

Reconstructing Archaeological Evidence with Digital Technologies: Emerging Trends, Challenges, and Prospects

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Abstract

The advancement of digital technologies such as photogrammetry, 3D scanning, Geographic Information Systems (GISs), and artificial intelligence has profoundly transformed archaeology by enabling more accurate documentation, analysis, and visualization of cultural heritage. These tools facilitate evidence preservation, enhance research processes, and broaden the possibilities for interpreting and disseminating archaeological knowledge. This scoping review synthesizes recent progress in the application of digital technologies for the reconstruction of archaeological evidence, emphasizing their main impacts on archaeological research while addressing existing challenges, limitations, and future perspectives, particularly focusing on the integration of artificial intelligence. A systematic review of the scientific literature was conducted using the PRISMA® methodology, analyzing documents retrieved from databases such as Scopus, PubMed, IEEE Xplore, and ScienceDirect. One hundred and sixteen papers were selected, with a Cohen's Kappa coefficient of 0.463 ensuring the reliability of the selection process. The findings reveal that the integration of digital technologies is redefining archaeological reconstruction methods and expanding the horizons of historical and heritage knowledge, requiring collaborative, ethical, and interdisciplinary approaches to achieve a more accurate, accessible, and sustainable archaeology in the future.

Keywords: digital reconstruction; archaeological evidence; 3D modeling; cultural heritage; photogrammetry; virtual archaeology

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1. Introduction

Traditional methods for the reconstruction of archaeological evidence face significant limitations regarding accuracy, preservation, accessibility, and reproducibility. Manual and analog approaches are often invasive, difficult to scale, and pose a risk of damaging

the findings. In this context, there is a pressing need to integrate advanced digital technologies that enable the documentation, reconstruction, and dissemination of archaeological heritage in a more efficient and accessible manner, thereby ensuring its long-term preservation and availability for research, education, and cultural dissemination. This article examines how photogrammetry, 3D scanning, Geographic Information Systems (GISs), and artificial intelligence are transforming the conservation and reconstruction of archaeological heritage. Figure 1 provides an overview of the 23 countries that possess 15 or more World Heritage Sites [1].

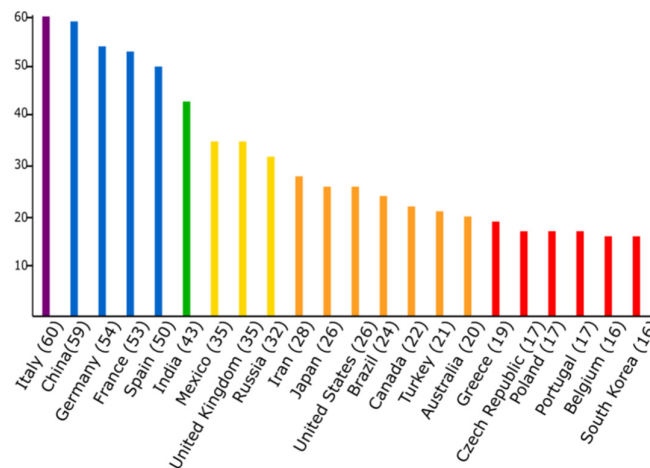


Figure 1. Top 23 countries with 15 or more World Heritage sites.

In a context where the destruction of cultural heritage remains a constant threat, these innovations are essential for safeguarding history and ensuring its accessibility to future generations. They also offer new opportunities for education, tourism, and research [2]. Digital technologies have revolutionized archaeology, particularly in the reconstruction of artifacts, by providing more accurate, rapid, and efficient methods. Tools such as 3D scanning and photogrammetry allow the creation of high-resolution digital models that are crucial both for faithful restorations and for technical analyses ensuring the integrity of the reconstruction process [3,4]. Moreover, these technologies have significantly reduced the time and resources required compared to traditional manual methods by incorporating partial automation into the assembly of fragments [3].

Furthermore, digital models make it possible to preserve heritage without the need for direct manipulation of fragile physical objects, thus protecting the most delicate pieces and facilitating their long-term storage and accessibility [5]. These technologies also expand analytical possibilities by revealing patterns or signs of deterioration that could go unnoticed using conventional techniques [6,7], as well as identifying unauthorized interventions, replacement of original materials, or the creation of replicas using contemporary substances.

Virtual reconstructions and interactive visualizations have also transformed the way archaeological findings are communicated, enabling immersive educational experiences that bring heritage closer to broader audiences, including students and museum visitors [8,9]. At the same time, digital models serve as precise visual guides that support restoration processes, preserving a copy of the original characteristics of artifacts through advanced 3D technology. Figure 2 presents a bibliometric graph generated from 592 studies related to digital technologies for the reconstruction of archaeological evidence.

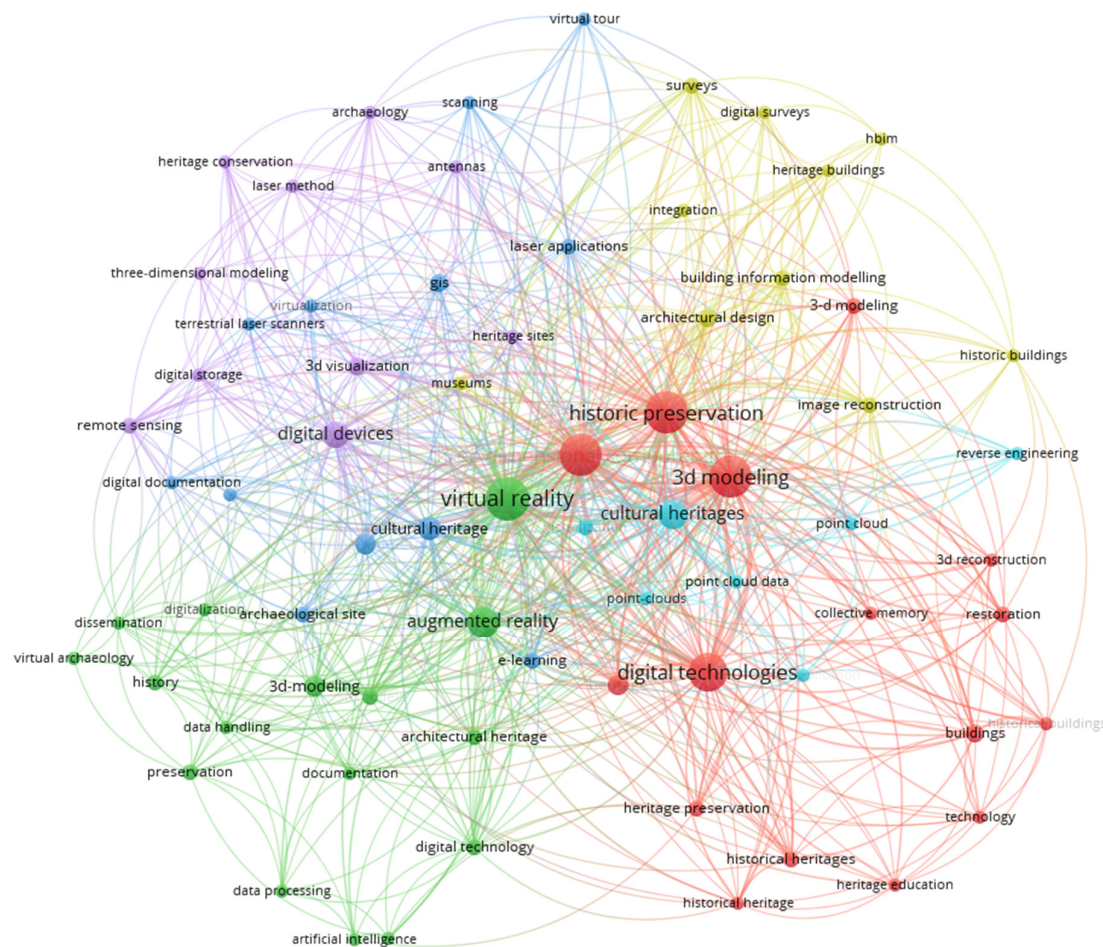


Figure 2. Bibliometric graph of studies related to digital technologies for the reconstruction of archaeological evidence. Generated using VOSviewer v1.6.20.

To identify the most studied areas in this field, a bibliometric map was generated (Figure 2), revealing major trends and associations in the study of digital technologies for the digitization of archaeological evidence. The analysis shows five clusters organized by term co-occurrence in the literature. In Figure 2, the red cluster, with nodes such as historic preservation, 3D modeling, digital technologies, and buildings, highlights the prominence of three-dimensional reconstruction and conservation of built heritage through technologies like point-cloud modeling and reverse engineering. The blue cluster, centered on virtual reality, augmented reality, cultural heritage, and e-learning, reflects the rapid growth of immersive tools for heritage interpretation, visualization, and education. These technologies expand access to cultural experiences via museums and digital platforms, even beyond original sites. The green cluster, including archaeological site, history, documentation, data processing, and artificial intelligence, underscores the increasing use of computational methods and AI to manage large datasets from excavations, scans, and records, enhancing the interpretation of complex contexts. The purple cluster, defined by terms such as remote sensing, laser method, digital storage, 3D visualization, and terrestrial laser scanners, points to the consolidation of advanced capture technologies for accurate, non-invasive documentation of fragile or inaccessible sites. The yellow cluster, related to heritage buildings, architectural design, BIM, and digital surveys, indicates convergence between archaeology, architecture, and construction technology. This integration supports virtual restoration, structural analysis, and preventive preservation throughout the life cycle of built heritage.

Various studies have addressed three-dimensional reconstruction and digital documentation from both technical and applied perspectives, providing a relevant theoretical framework for this field. For example, Gomes, Bellon, and Silva examined 3D reconstruction methods for the digital preservation of cultural heritage [10], while Yastikli analyzed heritage documentation through digital photogrammetry and laser scanning [11]. Likewise, Aicardi et al. discussed recent trends in 3D heritage surveying from the perspectives of computer vision and photogrammetry [12]. More recently, Samavati and Soryani presented a review of deep learning-based 3D reconstruction approaches and their impact on the automation of complex processes [13], whereas Liu et al. analyzed the evolution of reconstruction techniques from multiview geometry toward advanced models such as Neural Radiance Fields (NeRF) and 3D Gaussian Splatting [14]. Taken together, these studies reveal a growing trend toward the integration of machine learning-based methods, generative models, and hybrid architectures, which have enabled improvements in the accuracy, robustness, and applicability of 3D reconstruction. However, most of these contributions focused on specific technologies or domains, thereby justifying the need for an integrative review such as the one proposed in this work.

Overall, the bibliometric map illustrates a multidisciplinary field uniting archaeologists, engineers, historians, designers, and computer scientists. It emphasizes the centrality of 3D modeling and immersive technologies, while also addressing data interoperability, heritage education, and intelligent site management. These findings suggest that digital tools will be essential not only for preservation but also for democratizing access, interpretation, and enjoyment of cultural heritage across academic and public domains.

Figure 3 shows the relative frequency of keywords related to digital technologies for the reconstruction of archaeological artifacts, using the same parameters as Figure 2.

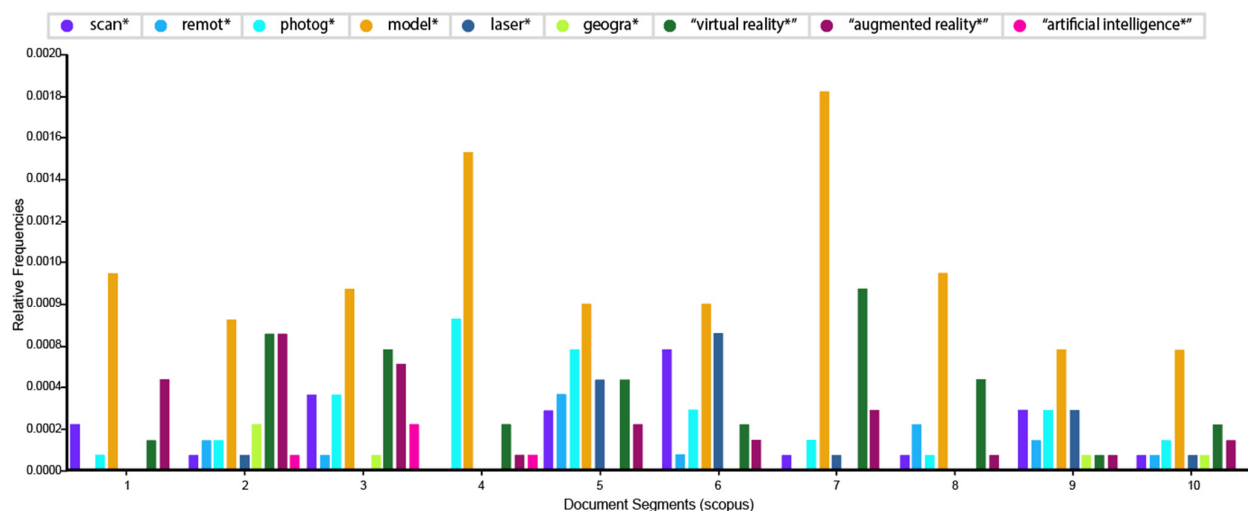


Figure 3. Relative frequency of mentions of digital technologies employed for the reconstruction of archaeological artifacts in related studies. The asterisk symbol * indicates a narrowed search.

The graph indicates that the most commonly used technologies for reconstructing archaeological evidence are digital modeling, photogrammetry, and scanning, with digital modeling being the most frequently employed across the analyzed sources. These methods create precise 3D representations of sites and objects, supporting study, conservation, and dissemination. Laser scanning, remote sensing, and GISs also play key roles in spatial digitization, while the emerging use of virtual reality, augmented reality, and artificial intelligence points to growing interest in immersive and automated heritage analysis.

Digital technologies also advance several Sustainable Development Goals (SDGs). For quality education (SDG 4), they expand access through documentation and virtual reconstruction [15]. In innovation and infrastructure (SDG 9), tools such as 3D scanning and VR improve efficiency and accessibility in research and restoration [3,16]. For sustainable cities (SDG 11), they help protect urban heritage and foster citizen engagement [17–19]. Regarding responsible production (SDG 12), sustainable digital archives address preservation, intellectual property, and data security [19,20]. Finally, international cooperation (SDG 17), exemplified by Korea’s assistance programs, shows how partnerships enhance cultural preservation [16].

