software. Early in the observed period (2015-2018), data-processing applications such as Agisoft Metashape and Autodesk Recap demonstrate steady adoption, reflecting the field's initial emphasis on photogrammetry and point-cloud management. A subsequent rise in 3D modeling software (notably Autodesk Revit and Blender) becomes evident around 2020, suggesting growing interest in both BIM-focused workflows and open-source modeling. The most pronounced surge occurred from 2021 onward, particularly in rendering engines like Unity and Unreal Engine, which indicates the increasing demand for interactive or real-time visualizations in digital heritage projects. By 2023-2024, all three categories converge at higher usage levels, peaking in 2025, revealing a more integrated approach that spans data capture, model refinement, and immersive presentation. In the context of this systematic review, these evolving trends highlight a pivot toward cross-platform interoperability and underscore the sector's expanding reliance on real-time, user-centered experiences to communicate and preserve cultural heritage.

Table 2 consolidates key software tools commonly used in digital heritage workflows, categorizing each by its principal function: data processing, 3D modeling, or visualization, and noting operating system compatibility. Photogrammetry programs such as Agisoft Metashape and Reality Capture fall under data processing, reflecting their emphasis on converting photographic input into 3D point clouds and textured

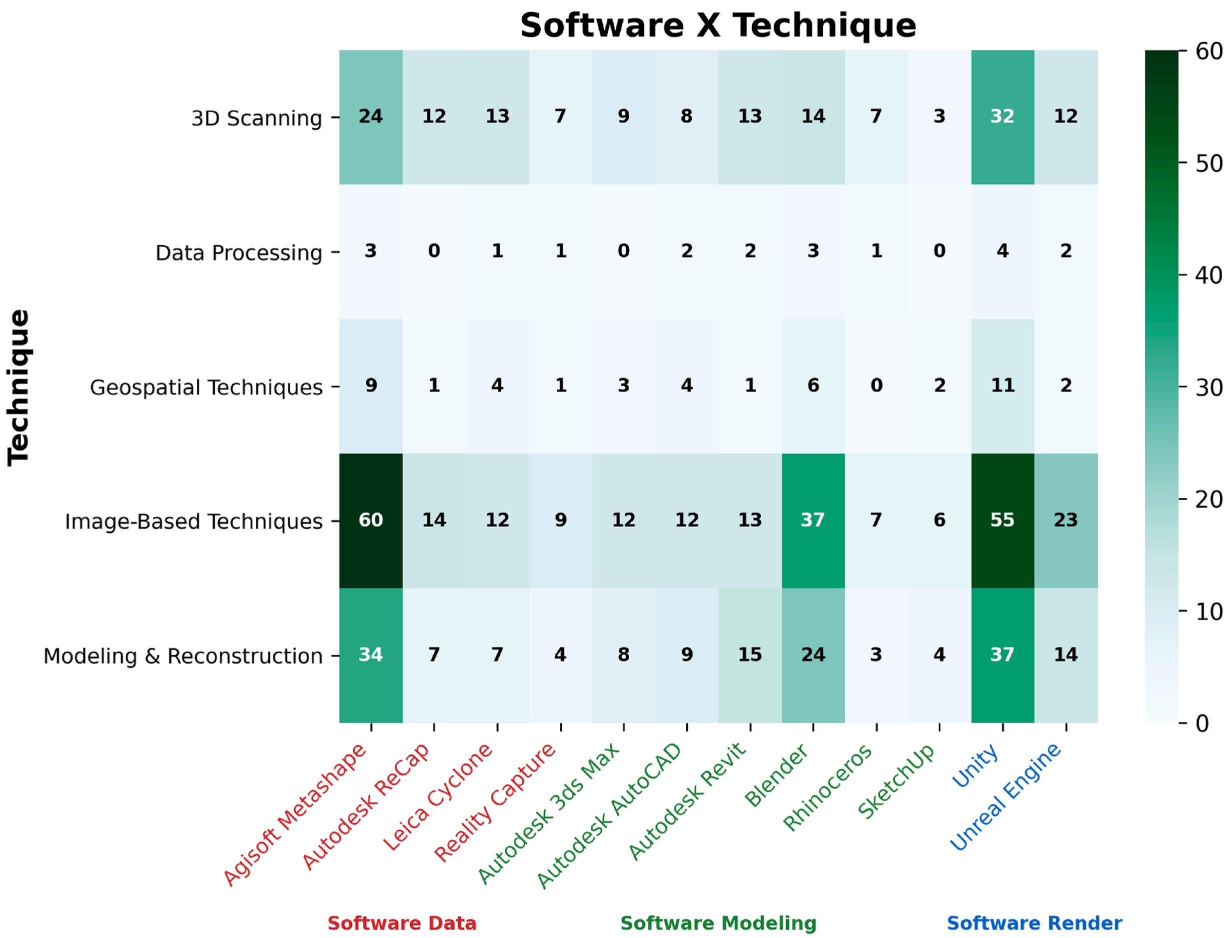

Fig. 10. Heatmap of techniques used with different software.

meshes. Tools like Autodesk Recap and Leica Cyclone likewise handle point-cloud data, although Leica Cyclone extends into modeling capabilities for scanned datasets. In contrast, the 3D modeling category features Blender, Autodesk 3D Max, Autodesk Revit, and Rhinoceros, each specialized in different modeling paradigms: from Blender's open-source mesh editing and animation to Revit's Building Information Modeling (BIM) framework. Visualization solutions such as Unity, Unreal Engine, V-Ray, and Lumion focus on real-time rendering or photorealistic output, catering to interactive experiences and architectural visualization. The table also notes platform support, underscoring that some tools like Blender, Unity, and Agisoft Metashape are cross-platform, while others remain Windows-exclusive. Taken together, the table offers a quick reference for selecting software that aligns with specific functions and operating systems, whether those entail capturing and processing high-fidelity data, developing complex 3D models, or delivering immersive, interactive renderings presented in Table 2.