Together, these technologies not only protect the past but also support a sustainable future. Figure 4 schematically illustrates these contributions.

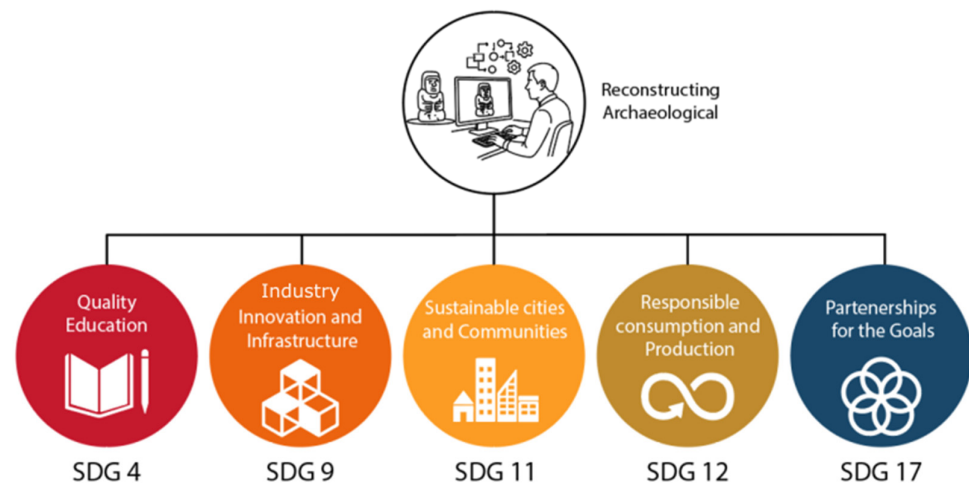


Figure 4. Contribution of digital technologies for the reconstruction of archaeological evidence to the implementation of the United Nations Sustainable Development Goals (SDGs).

This review will be of interest to researchers and professionals in virtual reality, digital archaeology, anthropology, museology, and cultural heritage, as well as to specialists in engineering, architecture, and applied digital technologies focused on immersive tools for conservation and dissemination. It may also engage policymakers, museum managers, and educators seeking innovative approaches to heritage teaching through advanced digital tools.

The document is structured into sections that address key aspects of the topic. The Methodology outlines the systematic review conducted under PRISMA® guidelines. The Results, organized around six research questions, examine employed technologies and future perspectives. The Discussion critically analyzes findings, emphasizing interdisciplinary implications, societal challenges, and opportunities for heritage conservation. Finally, the Conclusions synthesize contributions and propose future directions for academic and professional practice.

2. Methodology

This scoping review was conducted following the guidelines of the PRISMA® methodology. The dataset containing the details of the review can be consulted in [21]. The reference information includes scientific documents published within the last fifteen years, retrieved from databases such as Scopus, PubMed, IEEE Xplore, and ScienceDirect.

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) checklist was applied (Table A1 in Appendix A), specifying the page numbers where relevant information can be found in the different sections of the document. The review

process was developed in three stages: (i) formulation of the research questions, (ii) definition of the scope, and (iii) an exhaustive search aimed at extracting relevant information from the selected publications.

The main research question guiding this review was: How does the use of digital technologies impact the reconstruction of archaeological artifacts? This question enabled the identification of technological innovations such as 3D modeling, photogrammetry, and remote sensing and laser scanning techniques, allowing a deeper understanding of how these tools contribute to the advancement of archaeological research.

This review adopts a descriptive approach to digitization and three-dimensional reconstruction technologies as the central axis of the study. The methodology is structured around a digital workflow that integratively and complementarily incorporates processes of digital restoration, visualization through virtual and augmented reality, as well as simulation and analysis, which are considered derivative and functional stages in relation to the core objective of the research. This approach enables a clear delimitation of the scope of the investigation, avoiding an overly general treatment of digital technologies and prioritizing those tools and techniques directly related to the generation, processing, and analysis of 3D models.

The primary objective of this study was to identify the most relevant digital technologies used in the reconstruction of archaeological artifacts, explore the impacts of their implementation on cultural heritage conservation, and analyze the limitations and challenges faced by researchers and professionals in their adoption. For the introduction and for the identification of the aspects documented in relation to this topic, articles indexed in the SCOPUS database were explored using the following search string: (“digital technology” OR “digital tools” OR “digital methods” OR “digital innovation”) AND (“archaeology” OR “archaeological” OR “heritage” OR “cultural heritage”) AND (“data analysis” OR “3D modeling” OR “remote sensing” OR “GIS”) AND (“excavation” OR “site survey” OR “artifact analysis” OR “preservation”) AND (“virtual reality” OR “augmented reality” OR “simulation” OR “visualization”). The previous string made it possible to generate Figure 2 presented in the Introduction section.

To guide data extraction from the selected scientific articles, the following research questions were posed: RQ1. Which digital technologies have been developed for the reconstruction of archaeological evidence? RQ2. What impacts does the development of digital technologies have on the reconstruction of archaeological evidence? RQ3. What are the limitations and challenges in implementing digital technologies for the reconstruction of archaeological evidence? RQ4. What future perspectives exist regarding the reconstruction of archaeological evidence through digital technologies? RQ5. Which key technologies enable or enhance the use of digital technologies in the reconstruction of archaeological evidence?

Cohen’s Kappa coefficient was employed as a widely accepted statistic for assessing inter-rater reliability in systematic reviews. Two independent reviewers screened all retrieved records according to the predefined inclusion and exclusion criteria. Inter-rater agreement was quantified using Cohen’s Kappa, yielding a value of $\kappa = 0.463$, which indicates a moderate level of agreement beyond chance. Any discrepancies between reviewers were resolved through discussion and consensus, resulting in the final inclusion of 116 studies.

As quality assessment criteria for the scientific articles, the questions described in Table 1 were applied.

Table 1. Quality Assessment Questions for papers.

Quality Assessment Questions	Answer
Does the article describe digital technologies used in the reconstruction of archaeological evidence?	(+1) Yes/(+0) No
Does the article present case studies or real-world applications in archaeological contexts?	(+1) Yes/(+0) No
Does the article highlight the impacts of digital technologies on the research, preservation, or documentation of archaeological heritage?	(+1) Yes/(+0) No
Is the journal or conference in which the paper was published indexed in SJR?	(+1) if it is ranked Q1, (+0.75) if it is ranked Q2, (+0.50) if it is ranked Q3, (+0.25) if it is ranked Q4, (+0.0) if it is not ranked

2.1. Inclusion Criteria

For this review, scientific review articles and documents addressing digital technologies applied to the reconstruction, preservation, and documentation of archaeological evidence were selected. The search strings used in the queries are presented in Table 2.

Table 2. Search strings used for article retrieval in scientific databases.

Database	String	Studies Number
SCOPUS	TITLE (("digital technology" OR "digital tools") AND ("archaeology" OR "archaeological" OR "cultural heritage"))	698
PubMed	Search: (digital technology) AND (cultural heritage))	1066
IEEE Xplore	search: digital technology cultural heritage	25
ScienceDirect	Title, abstract, keywords: digital technology cultural heritage, archaeology	81
Total		1870

A total of 116 articles published over the last 15 years and addressing advancements in these reconstruction technologies were initially identified from the Scopus, PubMed, IEEE Xplore, and ScienceDirect databases, selected due to their high academic prestige, broad thematic coverage, and editorial quality; additionally, to provide contextual support for key theoretical foundations, 96 supplementary articles were also consulted. These platforms provide access to interdisciplinary literature relevant to archaeology, technology, engineering, and the applied sciences, thereby ensuring a robust, up-to-date, and representative review of the use of digital technologies in the reconstruction of archaeological heritage.

2.2. Exclusion Criteria

Articles that, despite partially matching the search string terms, did not specifically address the reconstruction of archaeological evidence or lacked a clear technological approach were excluded. Studies focused exclusively on other occupational groups or technologies not applied to the archaeological context were also discarded. Additionally, studies centered solely on intangible heritage, technologies applied in non-archaeological contexts (such as contemporary architecture or industrial/product design), non-peer-reviewed publications, duplicate documents, and technological solutions without preliminary validation or demonstrated application in real archaeological contexts were excluded from the review. Figure 5 presents the workflow followed for the selection of reference articles obtained from the search using the following keywords: digital technology, 3D reconstruction, 3D model, heritage, artifacts. Journal articles and conference papers published within the last fifteen years were considered.

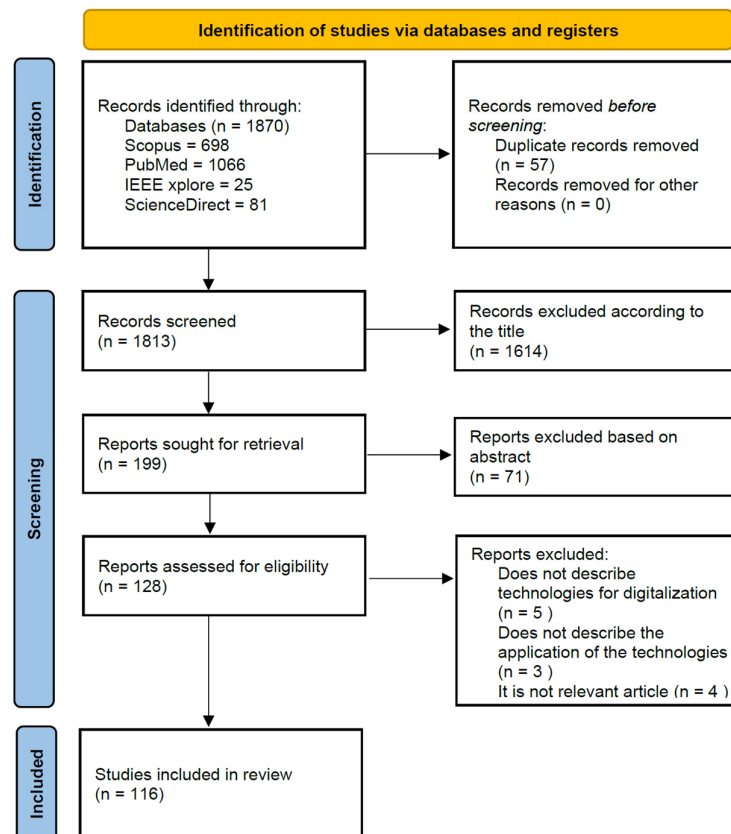


Figure 5. Workflow for the selection of information sources.

3. Theoretical Background

3.1. Photogrammetry

Photogrammetry is a versatile technique for deriving accurate three-dimensional (3D) spatial information from two-dimensional (2D) images and is widely applied in disciplines such as geodesy, medicine, and archaeology [22,23]. The process typically involves image acquisition using various cameras and platforms, followed by image processing based on algorithms such as Structure from Motion (SfM), supported by accurate camera calibration to ensure geometric reliability [24–26]. Although challenges remain—such as equipment costs, sensitivity to image quality and environmental conditions, and the need for user expertise—photogrammetry offers key advantages, including non-contact data acquisition, high spatial accuracy, and scalability. Furthermore, recent advances in digital technologies, particularly the integration of machine learning and artificial intelligence, are enhancing automation and robustness, thereby expanding its applicability in complex 3D reconstruction scenarios [27–31].

3.2. 3D Modelling

Three-dimensional (3D) modeling plays a fundamental role in the digitization and analysis of archaeological evidence, as it enables the creation, visualization, and reconstruction of objects, structures, and spatial contexts from limited, fragmented, or deteriorated physical information. In contrast to 3D digitization, which is primarily focused on capturing geometric and visual data from existing remains through techniques such as photogrammetry or laser scanning, 3D modeling allows the generation of interpretative virtual representations created from scratch or based on partial sources, including fragmentary remains, graphical records, or historical documentation [32–35]. This capability

is particularly relevant in archaeology, where the preservation of original materials is a priority and reconstructions must be grounded in scientific criteria and expert knowledge. Within this context, 3D modeling facilitates the digital preservation of archaeological heritage, comparative evidence analysis, and the creation of virtual environments for research, dissemination, and education, integrating with virtual reality (VR), augmented reality (AR), and computer-aided design (CAD) workflows that enhance its scientific value and applicability [36,37].

3.3. Digital Restoration

Digital restoration encompasses a set of techniques aimed at the recovery and enhancement of degraded digital media, with applications in image processing, film preservation, architecture, and cultural heritage conservation [6,38,39]. Although this process often requires considerable manual effort and specialized expertise, recent advances in semi-automated workflows and the development of sophisticated algorithms have improved both efficiency and accuracy, thereby expanding its potential for large-scale, high-fidelity restoration projects [40]. In this context, the reconstruction and interpretation of images, buildings, documents, and paleontological remains are facilitated by the application of methods such as noise reduction, contrast enhancement and recovery, spectral analysis, and three-dimensional (3D) modeling [41–45].

3.4. Virtual Archaeology

In archaeological research, virtual archaeology is defined as the application of integrated digital technologies for the reconstruction, analysis, simulation, and dissemination of archaeological evidence within virtual environments. This theoretical approach relies on complementary tools that enable precise documentation and interpretative modeling of cultural heritage, particularly when physical evidence is fragmentary or inaccessible. Key data acquisition techniques include LiDAR, Terrestrial and Portable Laser Scanning (TLS and PLS), structured light sensors, Structure-from-Motion (SfM) photogrammetry, unmanned aerial vehicles (UAVs), and high-resolution RGB imaging, which provide detailed geometric and visual information for accurate three-dimensional reconstruction [40–43]. These datasets are subsequently integrated into digital modeling and information management platforms, such as HBIM environments and specialized software including Blender, Revit, and SketchUp, allowing the representation of archaeological structures through adjustable Levels of Detail (LOD). In addition, virtual archaeology incorporates computational analysis and simulation techniques, such as Finite Element Analysis (FEA), parametric modeling, and game engines like Unity and Unreal Engine, supporting structural assessment, hypothesis validation, and immersive visualization of reconstructed contexts [46]. Finally, the integration of 3D printing and extended reality technologies—encompassing augmented, virtual, and mixed reality (AR, VR, and MR)—enhances interaction, interpretation, and dissemination, thereby expanding the educational and societal impact of digitally reconstructed cultural heritage [47–49].