4.1.5. Geographical trends

In Fig. 14, a bubble chart shows four main historical site types: Archaeological Site, Artistic Feature, Building, and Natural Space, across various countries, with each bubble's size corresponding to the number of studies (minimum of 1, maximum of 17) identified in the review. The country names along the horizontal axis are color-coded by region (Africa, Americas, Asia, Europe, Middle East), while the vertical axis lists the site types. Larger bubbles indicate higher frequencies of research focusing on a particular site type within that country. A notable observation is the prevalence of "Building" studies in several European countries, reflecting a strong emphasis on architectural reconstructions, whereas "Archaeological Site" also appears significantly in regions with rich ancient heritage. In contrast, "Artistic Feature" and "Natural Space" are comparatively less represented overall. By visualizing geographical distribution in this way, the figure underscores the uneven coverage of different site types across global regions, hinting at potential biases toward certain cultures or periods. This geographical perspective complements the earlier sections of the systematic review, highlighting the need for more balanced research that includes underrepresented regions and site categories in digital heritage projects.

Fig. 15 presents a world map titled "Geographical Distribution of Publications," which illustrates the global spread of publication activity across various countries. This map utilizes a color gradient to represent the number of publications per country, ranging from light yellow (indicating 0 publications) to dark red (denoting 25 or more publications). This visual representation highlights significant geographical disparities in publication output. Italy stands out as the leading contributor, marked by the darkest red shading, signifying a publication count of 25 or higher, and underscoring its dominant role in the field. Moderate activity, depicted by light yellow to pale orange hues (corresponding to 5 to 10 publications), is evident in North America, particularly the United States and Canada, as well as in parts of Europe, including Spain, France, Germany, and the United Kingdom, and in Asia, notably China and India. Conversely, vast regions such as South America, Africa, Australia, Russia, Eastern Europe, and Central Asia show minimal to no publication activity, as indicated by light blue or pale-yellow shading (close to 0 publications). The Middle East and Southeast Asia exhibit low to moderate output, with publication counts hovering around 5 to 10. This distribution reveals a stark concentration of publication

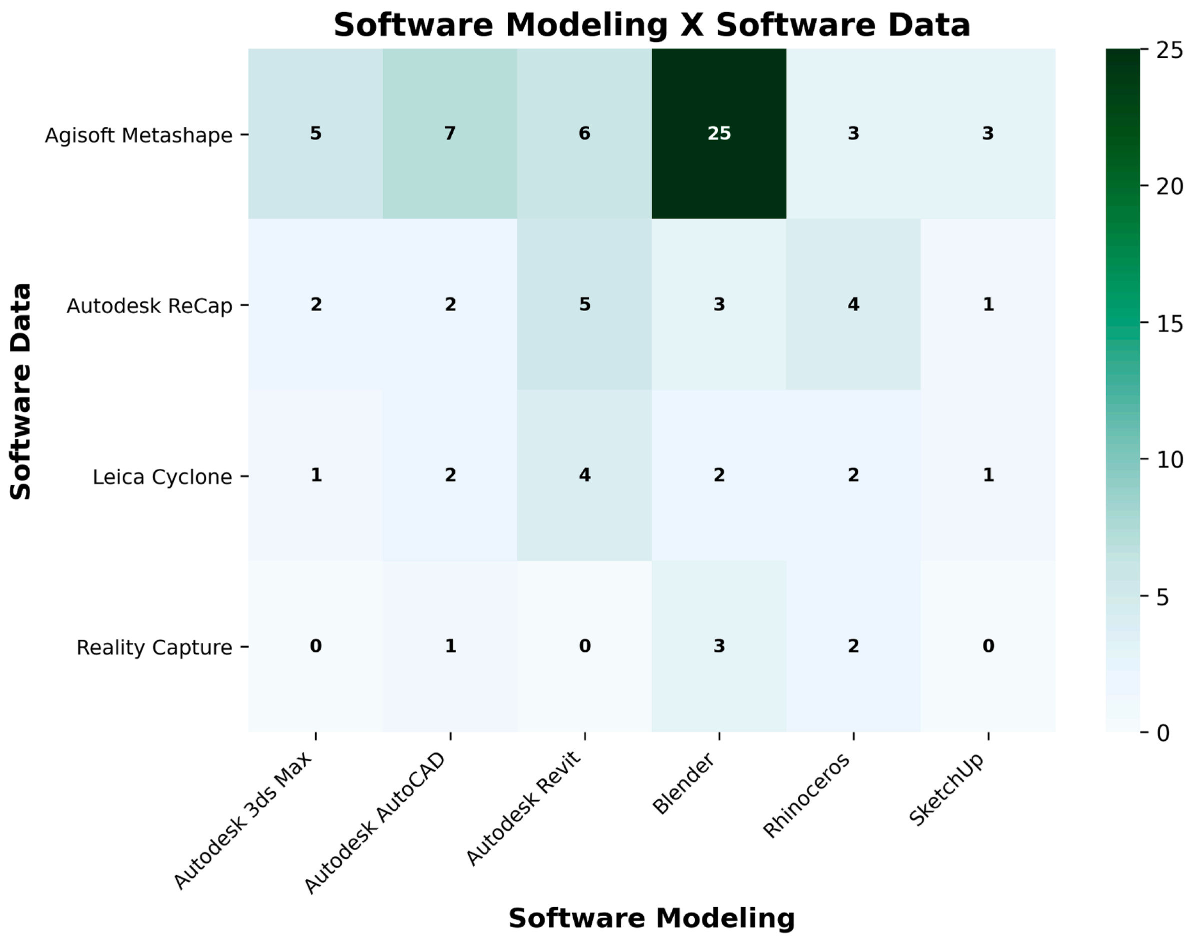

Fig. 11. Co-occurrence heatmap of software for modeling & data.