4. Results

This section presents the most relevant findings obtained based on the research questions formulated in the methodology. Section 4.1 presents a bibliometric analysis of the technologies addressed in this study, while Section 4.2 (Figure 6) classifies these technologies into three main categories: artifact reconstruction, visualization technologies for reconstructed objects, and archaeological site reconstruction. This classification framework enables a clearer understanding of the technological landscape, facilitating the identification of key advancements in the field and their primary application domains.

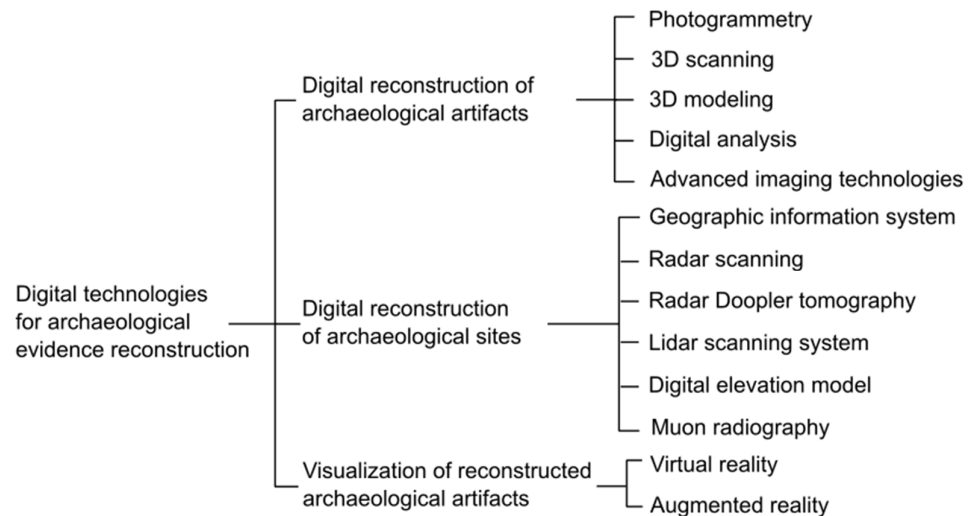


Figure 6. Summary of digital technologies for archaeological evidence reconstruction.

4.1. Bibliometric Analysis

The global distribution of countries with more than 15 UNESCO World Heritage Sites reveals a clear concentration in Europe and Asia, with nations such as Italy (60), China (59), Germany (54), France (53), and Spain (50) dominating the list, reflecting the historical and archaeological density accumulated over centuries. The Americas also feature prominent representatives, including Mexico (35), Brazil (24), and the United States (25), highlighting the recognition of both pre-Hispanic legacies and colonial and industrial structures. This trend suggests that international recognition of archaeological heritage is not solely determined by the antiquity of civilizations but also by the institutional and technical capacity to identify, preserve, and nominate sites before international organizations. Likewise, a notable parity in the number of sites can be observed among countries with distinct cultural contexts—such as Mexico and the United Kingdom or Japan and the United States—demonstrating the diversity of approaches to heritage conservation and representation worldwide. Figure 7 presents the top 15 countries with the highest number of world-level archaeological sites.

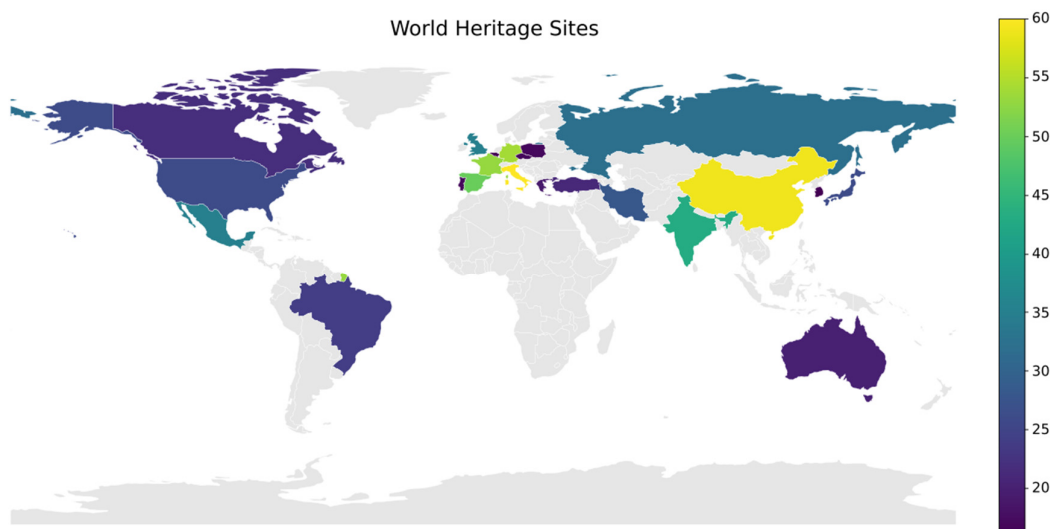


Figure 7. Comparative map of top 23 countries with the most world heritage sites.

4.2. Digital Technologies for the Reconstruction of Archaeological Evidence

A wide range of digital technologies has been developed for the reconstruction of archaeological artifacts, significantly transforming research and practice in archaeology. These technologies can be systematically categorized into three functional groups. The first group comprises tools designed for the reconstruction of relatively small-scale objects, such as individual artifacts. The second group includes large-scale technologies capable of reconstructing extensive archaeological contexts, including sites and settlements located on or beneath the ground surface. The third group encompasses technologies specifically oriented toward the visualization of archaeological evidence, which support the digital exploration, analysis, and manipulation of reconstructed objects while enhancing accessibility to these resources. Table 3 provides a synthesis of these technologies, outlining their principal applications and contributions to archaeological research.

Each of the technologies presented in Table 3 requires fundamental components to generate digital models from real-world evidence. Figure 8 illustrates the digital reconstruction techniques through multiple approaches, which are described in detail in the following sections.

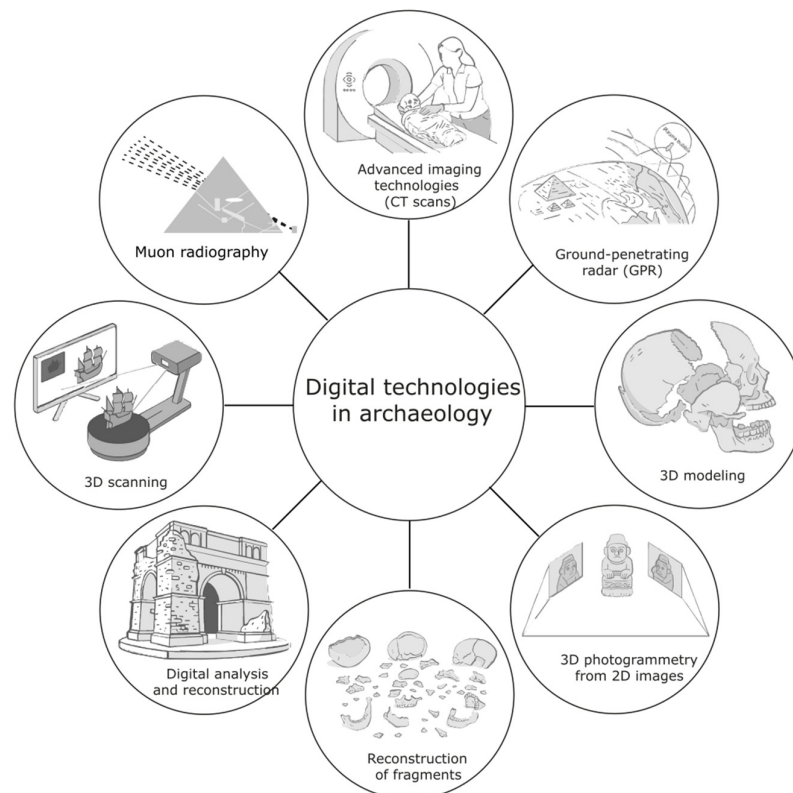


Figure 8. Digital technologies used for the reconstruction of archaeological artifacts.

Table 3. Digital Technologies for the Reconstruction of Archaeological Artifacts.

Technology	Main Application	Benefits
Technologies for reconstruction of archaeological artifacts		
Photogrammetry	3D models of artifacts and sites	High accuracy and detail
3D Scanning	Detailed geometry capture	Manipulable and analyzable models
CAD Modeling	Reconstruction of fragmented objects	Integration of missing parts
Physical Simulation	Reproduction of material behavior	Realism in reconstruction

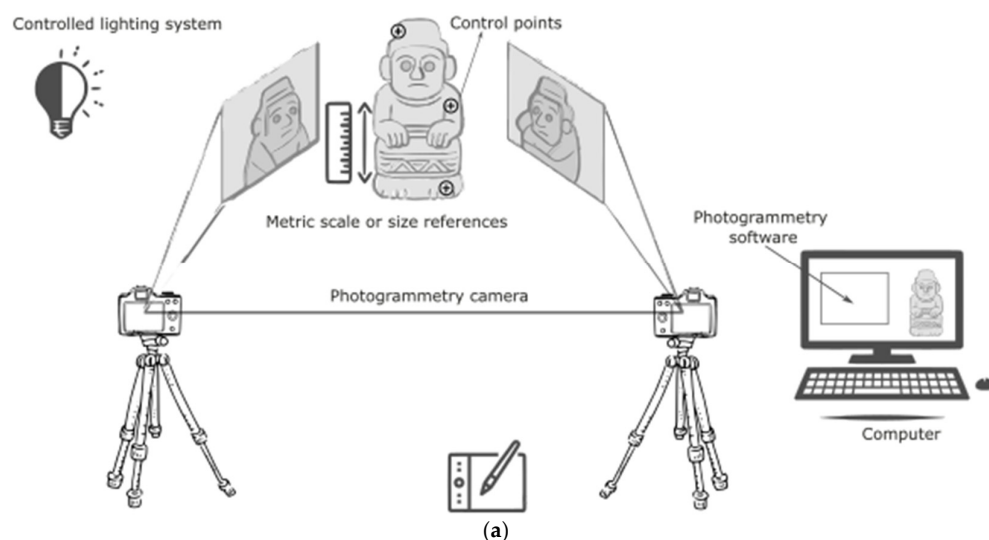
RTI (Reflectance Transformation Imaging)	Analysis of surface details	Enhancement of fine features
PTM (Polynomial Texture Mapping)	Representation of heterogeneous materials	Realistic visualization
Automatic Reconstruction	Fragment assembly	Efficiency in reconstruction
Reconstruction of archaeological sites		
Geographic Information System (GIS)	Spatial analysis of archaeological sites	Integration of geographic data
Remote Sensors and Radar Scanning	Remote terrain data capture	Broad and non-invasive coverage
Radar Doppler Tomography	Subsurface and structural visualization	Detection of underground anomalies
Digital Elevation Models (DEM)	Representation of terrain relief	Accurate geospatial analysis
Muon radiography	Study the internal large objects' structure	Accurate geospatial analysis
Visualization		
Virtual Reality (VR)	Virtual Reality (VR)	Virtual Reality (VR)
Augmented Reality (AR)	Augmented Reality (AR)	Augmented Reality (AR)

4.2.1. Reconstruction of Archaeological Artifacts

Photogrammetry

In the archaeological context, photogrammetry has established itself as an essential technique due to its ability to generate highly accurate three-dimensional models from images captured from multiple angles [50–56]. This tool has been widely adopted not only for its precision in reproducing fine details but also for its ease of use and accessibility. In recent years, an emerging trend has been the democratization of this technology, driven by the development of intuitive software and low-cost equipment, which has allowed even professionals with limited technical expertise to use it effectively [57].

A notable association is the combined use of photogrammetry with other complementary technologies such as laser scanning and unmanned aerial vehicles (UAVs), representing an evolution in archaeological documentation methodology [58–60]. This integration enables more robust data collection and a more comprehensive representation of the excavated environment. However, there is a clear tension between the perceived ease of use and the technical challenges that persist when combining different data sources, such as system calibration and the management of large volumes of information. This suggests that, although photogrammetry has advanced significantly in terms of accessibility, its optimal application in multidisciplinary settings still requires specialized expertise and standardized technical processes presented in Figure 9.



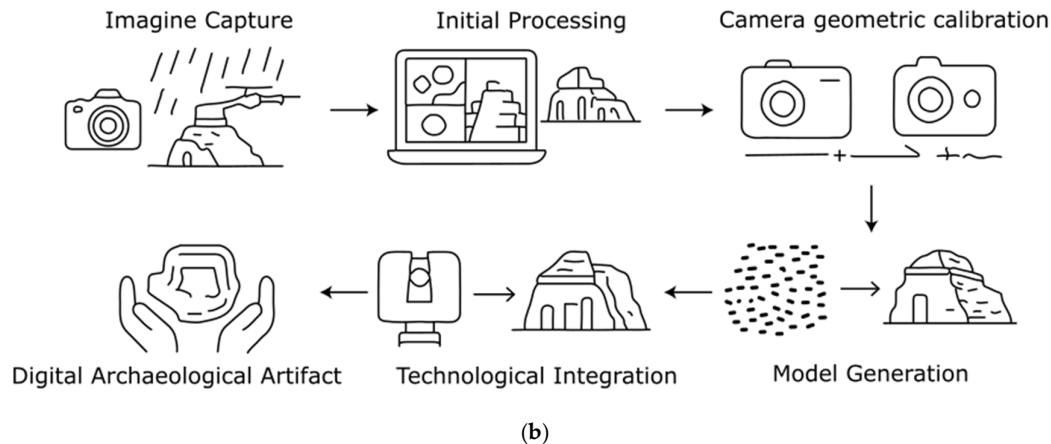


Figure 9. Simplified diagram of the photogrammetric process. (a) diagram of components for the photogrammetry technique, (b) processes for digitizing archaeological artifacts.