Table 2
Software comparison table.

Software	Category	Functionality	Compatibility
Agisoft Metashape	Data Processing	Photogrammetry	Windows, macOS, Linux
Autodesk Recap	Data Processing	Point Cloud Processing	Windows
Leica Cyclone	Data Processing	Point Cloud Processing & Modeling	Windows
Reality Capture	Data Processing	Photogrammetry & 3D Reconstruction	Windows
Blender	3D Modeling	Mesh Editing, Sculpting, Animation	Windows, macOS, Linux
Autodesk 3Ds Max	3D Modeling	Mesh Editing, Texturing	Windows
Autodesk Revit	3D Modeling	BIM (Building Information Modeling)	Windows
Rhinoceros	3D Modeling	NURBS Modeling, Surface Design	Windows, macOS
Unity	Visualization	Game Engine (3D Rendering)	Windows, macOS, Linux
Unreal Engine	Visualization	Game Engine (3D Rendering)	Windows, macOS
V-Ray	Visualization	Raytracing (Physical Based Rendering)	Windows, macOS
Lumion	Visualization	Architectural Visualization	Windows

activity in Europe, especially Italy, alongside moderate contributions from North America and select Asian countries, while much of the globe remains underrepresented.

These findings suggest a need for further investigation into the underlying causes of such disparities and the potential for promoting broader, more equitable participation in global publication efforts.

4.2. Qualitative analysis

The analysis includes 115 studies screened through the PRISMA methodology, which reveals critical trends, challenges, and opportunities in the use of digital technologies for historical site preservation, reconstruction, and visualization. These findings align with broader academic discourse while highlighting domain-specific advancements and gaps. Below, we synthesize key insights, contextualize them within existing literature, and propose future directions.

4.2.1. Technological development: Value and key trends

VR and AR emerged as pivotal tools for public engagement and education, enabling interactive exploration of inaccessible or fragile sites such as underwater shipwrecks [1] and Roman theaters [33]. Projects like the AI-driven avatars at the Temple of Demeter and the metaverse platform for the Chime Bells of Marquis Yi [30,34] demonstrate how immersive experiences enhance learning outcomes and emotional engagement. These results align with recent literature emphasizing VR/AR's role in democratizing heritage access [35].

The integration of HBIM, GIS, and photogrammetry [7,36] underscores the importance of multidisciplinary approaches. For instance, the

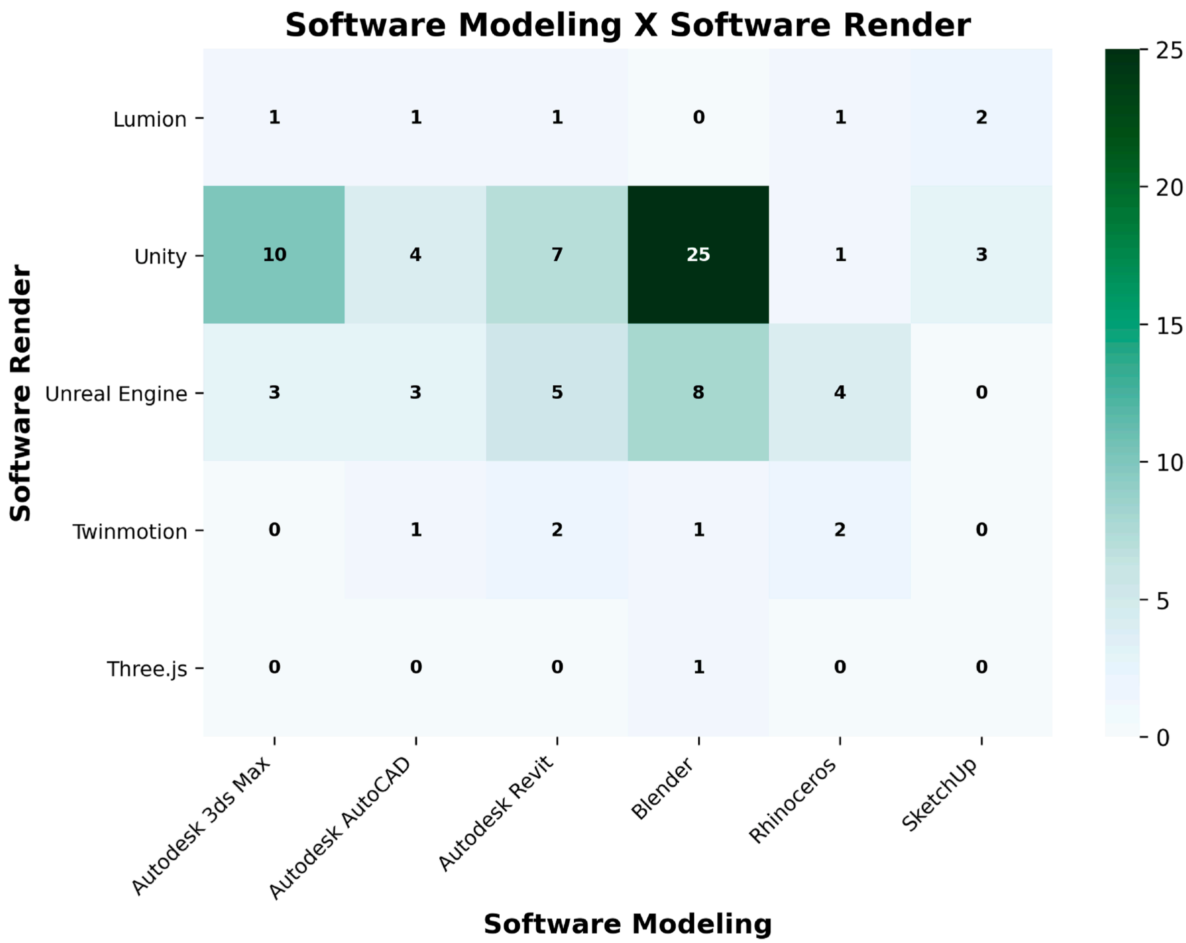

Fig. 12. Co-occurrence heatmap of software for modeling & rendering.

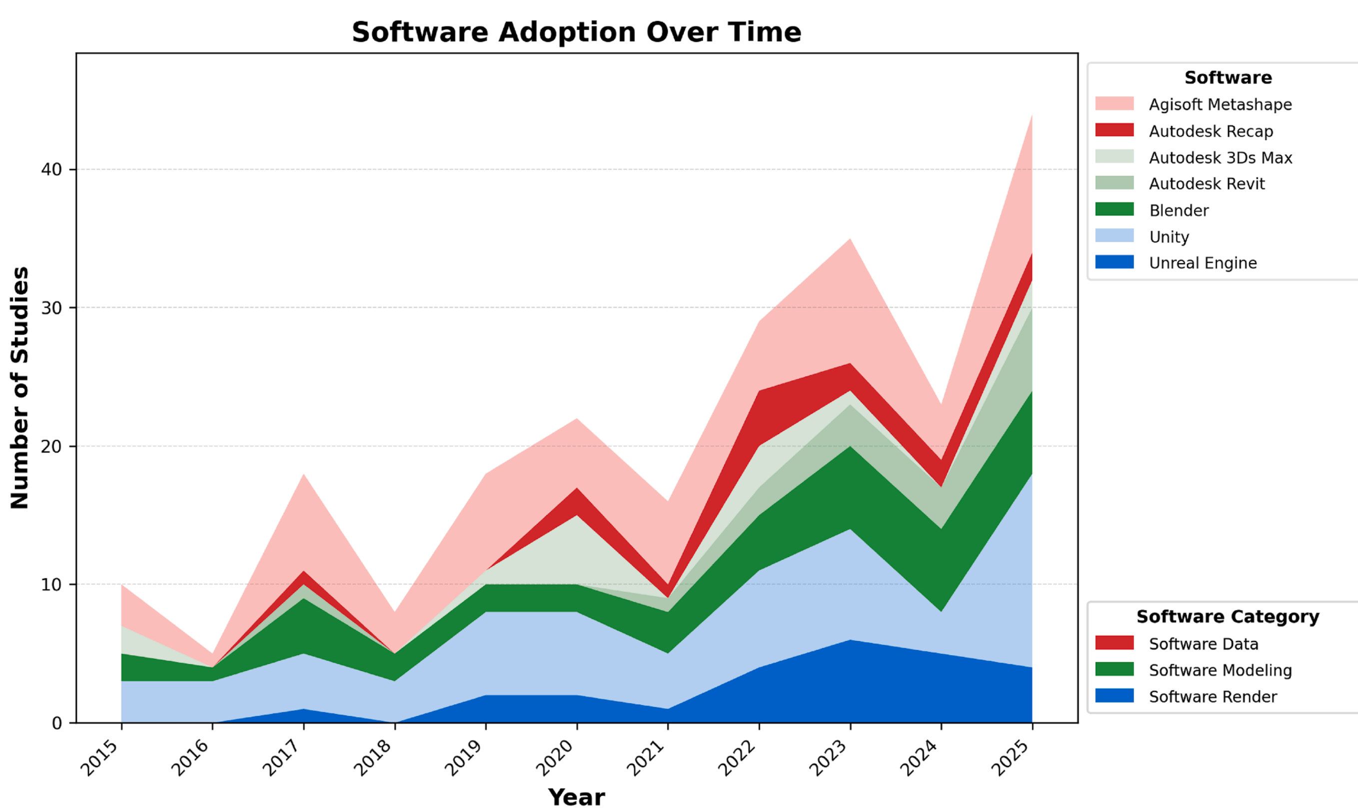

Fig. 13. Software usage trends over time.