Photogrammetry integrates several key components that allow for detailed 3D models of artifacts and archaeological sites. Digital cameras, specialized lenses, and drones are used to capture images from multiple angles and scales [61,62]. These images are processed using techniques such as Structure from Motion and 3D reconstruction software, including open-source options such as Meshroom [61,63]. Camera calibration and the use of on-the-ground control points ensure the accuracy and georeferencing of the models [62]. The processing generates dense point clouds that are transformed into textured and realistic three-dimensional models [64,65]. In addition, photogrammetric data can be merged with technologies such as terrestrial laser scanning, optimizing documentation and analysis [66]. Its main advantages are being a non-destructive, accessible, cost-effective, and highly versatile method in field and laboratory contexts [61,67,68]. In this context, the acquisition of simple images of planar surfaces, such as historical paintings, can be considered a form of planar or 2D photogrammetry, provided that camera calibration and geometric control are ensured. This approach enables accurate documentation and analysis of pictorial heritage without requiring volumetric reconstruction [69].

Figure 10 is a graph showing the relative frequency of occurrence of terms related to archaeological artifacts. The information has been obtained through a scientific literature search on the technologies discussed in this Section 3.1, and the metadata have been analyzed to identify the types of artifacts in which these technologies have been most commonly employed.

Figure 10a shows a relative frequency analysis of terms associated with different types of archaeological artifacts in documents related to photogrammetry, segmented according to their occurrence in a scientific database (Scopus). Among the evaluated terms are objects such as pottery, tomb, wood, mosaic, skull, metals, textile, sarcoph, seals, figurines, inscrip, and lands. Each term was tracked across different documentary segments, allowing the identification of thematic patterns in the scientific literature.

The terms pottery, tomb, and wood show particularly high frequencies across several segments, suggesting a sustained focus on these types of artifacts in studies applying photogrammetry. In contrast, other terms such as textile, sarcoph, and seals appear less frequently and in fewer segments, which may indicate less-explored areas or more specialized applications.

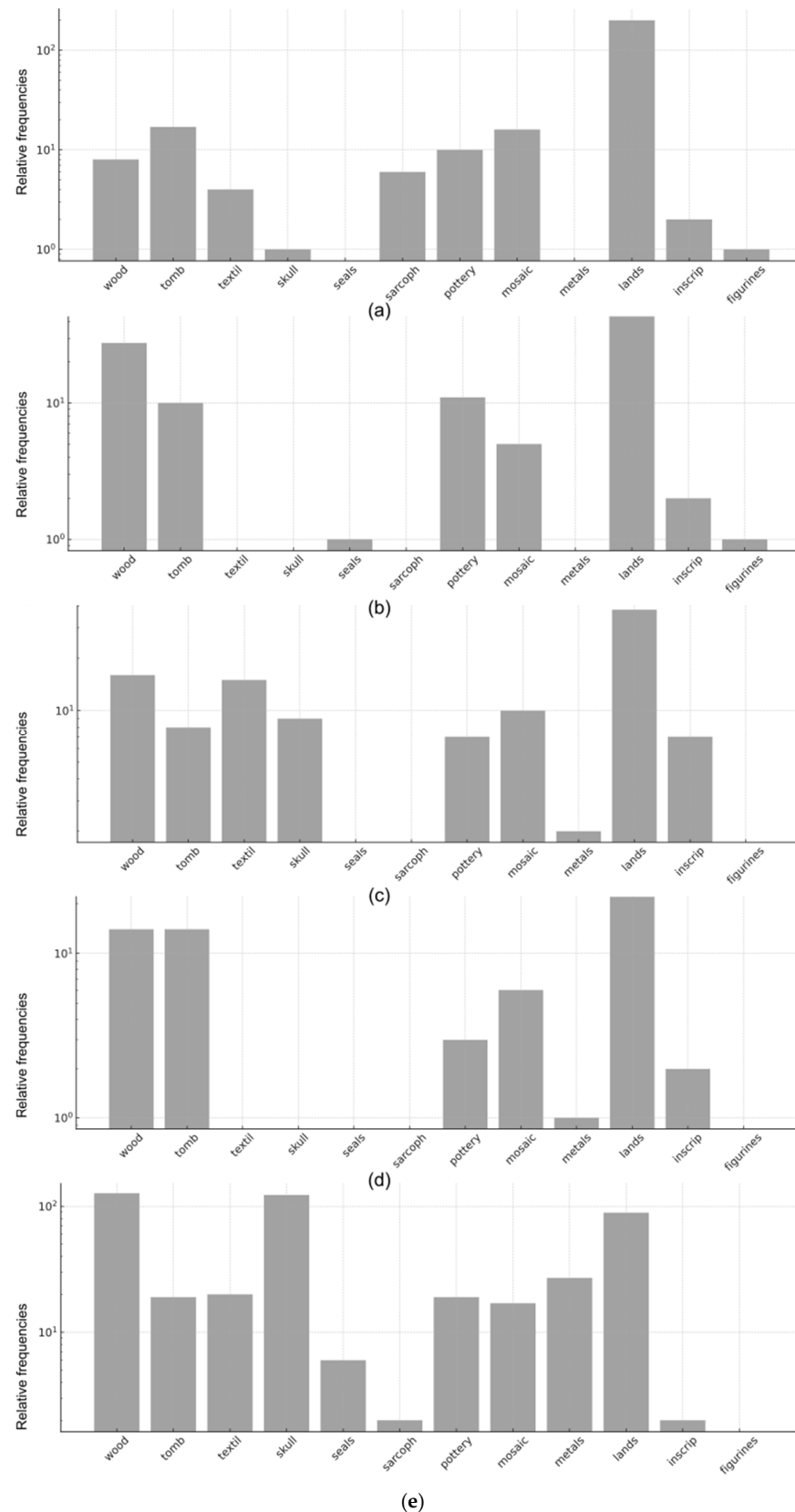


Figure 10. Most frequent archaeological artifacts that have been reconstructed using digital reconstruction technologies. (a) Photogrammetry technique; (b) 3D scanning technique; (c) 3D modeling; (d) Digital restoration techniques; (e) Advanced imaging analysis techniques.

This pattern reveals a tendency toward the application of photogrammetry in structural and durable elements such as ceramics, wood, and funerary architecture, while the scanning of more delicate materials or those less prevalent in the archaeological record remains an emerging field. Therefore, the analysis helps delineate current priorities in the three-dimensional documentation of archaeological heritage and highlights opportunities to expand its use in less-represented types of evidence.

3D Scanning

Three-dimensional (3D) scanning has emerged as a crucial tool in the digitization of archaeological heritage, enabling the precise capture of the geometry of objects and sites through specialized devices [50,55]. This technique not only facilitates the creation of high-fidelity digital replicas but also offers the advantage of being transportable to the archaeological site, thereby preserving the original context and respecting intangible heritage not yet identified in situ presented in Figure 11.

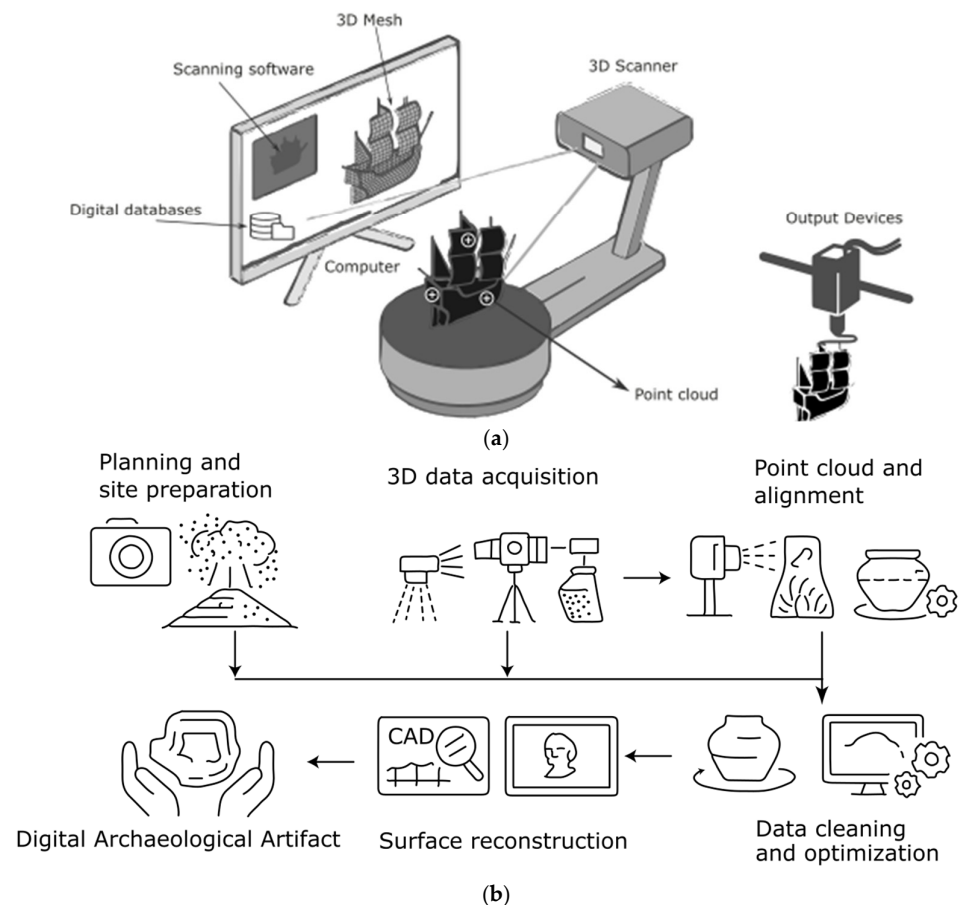


Figure 11. Schematic of the 3D Scanning technique. (a) Schematic of components, (b) General processes for the digitization of archaeological artifacts.

The components of 3D scanning integrate various systems that allow accurate and detailed models to be obtained. Among them, stereo cameras generate point clouds by mapping disparity and displacement [70,71], while industrial cameras avoid blind spots by capturing all surfaces [72] and photogrammetry cameras process images to reconstruct models [73,74]. Laser scanners, based on time-of-flight or phase comparison, produce depth maps, supplemented by line lasers that outline geometry [75]. The rotary tables, controlled by motors, allow multiple views of the object [75]. Processing is done with

imaging algorithms to reconstruct surfaces, photogrammetry software such as Agisoft Metashape and 3DF Zephyr [73], plus CAD and reverse engineering tools that refine the models [76].

One of the main technological associations in this area is the complementary use of different 3D scanning modalities, each with its own strengths and limitations, which has led to a trend toward hybrid and adaptive systems depending on the site conditions or the nature of the object being studied. Among these key technologies, laser scanning stands out for its ability to generate highly accurate geometric data, making it ideal for the detailed documentation of structures and artifacts [77,78]. However, this method has significant drawbacks, including high cost, operational complexity, and limited capability for capturing textures and colors [79].

Unlike photogrammetry, 3D scanning techniques involve greater implementation complexity but provide higher accuracy in the resulting models, making them more suitable when rigorous millimeter-level precision is required [80,81]. Structured light scanning has gained relevance for its effectiveness in capturing fine details on complex surfaces, which makes it a preferred option for generating highly detailed digital models [82,83]. However, this approach presents limitations when exposed to adverse environmental conditions such as inadequate lighting or humidity [84,85].

Micro-computed tomography (Micro-CT) represents a cutting-edge 3D scanning technology, capable of capturing both external and internal structures at high resolution and is particularly useful for small and complex artifacts [86,87]. Nonetheless, its application is limited by high costs, the need for specialized equipment, and the technical expertise required [85].

The evolution of 3D scanning technologies reveals a clear movement toward the specialization and complementarity of techniques, in which methodological decisions must balance geometric precision, visual fidelity, operational logistics, and environmental conditions. This movement reflects a transition from single-method approaches to integrated strategies for the documentation, conservation, and analysis of archaeological heritage, as presented in Table 4.

Table 4. Comparative analysis of key technologies for archaeological artifacts scanning 3D.

Technology	Geometric Accuracy	Texture/Color Accuracy	Cost	Ease of Use
Laser Scanning	High	Low	High	Moderate
Structured Light Scanning	High	High	Moderate	Moderate
Micro-CT	Very High	High (internal structures)	Very High	Low

The integration of multiple 3D scanning technologies enables the complementary strengths of each method to be effectively leveraged. For instance, combining photogrammetry for high-quality texture acquisition with laser scanning for precise geometric capture results in more comprehensive and detailed three-dimensional models [4,5,19]. This hybrid strategy enhances comprehensive documentation and broadens the applicability of digital models across various archaeological contexts.

3D scanning technologies have established themselves as fundamental tools for documentation, conservation, and analysis of archaeological heritage. Although each technique has its own specific advantages and limitations, their complementary use offers more robust solutions for accurately representing cultural objects.