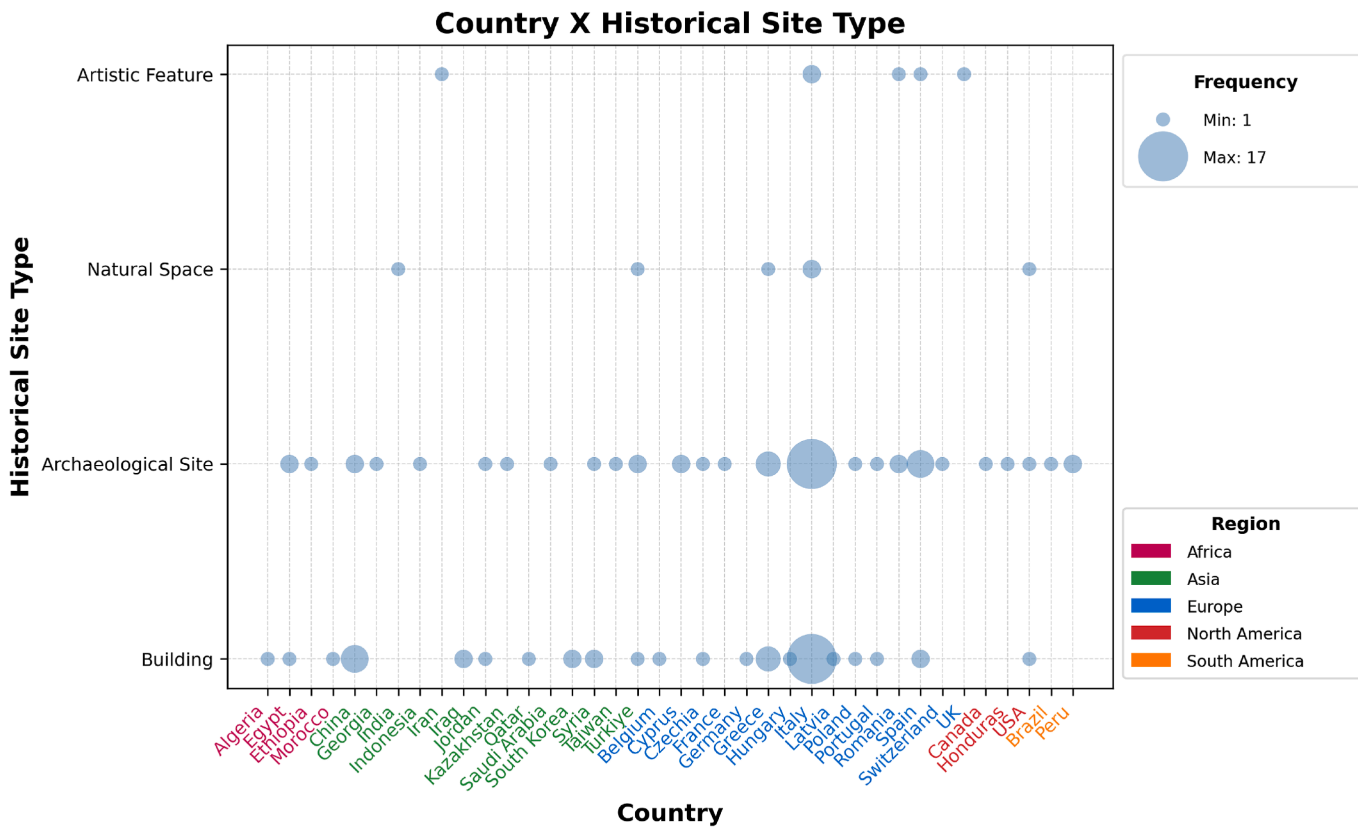

Fig. 14. Historical sites by country.

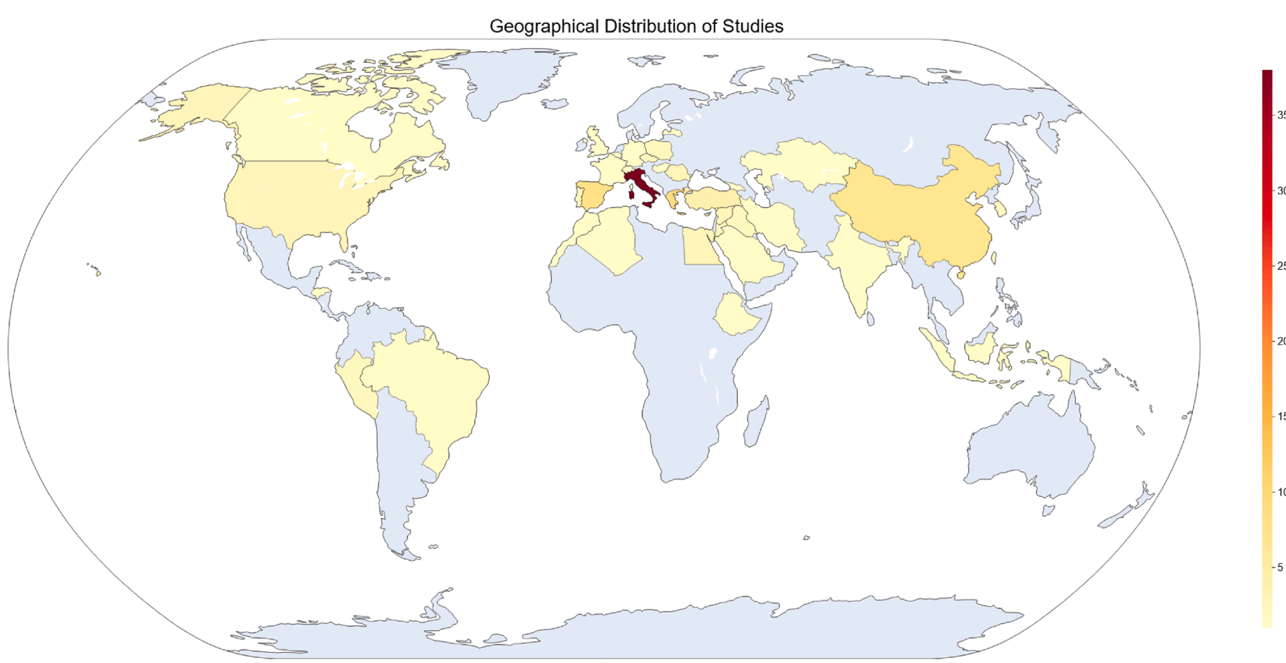

Fig. 15. Geographical distribution of publications.

scan-to-HBIM-to-VR pipeline [37] bridges documentation and visualization, ensuring accurate preservation while enabling real-time stakeholder collaboration. These workflows address longstanding gaps in cultural heritage management, where fragmented methodologies often hinder holistic conservation [14].

Photogrammetry dominated data acquisition, particularly for underwater and archaeological sites; Mazotos shipwreck [38] and Fuente Nueva 3 [39]. Its cost-effectiveness and compatibility with off-the-shelf tools (e.g., Agisoft Metashape, Reality Capture) made it a cornerstone for projects prioritizing accessibility [40,41]. However, challenges persist in scaling these methods for large sites, as seen in the partial reconstruction of the Temple of Bel [19].