Figure 9b shows the relative frequency of terms associated with archaeological artifacts in scientific documents related to 3D scanning technologies, specifically in contexts that also include photogrammetry, segmented from a review conducted in the Scopus database. The evaluated terms correspond to different types of physical evidence, such as

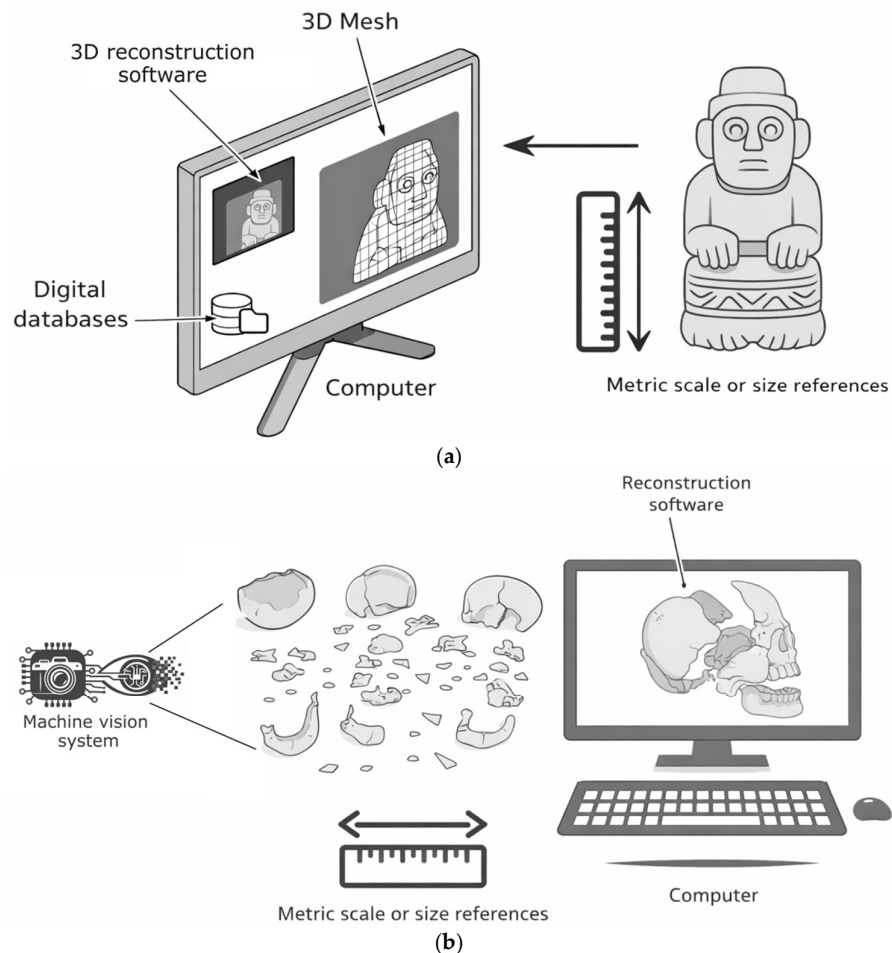
tools, pottery, tomb, wood, bone, skull, textile, metals, figurines, inscriptions, and mosaic, reflecting the diversity of objects subjected to digital reconstruction.

The high frequency of the term bone in segment 5 stands out, indicating a notable interest in applying these technologies to human or animal skeletal remains within that group of publications. Similarly, pottery and tools show consistent presence across multiple segments, suggesting their cross-cutting relevance in digital archaeological research.

Conversely, terms such as figurines and inscriptions display lower frequencies and more dispersed distributions, which may indicate a lesser degree of exploration or application of 3D techniques to these objects. The inclusion of textile and wood reflects a recent expansion toward organic materials, which have traditionally posed technical challenges for three-dimensional documentation due to their fragility or poor preservation.

3D Modeling and Reconstruction

3D modeling and reconstruction have become essential tools in digital archaeology presented in Figure 12. Research has demonstrated the use of methods such as Heritage Building Information Modeling (HBIM) based on historical sources, parametric modeling, and platforms such as ArchiCAD to recreate destroyed or deteriorated structures [46]. This approach not only enables the visualization of the original state of elements but also promotes their study and conservation from an inter- and transdisciplinary perspective [88].



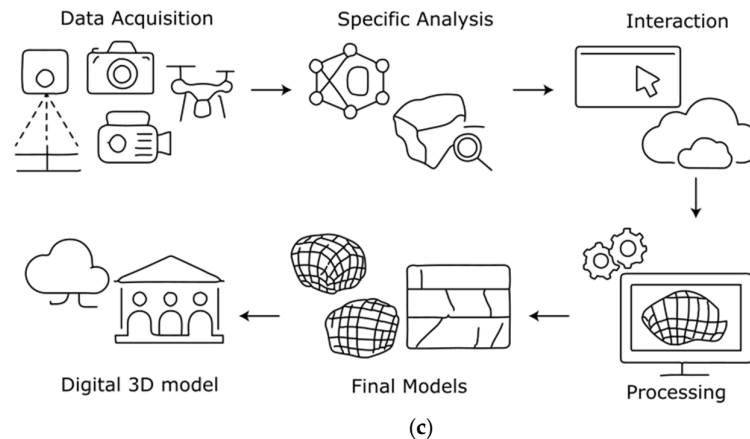


Figure 12. 3D modeling and reconstruction technique. (a) 3D measurement and modeling of objects. (b) Scanning of parts and digital reconstruction. (c) General 3D digital model modeling and reconstruction process.

The 3D modeling and reconstruction of archaeological pieces integrates various phases and elements that guarantee digital precision. Data acquisition is done by laser scanning, photogrammetry and structured light [89–91], complemented by drones for aerial views [92]. Processing includes data recording and fusion [6], parametric modelling [93] and procedural techniques for detailed reconstructions [94], along with uncertainty visualisation and augmented reality [94,95]. As for the specific elements, the classification of fragments with algorithms and neural networks, the analysis of rupture surfaces [96] and the documentation of archaeological contexts using volumetric modeling [97] stand out. Interaction is favored with user interfaces and remote access for model manipulation [98]. Finally, model creation encompasses mesh generation and orthophotos [92], while digital storage and dissemination ensure the preservation and socialization of cultural heritage [99]. Figure 10c presents the artifacts that have most frequently been reconstructed using this technique.

Artificial intelligence (AI) has become a key tool for the digital reconstruction of archaeological artifacts, particularly in contexts involving large volumes of fragments. Machine learning-based methods enable the automation of fragment classification, geometric feature extraction, and the reassembly of original objects through 3D puzzling techniques, thereby reducing reliance on manual intervention [100,101]. In addition, probabilistic approaches and generative models facilitate the evaluation of multiple reconstruction hypotheses when evidence is incomplete, enhancing the reproducibility and transparency of the interpretative process [102]. When integrated with 3D digitization workflows and archaeological information systems, AI increases the efficiency and scalability of digital reconstruction, enabling the systematic and scientifically robust handling of large fragment assemblages [103].

Digital Analysis and Restoration

The use of digital tools for the analysis and restoration of artifacts has evolved toward multidisciplinary approaches that integrate various techniques. Finite Element Analysis (FEA) has emerged as an essential resource not only for evaluating the structural integrity of digitally restored artifacts, ensuring robust and reconstructions [50], but also for performing analyses in diverse fields such as fluid mechanics, aerodynamics, material structural behavior, and applied mathematical geometry. This versatility makes FEA a powerful tool with the potential to generate predictive models that optimize restoration processes.

Key components and elements in archaeological 3D reconstruction include data acquisition technologies, such as digital photogrammetry using stereoscopic cameras [104], laser scanning for high-resolution point clouds [104], and the use of GPS/GNSS and depth sensors for documentation [104,105]. Data processing involves the creation of 3D models with specialized software [106,107] and image analysis to assess colors, textures, and damage. Virtual restoration employs digital reconstructions that prevent physical damage [106,108] and virtual anastylosis techniques to validate hypotheses [106]. Documentation and management are supported by knowledge systems that integrate augmented and virtual reality [106] and geospatial databases that combine aerial, satellite and GPR imagery. This process is structured in acquisition, modeling, restoration and management, guaranteeing accuracy and accessibility of cultural heritage (Figure 13).

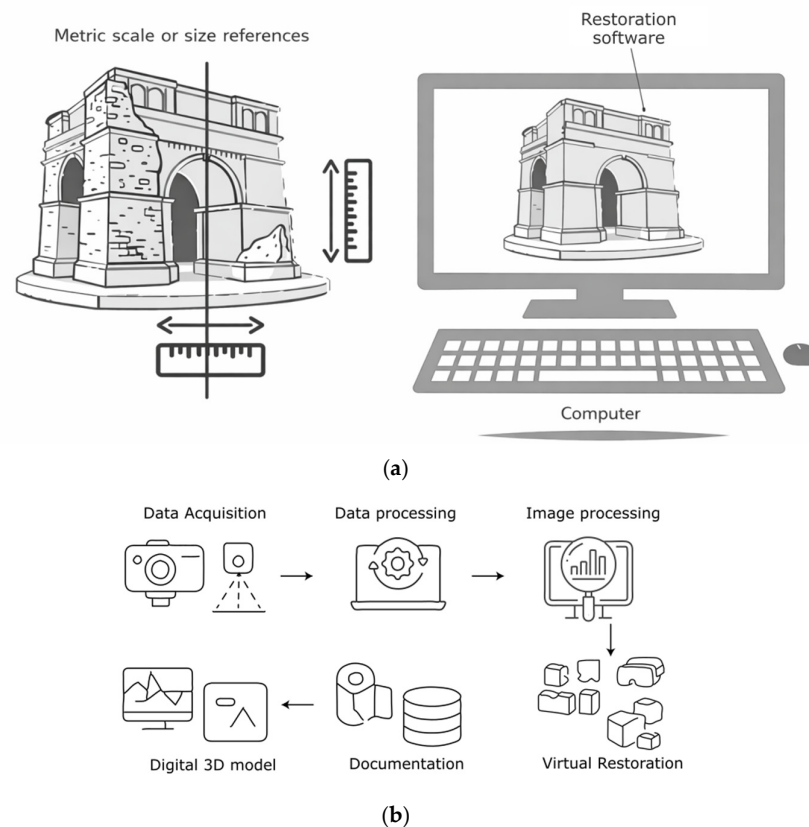


Figure 13. Schematic of 3D digital restoration technique. (a) Obtaining a 3D model for restoration. (b) General process of restoration and obtaining a 3D digital model.

In parallel, Virtual Restoration has emerged as a trend that allows interventions on artifacts without the risk of physical damage, offering significant advantages in comparing reconstruction hypotheses and conserving heritage [109]. Unlike FEA, whose nature is predominantly analytical, virtual restoration focuses on visualization and reconstruction, highlighting a contrast between analytical methods and interpretive methods within the field of digital restoration.

Additionally, advances in modeling and comparative analysis of images obtained through scanning or photogrammetry have opened the possibility of developing more standardized digital restoration processes [88]. This approach aims at creating documentation standards that facilitate the replication and validation of results, representing a trend toward the global integration of researchers and disciplines. While FEA provides structural rigor and virtual restoration offers flexibility in experimentation, the

standardization of methodologies strengthens scientific reproducibility and fosters international collaboration. Figure 10d presents the artifacts that have most frequently been reconstructed using this technique.

Advanced Imaging Technologies

Advanced imaging technologies have significantly expanded the possibilities for documentation and analysis in digital reconstruction, with an increasingly precise and non-invasive approach. The use of high-resolution RGB cameras mounted on UAV drones, complemented by specialized sensors, has represented a crucial breakthrough in capturing detailed visual information from multiple angles and altitudes. This approach has improved the accuracy of 3D modeling and optimized the recording of archaeological contexts in their original state [46,88].

The main components and technologies in archaeological documentation combine optical, digital and laser methods to obtain accurate and non-invasive records. Photogrammetry creates detailed 3D models using superimposed images [99], while TLS captures data from complex surfaces with lasers [110]. Reflectance Transformation Imaging (RTI) records reflectance properties with different illuminations for interactive visualization [111]. Computed tomography (CT) and digital radiography make it possible to study internal structures without damaging objects (Modernization of the CCR X-ray imaging system “La Venaria Reale”: the case study of an Egyptian wooden figurine), presented in Figure 14a.

Hyperspectral and multispectral imagery identify materials and conservation states [112]. In addition, 3D modeling and rapid prototyping facilitate analysis, preservation, and replication creation (8,10,14), supported by nonlinear microscopy and high-resolution laser scanning to capture fine details [113]. These processes are complemented by cameras, sensors, controlled lighting, software, and specialized equipment [113], providing benefits in documentation, conservation, analysis, restoration, and cultural dissemination [114].

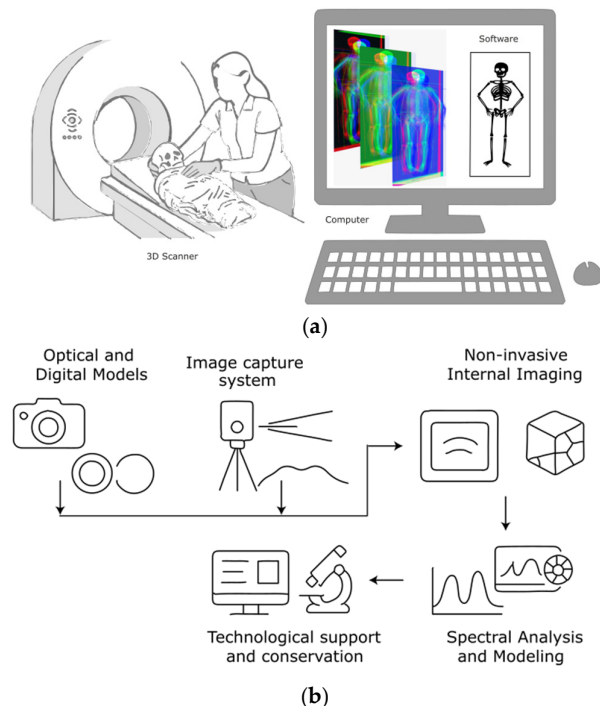


Figure 14. Schematic of advanced image analysis technology. (a) Scheme for the use of computed tomography to obtain a 3D digital model. (b) General process for obtaining a 3D digital model.

In parallel, RTI has become a key tool for recording surface details of artifacts that would be imperceptible using conventional imaging techniques [57]. Unlike UAVs, whose strength lies in large-scale contextual capture, RTI specializes in micro-detailed analysis, underscoring the trade-off between spatial breadth and depth of detail in capture approaches.

CT has also emerged as a cutting-edge solution for internal visualization of archaeological finds, eliminating the need for immediate physical interventions [115]. This technique has overcome the limitations of traditional radiography, which is characterized by low precision and a high requirement for technical training, allowing for faster and non-destructive evaluations.

Taken together, these technologies demonstrate a trend toward the integration of complementary methods that combine the contextual mapping capability of UAVs, the surface detail provided by RTI, and the internal analysis offered by CT. This integrated paradigm points toward the development of increasingly comprehensive documentation protocols, with applications that strengthen both conservation and archaeological research. Figure 10e presents the artifacts that have most frequently been reconstructed using this technique.

Figure 15 summarizes the normalized frequency of technologies according to archaeological evidence reported in scientific studies indexed in the SCOPUS database.