AI-driven tools, such as automated scanning pipelines and generative models [30], are transforming heritage workflows. These technologies reduce reliance on manual processes, enabling rapid digitization and crowd-sourced reconstruction. While promising, their ethical implications, such as balancing automation with historical accuracy, require further exploration.

4.2.2. Application cases: Methodological workflows in practice

Despite advancements, heterogeneity in software, as shown in Fig. 9: Software Usage by Category, complicates interoperability. However, co-occurrence between data processing tools like Agisoft Metashape and modeling software like Blender (Fig. 11) reflects convenient workflows. Standardized protocols, akin to those proposed for HBIM integration [42], share similar issues, too.

Few studies addressed the long-term preservation of 3D models or metadata [43]. While projects like the WebGIS for WWI forts [44] demonstrate progress, the field lacks consensus on archiving practices, risking data obsolescence.

Though VR/AR applications received positive feedback [33,45], few incorporated rigorous user testing. Exceptions, like the performance analysis of Al Zubarah Fortress [6], highlight the need for optimizing hardware-software compatibility to prevent cybersickness and ensure accessibility.

To illustrate the practical effectiveness and limitations of these technologies, several representative case analyses from the reviewed literature provide critical insights:

Underwater Archaeological Sites (e.g., The Mazotos Shipwreck): Underwater heritage poses severe accessibility and environmental limitations. Projects like the Mazotos shipwreck [38] relied heavily on image-based modeling (IBM) to generate high-fidelity VR experiences. The primary effectiveness of this approach is democratizing access to sites otherwise restricted to specialized divers. However, the limitation lies in the complex data acquisition process, where water turbidity and lighting constraints frequently require extensive post-processing in software like Agisoft Metashape before the geometry is clean enough for Unity-based VR platforms.

Destroyed or Lost Heritage (e.g., Palmyra Roman Theatre): For sites obliterated by conflict, physical preservation is impossible, making digital reconstruction the only viable preservation method. The speculative reconstruction of Palmyra's Roman Theatre [2] demonstrates the effectiveness of combining geospatial techniques (GIS) with archived spherical photogrammetry. While this methodology successfully resurrected the site within a digital metaverse, its primary limitation is historical fidelity; relying on pre-destruction crowdsourced data or archived imagery inherently introduces geometric approximations that require transparent paradata documentation to maintain scholarly rigor.

Fragile Architecture and Artifacts (e.g., Hetepheres Tomb VR): For highly sensitive or degraded environments, hybrid workflows have proven essential. The digital rebuilding of the Hetepheres Tomb and its artifacts [46] effectively combined high-precision scanning (Polycam) with manual 3D modeling (Blender). This approach allows users to experience the scale and context of the burial chamber via HMDs without risking physical deterioration to the actual site. The limitation here is the scalability of the workflow; achieving low-poly, optimized meshes for seamless VR locomotion requires intense manual retopology that is difficult to automate for larger urban-scale heritage sites.

Beyond architectural scale, the fundamental engineering challenge in executing these hybrid workflows lies in **data fusion optimization and coordinate system alignment**. When merging TLS point clouds with UAV-derived photogrammetric meshes, engineers face critical bottlenecks in spatial registration. Traditional manual alignment is highly error-prone; thus, modern pipelines increasingly rely on Iterative Closest Point (ICP) algorithms to computationally minimize the distance between distinct spatial datasets. Furthermore, a primary source of distortion in generating digital twins is reconciling the local Coordinate Reference Systems (CRS) typical of terrestrial scanners with the global GPS-tagged CRS of aerial photogrammetry. If robust geodetic transformation protocols are not rigorously applied, these alignment errors cascade, resulting in severe global geometric warping over large-scale heritage landscapes.

A critical, yet frequently underreported, challenge in these pipelines is the technical conversion of raw, high-density 3D models into optimized assets for XR environments. Raw photogrammetric or laser-scanned meshes are often too heavy for real-time rendering. Consequently, the model must undergo severe decimation (polygon reduction). To retain the high visual quality of the original asset, workflows rely heavily on texture baking specifically, generating normal maps from the high-resolution mesh and applying them to the decimated low-poly model to simulate complex surface details. Furthermore, the current industry trajectory favors AR over VR. While VR requires dedicated, often expensive head-mounted displays, AR leverages devices the public already owns (smartphones, tablets, and laptops), making it crucial for the widespread visualization of monuments. To overcome the processing limitations of mobile hardware, modern AR and WebXR applications increasingly utilize progressive rendering. This technique streams and renders complete, high-quality models incrementally based on internet connection speed, delivering maximum visual fidelity without overloading local device memory.

To underscore the rapid evolution of these conversion pipelines, recent literature explicitly details the methodologies for transferring raw 3D data into highly optimized VR and AR models, particularly within complex architectural and religious contexts. For example, Pavelka et al. [47] provide a comprehensive analysis of 3D documentation methods for the Shrine of the Prophet Nahum, outlining the specific data transfer technologies required to transition detailed models into immersive realities without compromising high-fidelity geometry a principle similarly demonstrated in the accessibility-focused XR integration at the Church of Madonna dell'Itri [48]. To handle massive spatial scale, Pervolarakis et al. [49] demonstrate how to process hybrid datasets (combining aerial/terrestrial photogrammetry and laser scanning) by exploiting modern game engines to render synthetic representations of entire archaeological sites. This reliance on progressive rendering and real-time engines fundamentally solves historical processing bottlenecks, as showcased by the integration of immersive analytics at the Mausoleum of Emperor Maxentius [50] and the reality-based modeling of historical architectural changes [51]. Furthermore, Bianconi et al. [52] establish practical workflows for taking previously elaborated 3D reconstructions (such as the unbuilt architectural design of a historic station in Perugia) and optimizing them into fully navigable VR applications. Collectively, these frameworks, alongside large-scale immersive visualizations of Turkish cultural heritage [53], confirm that modern pipelines have successfully bridged the gap between raw data acquisition and real-time visualization, proving that contemporary digital twins can now support complete, non-decimated environmental storytelling across both mobile AR and HMD VR platforms.