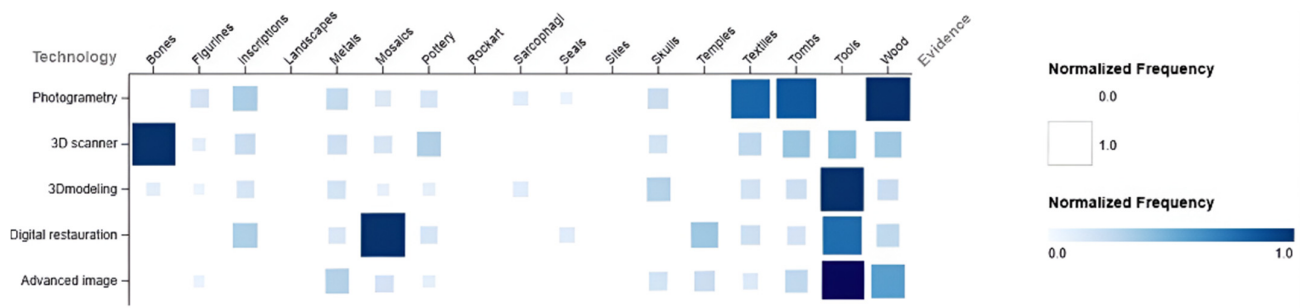


Figure 15. Normalized frequency of technology use for the digital reconstruction of archaeological objects.

Figure 15 makes it possible to identify a greater use of photogrammetry in the reconstruction of textile remains, tombs, and wooden designs, while scanners have been preferred for studies focused on capturing bone remains. Modeling techniques have been primarily applied to the reconstruction of tools, whereas digital restoration and advanced imaging analysis have been used to reconstruct mosaics and tools in most studies.

4.2.2. Reconstruction of Archaeological Sites

Geographic Information System (GIS) and Geodesic Positioning Technologies

The use of Geographic Information Systems (GISs) in archaeology has gained significance as a comprehensive tool for reconstructing ancient landscapes and preserving cultural heritage. Its ability to integrate and analyze historical, topographic, and archaeological data in multi-scale environments allows for the generation of precise maps and databases that facilitate the planning of interventions and conservation strategies [116]. The GIS is particularly noteworthy for its ability to identify spatial relationships among archaeological sites, their connection with the surrounding landscape, ancient infrastructure, and the human dynamics that developed over time. Unlike other technologies focused on three-dimensional visualization or structural analysis, the GIS provides a more systemic and contextual approach, enabling the understanding of patterns of land use and occupation over broad temporal and geographical scales.

Current trends point toward the integration of GISs with other advanced technologies, such as 3D scanning, UAVs, and predictive models based on artificial intelligence, to produce more complete and accurate reconstructions. This combined approach not only strengthens the interpretation of archaeological findings but also optimizes decision-making for the protection and management of heritage. In this way, the GIS has become a key tool for linking the spatial and temporal dimensions in archaeological analysis, complementing other digital reconstruction techniques.

Figure 16 was generated to identify evidence of territorial extensions much larger than common artifacts such as mounds, terraces, roads, walls, foundations, fields, canals, reservoirs, sites, tombs, vegetation, temples, landscapes, and structures, which have been reported in scientific studies related to the techniques addressed in this section. Figure 16a shows the archaeological evidence most commonly associated with the use of GISs.

Closely related to Geographic Information Systems (GISs), high-precision GPS/GNSS positioning and other emerging geomatics techniques constitute an essential component for the rigorous digital reconstruction of archaeological sites. While the GIS enables the spatial analysis, integration, and visualization of information, geodetic techniques provide the planimetric and altimetric framework that ensures metric accuracy and spatial coherence of the data. The use of high-precision GPS/GNSS, through techniques such as RTK and PPK, together with total stations, geoid models, and vertical reference systems, is fundamental for precise elevation control and the three-dimensional georeferencing of archaeological structures, stratigraphic units, and landscapes [102,104]. Moreover, the integration of these geomatics techniques with GISs facilitates multiscale and multitemporal data fusion from photogrammetry, LiDAR scanning, and remote sensing, thereby reinforcing the reproducibility and scientific validity of digital reconstruction models, as highlighted in recent studies on the documentation and spatial analysis of archaeological heritage [103].

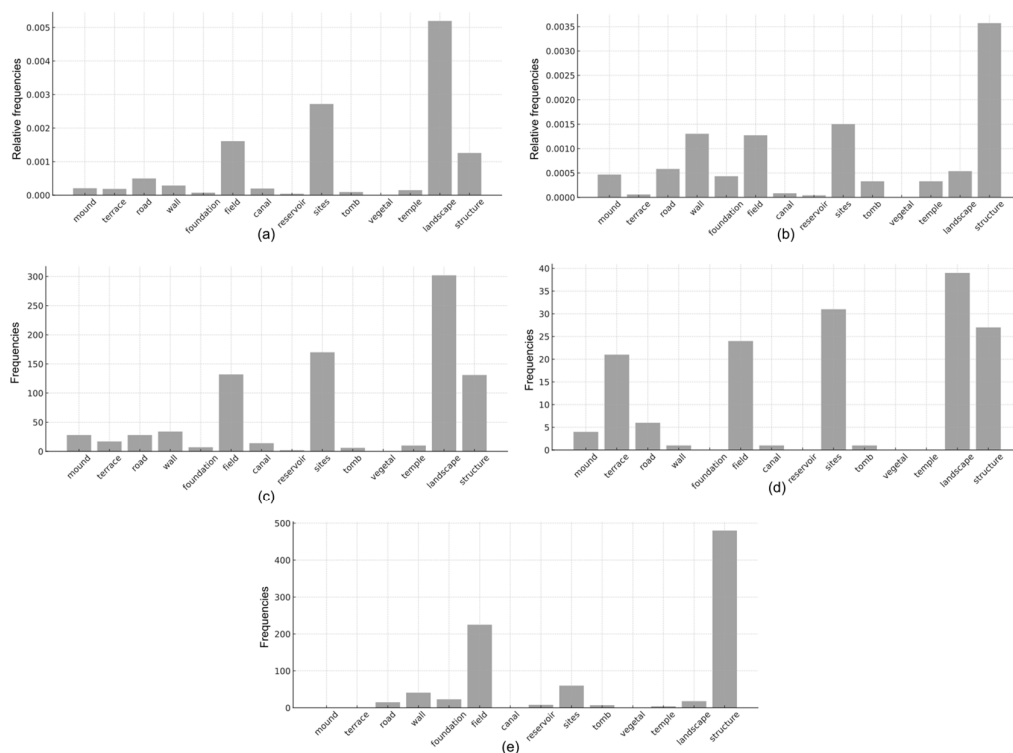


Figure 16. Relative frequency of the archaeological evidence most frequently reconstructed using Archaeological Site Reconstruction techniques. (a) Geographic Information Systems; (b) Radar scanning; (c) Radar Doppler; (d) LiDAR scanning; (e) Digital elevation model (DEM).

Radar Scanning

Radar scanning and remote sensing technologies play a fundamental role in the monitoring, documentation, and preservation of archaeological heritage, as they enable non-contact data acquisition while minimizing the risk of physical alteration of sensitive sites [117]. However, it is important to distinguish clearly between the different categories of radar- and sensor-based approaches, as their objectives and outputs differ significantly. In particular, Synthetic Aperture Radar (SAR) techniques are primarily designed for detecting surface changes, deformation patterns, and elevation differences over time, rather than for direct geometric reconstruction. SAR systems are especially effective under low-visibility conditions and support multitemporal analyses aimed at identifying landscape evolution and structural instabilities [118]. This capability allows for the generation of detailed digital models of monuments and archaeological sites, providing valuable information for documentation, conservation, and reconstruction efforts presented in Figure 16b. Figure 17 presents a schematic representation of the field application of this technology. Specifically, Figure 17a illustrates its use of radar waves, while Figure 17b depicts the general processes involved in its operation.

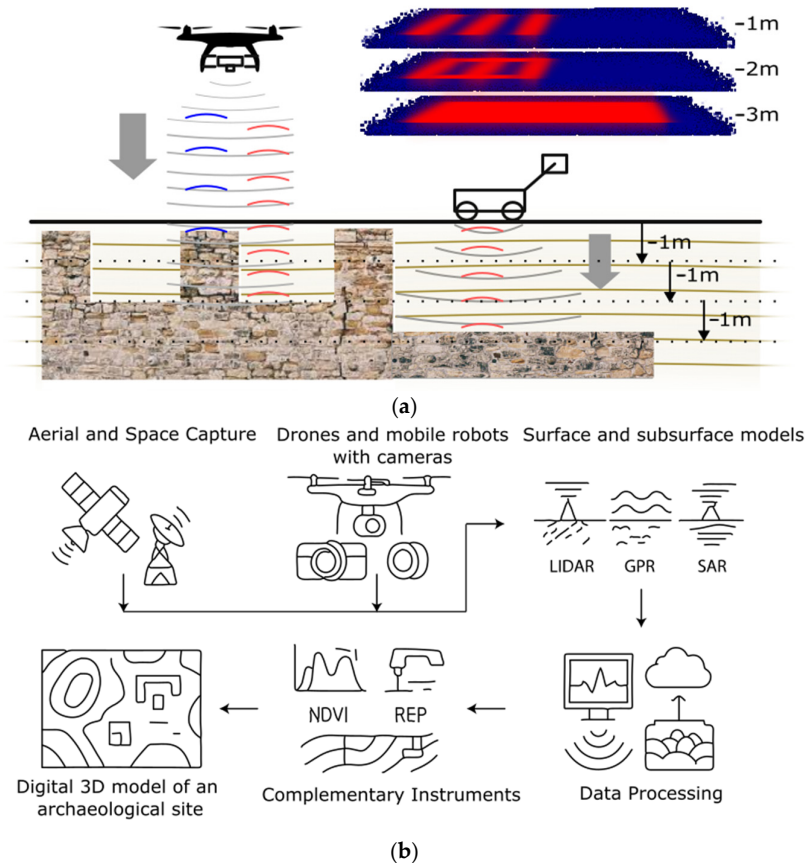


Figure 17. Schematic of the remote sensing and radar scanning technique. (a) Schematic of components of the technique. (b) General process of obtaining the 3D model of the archaeological site.

Within the broader remote sensing framework, optical and radar sensors deployed on satellites and aircraft provide large-scale spatial coverage for archaeological prospection and monitoring [119,120], while unmanned aerial vehicles (UAVs) equipped with multispectral and hyperspectral cameras enable high-resolution documentation at site scale [121–123]. Complementarily, Ground Penetrating Radar (GPR) facilitates the detection of subsurface features by exploiting radar wave propagation, making it particularly

suitable for identifying buried structures without excavation [124]. In contrast, Terrestrial Laser Scanning (TLS) focuses on the precise geometric capture of visible surfaces through dense 3D point clouds, supporting detailed documentation and reconstruction workflows rather than deformation monitoring.

A specific and highly relevant subset of radar-based techniques is Ground-Based Synthetic Aperture Radar Interferometry (GBInSAR), which is specifically designed for continuous structural monitoring rather than static 3D reconstruction. GBInSAR systems emit radar waves toward the target surface and analyze phase variations in the reflected signals to detect millimetric displacements over time [117]. This capability enables the generation of displacement maps that are essential for assessing structural stability and anticipating deterioration processes in archaeological sites. Unlike TLS, which provides high-fidelity geometric models at discrete acquisition times, GBInSAR offers a dynamic and preventive monitoring approach, capable of detecting early-stage deformations before irreversible damage occurs.

Data processing in radar and remote sensing-based archaeological applications typically integrates specialized software platforms such as PG-Steamer and MATLAB R2025a [125], multi-sensor data fusion techniques [126], and spectral index analyses including NDVI and REP [127]. Additional instruments, such as spectroradiometers, thermal cameras, and electrical resistivity tomography (ERT), further enhance anomaly detection and subsurface characterization, reinforcing the interpretative robustness of remote sensing workflows.

Current research trends emphasize the integration of SAR-based monitoring, GBInSAR, and complementary remote sensing techniques with 3D modeling and artificial intelligence-driven predictive analyses to support risk assessment and preventive conservation strategies [128]. Through this integrative approach, radar scanning and remote sensing technologies not only complement visualization and reconstruction techniques but also strengthen the preventive dimension of archaeological heritage management, positioning them as essential components of comprehensive and sustainable monitoring frameworks.

Radar Doppler Tomography

Radar Doppler Tomography has emerged as a cutting-edge technique for the internal analysis of archaeological structures. Its operating principle is based on the analysis of micro-movements or extremely small vibrations within the structures under study. These vibrations, generated by background seismic waves from human activities, wind, or internal movements of the structure itself, are leveraged to reconstruct three-dimensional images of its interior without the need for physical intervention [129].

A notable example of its application is the study of the Pyramid of Khnum-Khufu, where Radar Doppler Tomography provided detailed information about its internal architecture, overcoming the limitations of more traditional methods. Unlike technologies such as Ground-Based Synthetic Aperture Radar Interferometry (GBInSAR) or Terrestrial Laser Scanning (TLS), which focus on detecting external displacements or surface geometry, Radar Doppler Tomography offers a unique capability for internal volumetric exploration presented in Figure 18a.

The main components of these systems include a transmitter, which emits electromagnetic waves, and a receiver, which captures the reflected signals with information about motion and structure [130]. Key elements include Doppler spectra-based tomographic projections for time-frequency domain imaging [131]. Processing is supported by algorithms such as remapped spectrogram, which improves resolution [132], and convolution rear projection for images with single-tone signals [133]. In addition, spatial frequency spaces (k-spaces) allow the resolution of radar imaging systems to be described

and analyzed [134]. Within the parts of the system, the passive dispersion radar, which uses LTE towers to detect targets [135], and the acoustic micro-Doppler radar, effective in the analysis of human movement signatures [136] stand out. Finally, imaging methods include extended coherent processing (ECP) and BENI non-coherent imaging, which optimize resolution and sensitivity [137] shown in Figure 18b. Figure 16c shows the evidence most commonly associated with the use of digital reconstruction technologies employing Doppler radar.

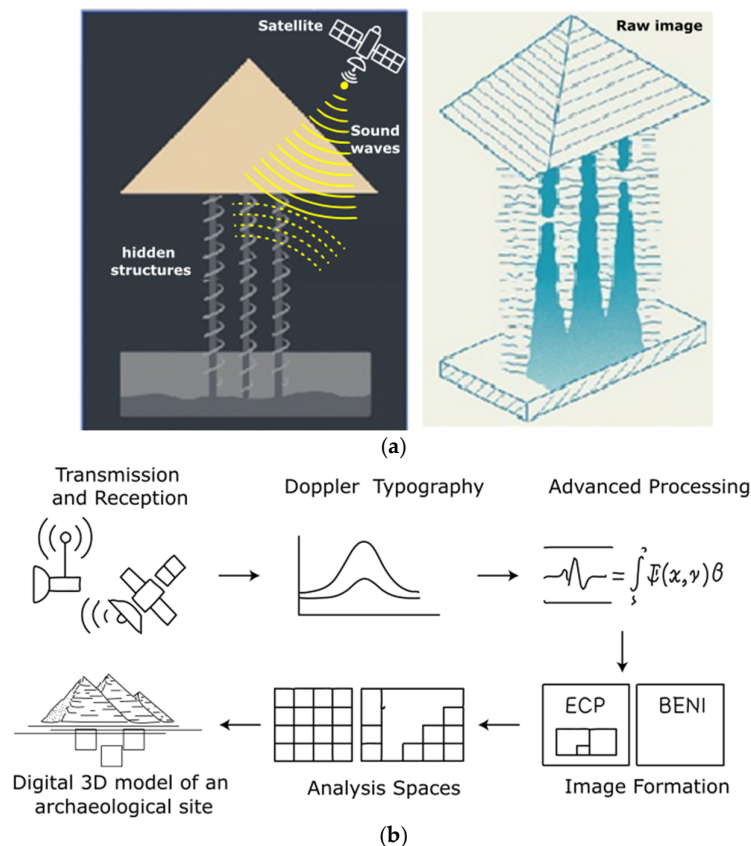


Figure 18. Diagram of the Doppler tomography radar technique. (a) Scheme of use of the technique. (b) General process for obtaining the 3D model of the archaeological site.

LiDAR Scanning System

LiDAR (Light Detection and Ranging) is an active remote sensing technique that uses laser pulses to measure, with high precision, the distance between a sensor and the Earth's surface, enabling the generation of 3D surface models [124]. This technology produces a three-dimensional point cloud in which each point contains detailed spatial information about the terrain and the objects present, such as trees, buildings, or archaeological remains. Its ability to partially penetrate vegetation makes it an essential tool in archaeology, as it allows the identification of hidden structures, micro-topographies, and cultural features with a level of detail that is difficult to achieve with other survey techniques. Its main advantage lies in its high resolution and accuracy, although the cost of data acquisition and processing can be considerable. The processing workflow is similar to that shown in Figure 17b.

Digital Elevation Models (DEMs)

The Digital Elevation Model (DEM) technology acquires data points from the terrain, including ground surfaces, buildings, and archaeological features, which are then

interpolated into a regular grid of elevations over a specific area [138]. Digital Elevation Models (DEMs) include Digital Terrain Models (DTMs), which represent the bare-earth surface, and Digital Surface Models (DSMs), which incorporate above-ground features. In archaeological site reconstruction, DTMs support the identification of buried structures and landscape modifications, while DSMs aid in contextualizing surface features. Although DEMs do not provide detailed structural reconstruction, they are essential for reconstructing site morphology and integrating archaeological data within GIS-based spatial analyses (Figure 19a).

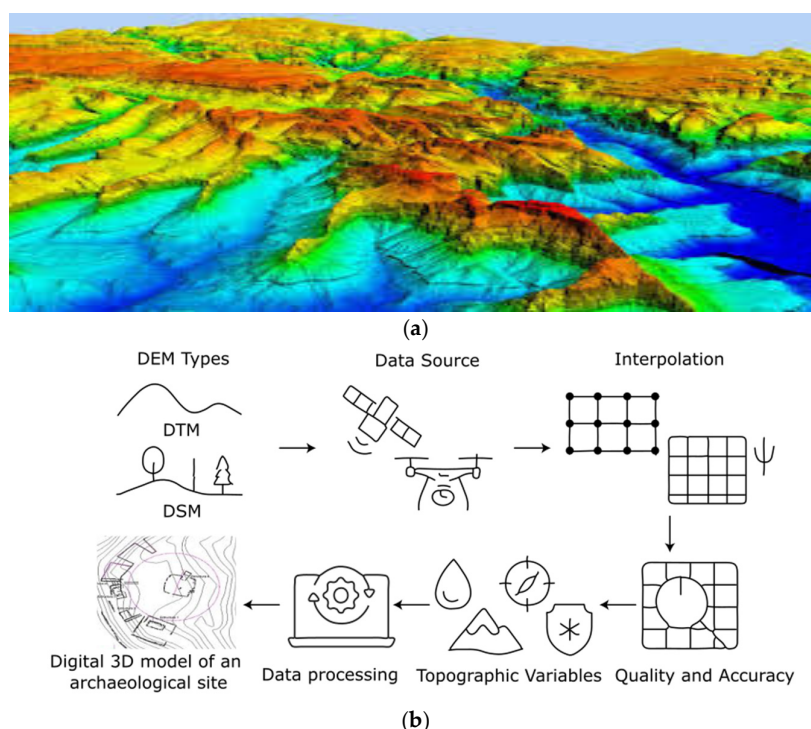


Figure 19. Digital Elevation Models technology schematic. (a) Example of a surface map obtained with DEM technology, the colors represent the different terrain elevations through a chromatic scale, where cool tones indicate lower elevations and warm tones indicate higher altitudes. (b) General process for obtaining a 3D digital model of an archaeological site.

Digital Elevation Models (DEMs) represent the Earth's surface in three dimensions and are composed of elevation data such as the DTM, which shows bare land, and the DSM, which includes objects above the surface [139]. Data sources include satellite imagery (ASTER, SRTM, PRISM) [140], stereoscopic aerial photographs [141], high-precision LiDAR [140], and radar imagery using radargrammetry and interferometry [142]. Interpolation methods, such as inverse weighted distance, natural neighbor, and wavelet decomposition, allow continuous surfaces to be generated from known points [143]. Among the elements, grid resolution determines the detail of the model, while filtering and error correction improve the accuracy of DEMs [144], and 3D visualization tools facilitate analysis [145]. The parts include primary topographic variables such as slope, appearance, and curvature [146] and secondary variables such as the relief index (RFI) [147]. Its applications include hydrology and geomorphology [148] presented in Figure 19b. The most prominent archaeological evidence associated with this reconstruction technology is presented in Figure 16d.

The DEM (Digital Elevation Model), in turn, is a derived product that represents the terrain surface in a continuous digital format, generally through a two-dimensional raster

grid containing elevation values. Although their resolution is typically lower than that of the original point cloud, they constitute a fundamental basis in geographic information systems (GISs) for topographic mapping, hydrological modeling, watershed analysis, and territorial planning. In archaeology, DEMs allow the reconstruction of a site's relief, facilitate the visualization of buried structures, and support heritage management at a more accessible cost than unprocessed LiDAR data.

While LiDAR provides high-precision raw data, DEMs represent a processed and simplified model that serves as input for multiple spatial analyses. Both are complementary and, depending on the research objectives, can be integrated to obtain a more comprehensive understanding of the archaeological environment, as presented in Table 5.

Table 5. Comparison LiDAR and DEM techniques.

Characteristic	LiDAR (Light Detection and Ranging)	DEM (Digital Elevation Model)
Nature	Active remote sensing technology that emits laser pulses and measures their return.	Processed digital model representing the elevation of the Earth's surface.
Main Output	High-resolution 3D point cloud (includes terrain and objects).	Continuous surface in raster/grid format with elevation values.
Level of Detail	Very high, capable of capturing micro-topography and hidden structures.	Lower detail, resolution depends on the input data source.
Accuracy	Centimeter-level in optimal conditions.	Typically decimeter to meter level, depending on the source.
Data Sources	Laser pulses from airborne or terrestrial sensors.	Derived from LiDAR, photogrammetry, radar, or satellite imagery.
Cost	High (specialized equipment and intensive data processing).	More cost-effective, with free or low-cost datasets often available.
Applications in Archaeology	Detection of hidden structures, high-resolution 3D modeling, detailed documentation.	Terrain reconstruction, spatial analysis in GIS, heritage management and planning support.

Muon Radiography

Muon Radiography (muography) is a non-invasive technique that uses cosmic muons—subatomic particles produced by the interaction of cosmic rays with the Earth's atmosphere—to study the internal structure of large objects [149]. These highly energetic muons penetrate solid materials, and their flux is attenuated depending on the density of the material encountered. By placing specialized detectors (muon telescopes) in different positions, it is possible to measure the flux of muons passing through a structure and compare it with the flux recorded from open sky presented in Figure 20a. Denser areas block more muons, while cavities or empty spaces allow a greater number of particles to pass through. This enables the generation of internal density images and, through the use of multiple perspectives, three-dimensional reconstructions of the studied structures [150].

Muon radiography or muography is a non-destructive imaging technique that uses cosmic muons, subatomic particles with high penetration and natural abundance, ideal for studying the internal structure of large objects [151]. Muon detectors, such as nuclear emulsions and telescopes, offer high angular and spatial resolution and can be configured in a modular manner for harsh environments [152,153]. Processing is done using reconstruction algorithms, such as PoCA and statistical tests, which generate accurate 2D and 3D images [154–158]. The technique measures the attenuation of the muon flux, comparing the observed flux with the expected flux to infer the density and thickness of the materials [159]. The spatial resolution of the detectors can reach up to 4 mm and the angular accuracy is enhanced by plastic layers in nuclear emulsions [156]. These components, elements, and methods allow detailed internal reconstructions without damaging the objects

under study. Figure 16e presents the evidence most commonly associated with the use of this technology, which is relatively new and a current trend in ongoing research lines. Figure 20b schematically illustrates the general processes involved in the operation of this technology.

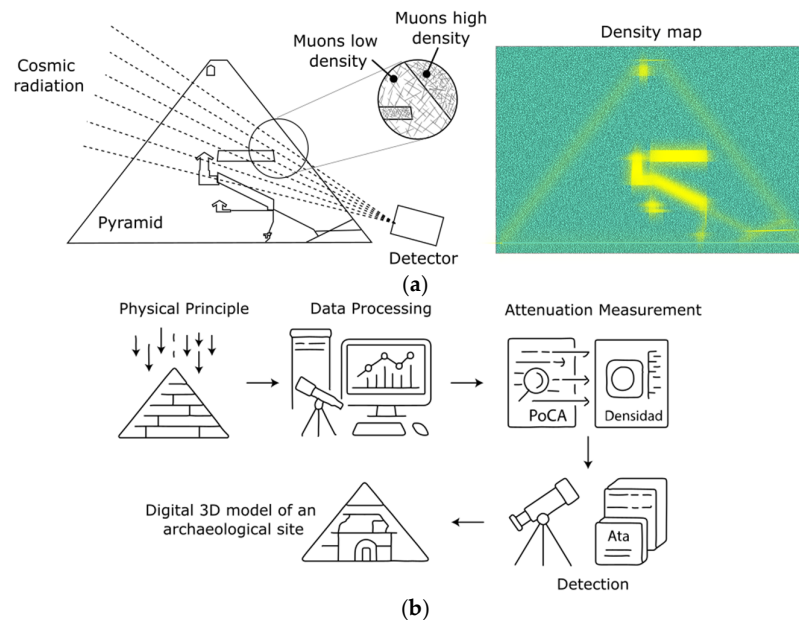


Figure 20. Muon radiography technology schematic. (a) Components of Muon radiography technology, a more intense color corresponds to a low muon density. (b) General process of obtaining the 3D model of an archaeological site.

This technique has been successfully applied in archaeological and geophysical contexts. For example, in 2017, the ScanPyramids project used muography to discover a large void above the Grand Gallery of the Great Pyramid of Khufu in Egypt [160], revealing a cavity approximately 30 m long. Similarly, the ScIDEP project is employing muon telescopes based on scintillator technology to scan the Pyramid of Khafre from the burial chamber and external positions in order to identify hidden chambers or structural voids. The aforementioned technologies have been primarily used to study the interior of volcanoes, such as Mount Asama in Japan, and to locate underground tunnels and deposits (Figure 21), demonstrating their significant potential for non-destructive research across various disciplines [161,162].

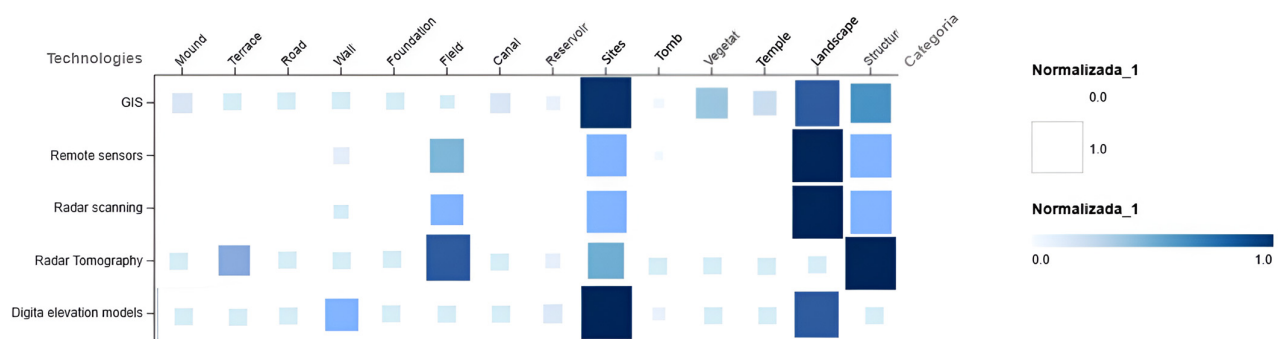


Figure 21. Normalized frequency of the use of archaeological site reconstruction technologies and their findings in archaeological evidence.