4.2.3. Implications for practice and policy

Immersive tools are reshaping pedagogy, as evidenced by the Delphi Sanctuary project [25], where VR improved student assessment scores by 16.5/20. Such outcomes advocate for institutional adoption of 3D/VR curricula to bridge theoretical and experiential learning.

Projects integrating local narratives, such as Castle of Corsano [22], Chan Chan [5], demonstrate how digital tools empower communities to reclaim cultural memory. Policymakers should prioritize participatory frameworks to avoid "technological determinism" in heritage preservation [54].

The reconstruction of destroyed sites, for instance, Palmyra Roman Theatre [2], raises ethical questions about authenticity and ownership. Transparent paradata documentation, as seen in the Madre de Deus Monastery [18], offers a model for balancing speculative reconstructions with scholarly rigor.

4.2.4. Significance of core studies

In the broader context of historical site preservation, these studies contribute to advancing innovative preservation methods by leveraging VR and AR technologies. They show how these technologies can bridge knowledge gaps in cultural heritage by enabling new visualization methods and improving user engagement. The findings from these studies have implications for practitioners seeking to apply similar methodologies to other historical sites, emphasizing the need for tailored approaches that balance technological innovation with historical accuracy.

5. Discussion: Challenges with future prospects

This systematic review highlights the growing role of immersive technologies in historical site preservation. To provide a high-level synthesis of the 115 eligible studies, we structure our findings through the proposed **Modular XR Engineering Framework (MXEF)**. This framework abstracts specific software trends (RQ3) and technique usages (RQ2) into four generalized engineering mechanics, providing a structured paradigm for future system design:

- **Layer 1: Geometric Data Fusion:** The literature demonstrates that single-sensor data acquisition is insufficient for complex heritage sites. Engineering robust digital twins requires hybrid workflows (e.g., merging UAV photogrammetry with terrestrial laser scanning). This fusion is mechanically essential to balance structural dimensional stability with high-resolution textural fidelity [49,55].
- **Layer 2: Algorithmic Optimization:** Historically, transferring massive 3D datasets into interactive environments required severe, manual mesh decimation to accommodate hardware VRAM limits. The current paradigm shift heavily favors algorithmic optimization, transitioning from standard polygonal reduction to automated texture-baking and normal-map generation to preserve geometric illusion on low-poly assets [26].
- **Layer 3: Real-Time Rendering Mechanics:** Modern software pipelines have shifted to solve historical computational bottlenecks. The transition toward engines like Unreal Engine 5 relies on virtualized micro-polygon geometry (e.g., Nanite). This fundamentally changes the engineering approach by dynamically streaming only visible polygons based on user proximity, effectively eliminating traditional rendering limitations for multi-billion polygon environments.
- **Layer 4: Immersive Deployment:** Platform adoption (RQ1) is dictated by deployment constraints. While HMD-driven VR [2] provides true architectural scale through binocular disparity, mobile AR/XR is rapidly gaining ground. The integration of consumer-grade LiDAR and progressive web rendering shifts the computational burden from local hardware to cloud infrastructure, maximizing global accessibility [35].

Rather than merely serving as technical benchmarks, the engineering outcomes synthesized in this review have profound theoretical implications for user perception and experiential learning. Drawing on the psychological constructs of immersion and presence [15,16], we observe that achieving high structural fidelity, such as through the hybrid capture methods and virtualized micro-polygon geometry identified in our findings, is fundamentally linked to the psychological sensation of “being there.” Furthermore, engaging with the vast heterogeneity of applications across the reviewed literature reveals that hardware modality acts as a critical moderator effect on the user experience. For instance, while HMD-driven VR isolates the user to maximize spatial presence and deep experiential learning, mobile AR introduces environmental heterogeneity, where the user’s physical surroundings moderate their cognitive load and immersion [17]. Consequently, the interoperability and rendering bottlenecks identified in our results are not merely software issues; they act as negative moderators that directly limit the psychological efficacy and educational impact of the heritage digital twin.

Beyond these technical and psychological layers, immersive deployment ultimately serves a broader socio-technical purpose: fostering stewardship. Digital reconstructions empower communities to reclaim cultural narratives, as evidenced by participatory projects like the Castle of Corsano [22] and the Chan Chan AR app [5]. For example, the Chan Chan AR app [31] empowers visitors to explore hidden artifacts, merging education with cultural pride. The Madre de Deus Monastery project [18] integrates paradata to communicate reconstruction hypotheses, addressing ethical concerns. Despite progress, 73% of studies focus on European sites (Figs. 14–15), neglecting regions like Sub-Saharan Africa. Meanwhile, AI and blockchain, tools for automating reconstructions and ensuring metadata traceability, remain underexplored [19,30].

For data acquisition, prioritizing photogrammetry (e.g., Agisoft Metashape, Reality Capture) for cost-effective 3D data capture, supplemented by laser scanning for high-precision details (Fig. 8, Table 2).

The modeling and rendering software mostly used is Blender. For the real-time visualization software, the most frequent is Unity (Figs. 9–12). These tools dominate the literature due to their flexibility, cross-platform compatibility, and integration with photogrammetry outputs.

To optimize fidelity and scalability (RQ2), modern preservation increasingly demands hybrid workflows that merge terrestrial laser scanning (TLS) and photogrammetry. As highlighted in recent literature, photogrammetry alone is inherently dimensionless; assigning accurate real-world scale requires ground control points or physical object measurements. Furthermore, while photogrammetry excels at capturing high-resolution, photorealistic textures and minute details at close range, it can suffer from geometric deformation over larger spatial areas. Conversely, laser scanning provides highly accurate, dimensionally stable topological shapes over longer distances but often yields inferior color textures. By combining these technologies often processed simultaneously in software like RealityCapture practitioners achieve the ideal digital twin: leveraging TLS for structural and dimensional stability, and photogrammetry for high-fidelity surface textures, as successfully demonstrated in projects like the Portes Mordelaises gate [8] and the Forum of Augustus [56].

For ethical and sustainable practices, document reconstruction processes with robust metadata and archiving digital assets using standardized formats may help to guarantee long-term accessibility.

This systematic review lays a robust theoretical foundation for our subsequent case study on the Zelemer Church reconstruction. The dedicated analysis of the 6 core studies not only highlights state-of-the-art practices in religious building reconstruction but also informs the following phases of our case study:

- **Phase 1 - Data Capture:** Utilize Agisoft Metashape and laser scanners for comprehensive site documentation.
- **Phase 2 - Modeling:** Refine geometries using Blender, augmented by historical archival data to resolve ambiguities.
- **Phase 3 - Visualization:** Develop an interactive, HMD-based VR experience in Unity, integrating narrative elements for enhanced public engagement.

This dual-publication strategy, where the systematic review provides a validated roadmap and the case study demonstrates practical application, underscores our commitment to both scholarly rigor and innovation in digital heritage preservation. By aligning with methodologies validated in this review, such as the scan-to-BIM-to-VR pipeline [14], this project can achieve both technical rigor and cultural resonance. This approach not only addresses the how of digital reconstruction but also the why, ensuring technologies serve as bridges between past heritage and future stewardship.

By aligning technological advancements with ethical and sustainable practices, this review not only charts the current state of immersive technologies in heritage reconstruction but also offers actionable guidelines for future research and practical implementations. Together, these insights pave the way for a holistic approach that bridges academic research with real-world applications, ensuring that digital heritage remains a dynamic link between past legacies and future stewardship.

Moving forward, overcoming the structural challenges identified in this review requires a concrete engineering and research roadmap. First, future practitioners must adopt standardized fusion protocols, such as mandatory ICP registration and rigid Coordinate Reference System (CRS) documentation, when merging TLS and UAV photogrammetry to prevent large-scale geometric warping [55]. Second, to prevent 3D data obsolescence, developers must transition toward open-source interoperability standards (e.g., WebXR, OpenXR) to future-proof digital archives.

Furthermore, a temporal bias is evident, reflecting the rapid recent adoption of immersive technologies (Fig. 2), raising questions about longitudinal impacts and the sustainability of digital assets. Geographically, a predominant focus on European sites risks homogenizing heritage narratives. Future efforts must prioritize inclusive digitization in underrepresented regions like Sub-Saharan Africa and Southeast Asia. To achieve this, researchers should focus on collaborative frameworks, such as the Metaverse platform for the Monastery of Simonos Petra [57], which combined static and dynamic data for remote interaction, and expand AI-driven tools to automate labor-intensive point cloud cleaning [13]. While advancements in AI and photogrammetry are transformative, emerging frontiers like blockchain for decentralized metadata traceability and quantum computing for simulating large-scale landscapes remain underexplored. By addressing these gaps, immersive technologies can evolve from isolated visual novelties into equitable tools for global heritage stewardship.

6. Conclusion

This systematic review synthesizes the current trajectory of immersive technologies (VR, AR, MR, XR) in historical site preservation. By conducting a PRISMA-guided analysis of 115 empirical studies, this research moves beyond descriptive cataloging to map the critical relationships between geometric data capture, algorithmic optimization, and immersive deployment. Through the introduction of the Modular XR Engineering Framework (MXEF), the study identifies how specific hardware and software pipelines mitigate traditional bottlenecks, enabling the real-time rendering of multi-billion polygon heritage environments.

Theoretically, this research bridges the gap between geomatics engineering and psychological perception, demonstrating how structural fidelity and hardware modality directly moderate user immersion and experiential learning. Practically, it provides a validated technical roadmap for balancing dimensional accuracy with photorealistic textures through the hybridization of terrestrial laser scanning and photogrammetry.

The contributions of this study are specifically articulated for three primary stakeholders:

- **For Researchers:** This study identifies critical geographic disparities and the lack of standardized workflows in hybrid data fusion. It sets a clear agenda for future investigations into automated AI processing, open-source interoperability (WebXR), and decentralized metadata management (blockchain) to ensure long-term digital preservation.
- **For Practitioners and Geomatics Engineers:** The findings establish explicit parameters for modern system design. By highlighting the paradigm shift toward virtualized micro-polygon geometry (e.g., Unreal Engine 5 Nanite), the review provides actionable pipelines for bypassing historical mesh decimation limits, ensuring that digital twins remain both architecturally accurate and visually lossless.
- **For Educators and Heritage Institutions:** The review demonstrates how shifting computational burdens to cloud infrastructure via mobile AR and WebXR can democratize access. By removing the socioeconomic and physical barriers of global travel, these technologies ensure that digital reconstructions serve not merely as technical novelties, but as equitable, accessible platforms for community stewardship and cultural pride.

Ultimately, by aligning technological innovations with ethical and sustainable practices, immersive technologies offer a robust mechanism for the permanent preservation of human history, ensuring that cultural heritage remains a dynamic and universally accessible link to the past.

Declaration of generative AI in scientific writing

During the preparation of this work, the authors used ChatGPT-4 to improve readability and language. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

CRediT authorship contribution statement

Kerem Düzenli: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Visualization, Writing – original draft, Writing – review & editing; **Abdullah M. Albazooni:** Data curation, Formal analysis, Validation; **Abdallah Al-Hamad:** Project administration; **Attila Gilányi:** Project administration, Supervision.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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