4.2.3. Visualization

Virtual Reality (VR) and Augmented Reality (AR)

The incorporation of immersive technologies such as Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality is transforming archaeological reconstruction processes by offering new possibilities for the visualization and interpretation of artifacts and structures [52,163]. These tools allow the superimposition of digital information onto the physical environment, thereby enhancing access and understanding for both researchers and the general public.

VR stands out for its ability to immerse users in fully virtual reconstructions of archaeological artifacts and sites, enabling the exploration of reconstructed scenarios that no longer exist or are inaccessible. AR, on the other hand, adopts a complementary approach by overlaying digital information in real time onto physical artifacts, significantly enriching educational and exhibition experiences [164]. This distinction highlights how VR provides entirely virtual environments, while AR integrates digital information directly into the physical space, promoting situational learning. Additionally, AR-based interactive exhibition systems have incorporated advanced techniques such as polynomial texture mapping and projection mapping, allowing for highly realistic representations of cultural artifacts [165]. These innovations not only improve visual quality but also foster greater interaction with archaeological heritage.

Collectively, these technologies reflect a trend toward immersive and participatory experiences in which the integration of AR, VR, and interactive systems is redefining the way archaeological evidence is documented, communicated, and preserved. The future points to the combination of these tools with standardized methodologies, which will strengthen their application in research, education, and museum exhibitions.

Figure 22 presents the most prominent applications for which various extended reality technologies have been employed, based on an analysis of related texts in the scientific literature indexed in the SCOPUS database. Figure 22a shows the archaeological evidence most frequently adapted for visualization using VR.

Figure 22b presents the evidence most frequently developed for use with AR. Figure 22c illustrates the archaeological evidence that has been adapted for MR applications.

Figure 23 presents a matrix of the normalized frequencies of the use of VR, AR, and MR for the visualization and study of archaeological objects.

Figure 23 highlights a greater use of VR and AR in research related to textiles, tombs, and specific sites, while MR is primarily employed for the visualization and recognition of archaeological sites.

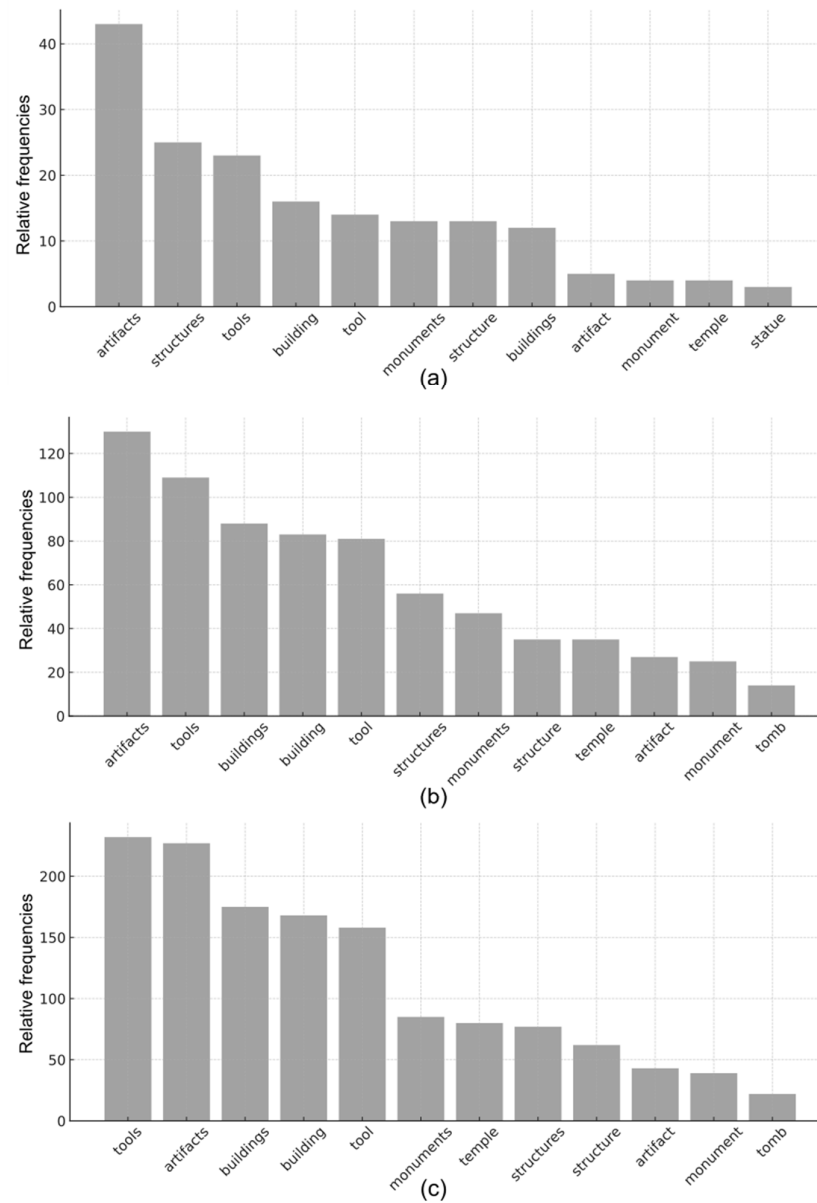


Figure 22. Relative frequency of the archaeological evidence most extensively developed for visualization using XR technologies. (a) VR; (b) AR; (c) MR.

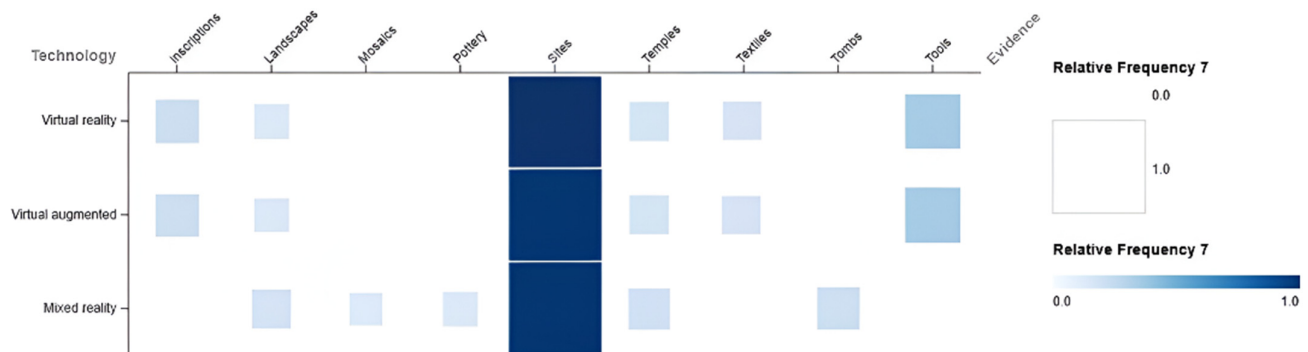


Figure 23. Normalized frequency of use of VR, AR, and MR technologies for the visualization of archaeological objects.

4.3. Impacts of Digital Technologies in the Reconstruction of Archaeological Artifacts

The development of digital technologies has significantly transformed the way archaeological evidence is documented, preserved, and studied. Figure 24 summarizes these impacts and their current scope.

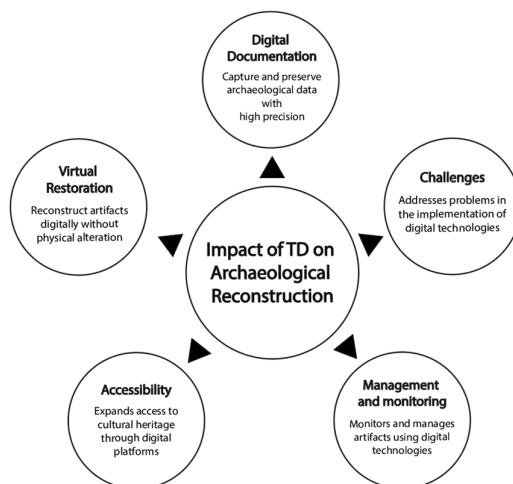


Figure 24. Impacts of Digital Technologies on the Reconstruction of Archaeological Evidence.

4.3.1. Documentation and Preservation

The use of digital technologies has enabled precise, flexible, and high-resolution archaeological documentation, ensuring fidelity in reconstruction processes [46]. These tools facilitate effective digital preservation that helps maintain the morphological, textural, and chromatic details of heritage objects [47]. They also promote traceability and the continuous updating of the knowledge generated.

Technologies such as photogrammetry, laser scanning, allow for the creation of highly accurate and detailed three-dimensional models of cultural artifacts. These models are essential for conservation and restoration, as they provide precise data on the condition of objects and enable analyses without causing damage to the originals [5,9].

4.3.2. Restoration and Reconstruction

Digital technologies have made it possible to represent historical structures and environments through virtual recreations, without the need for intermediate physical modeling, thereby facilitating both restoration and structural and archaeological analysis. A considerable improvement has also been observed in the speed of model creation and editing, as well as a significant reduction in the human effort required. This advancement facilitates the cleaning of 3D data, enabling precise and realistic reconstruction [46].

Digital restoration allows for comparisons and the formulation of reconstruction hypotheses without directly intervening in the original objects. This is particularly useful for pieces that are damaged or incomplete [6,9].

The creation of three-dimensional models facilitates the restoration of artifacts, as demonstrated in projects such as the restoration of Michelangelo's David, where digital models were used to guide the restoration process [9]. In addition, there are non-invasive and non-destructive techniques that help protect and preserve cultural heritage without physically altering the artifacts [7,166].

4.3.3. Accessibility and Dissemination

The integration of these technologies has broadened access to heritage, making immersive and remote visualization possible, even for underwater or hard-to-reach heritage sites [163]. Moreover, these tools strengthen inclusion and public participation through interactive experiences and digital museum environments, thereby enhancing cultural perception and learning [46].

Virtual and augmented reality applications allow users to interact with digital models of artifacts, improving the understanding and appreciation of cultural heritage. These technologies enable both experts and the general public to access detailed information and visualize artifacts within virtual contexts [4,167,168].

Tools such as kanON, which use machine learning algorithms to predict missing archaeological data and generate real-time renderings, have proven effective in educational settings, increasing student participation and understanding [169]. They have also allowed experts to make inferences about the geometric composition and form of archaeological objects.

4.3.4. Management and Monitoring

Digital techniques enable the precise assessment of the degradation of historical buildings and artifacts, facilitating preventive conservation and the planning of restorations [7]. The integration of technologies such as the Internet of Things (IoT) and Extended reality (XR) allows for real-time monitoring and dynamic interaction with artifacts, thereby improving the management and conservation of cultural heritage [170].

From a management perspective, digital technologies make it possible to optimize the control of heritage property as well as to develop graphical presentations for institutional dissemination presented in Table 6. These capabilities also enhance the reuse of 3D content in various educational and cultural management contexts [46].

Table 6. Impact of Digital Technologies on the Reconstruction of Archaeological Artifacts.

Impact Area	Description
Documentation and Study	Enhanced precision and detail through photogrammetry and 3D modeling. Non-invasive techniques protect artifacts.
Recreation and Restoration	Creation of 3D models for virtual reconstruction of damaged pieces. Allows for hypothesis testing without physical intervention.
Accessibility and Diffusion	Increased public access to archaeological knowledge through digital platforms. Supports education and sustainable tourism. Transdisciplinary Studies.
Challenges and Considerations	Risk of data loss due to rapid technological changes (digital dark age). Need for balance between traditional and digital methods.

4.4. Challenges and Limitations in the Implementation of Digital Technologies for the Reconstruction of Archaeological Artifacts

The implementation of digital technologies in the reconstruction of archaeological artifacts presents several limitations and challenges that must be considered. These have been summarized in Figure 25.

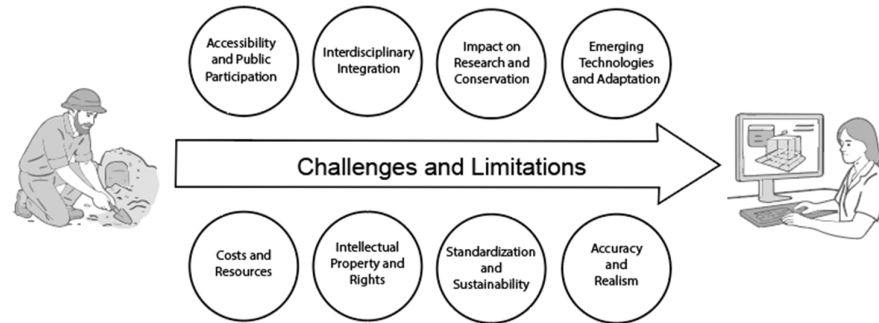


Figure 25. Implementation of Digital Technologies for the Reconstruction of Archaeological Artifacts.

Several studies have been conducted to mitigate the challenges in the implementation of the technologies outlined in Section 4.1. Table 7 presents some technological findings in this area that may contribute to improving their implementation in archaeological research.

Table 7. Challenges and Solutions in the Use of Digital Technologies for the Reconstruction of Archaeological Artifacts.

Challenges	Solutions
Lack of standardization and interoperability	Standardization of 3D digital modeling and computer vision techniques [171]
Technical complexity	Open source and affordable tools [172]
Ethical considerations	Integrated approaches combining different software [3]
Data integrity and realism	Machine learning for data enrichment [173]
Public engagement and communication	Narrative strategies for public engagement [7]
Resource intensity	Federated learning for trustworthiness [174]

4.4.1. Limitations

Costs and Resources

One of the primary obstacles identified in the implementation of digital technologies is the high cost of specialized hardware, together with operational complexity, which constitutes a significant barrier for both small institutions and independent initiatives [163]. These systems also present a high computational load that requires advanced processing equipment [46].

The digitization and reconstruction of cultural heritage can be costly, requiring significant investments in specialized hardware and software [60]. The lack of appropriate resources and skills can also limit the effective application of these technologies [18].

Intellectual Property and Rights

There are restrictions related to intellectual property and data ownership rights, which can complicate the dissemination and sharing of digital information [18]. Additionally, there are noted needs for legal and technical coordination, particularly when integrating digital by-products derived from cultural heritage [46]. This situation highlights emerging challenges related to intellectual property and usage rights of digital models.

Standardization and Sustainability

The lack of standardization in digital methods and tools can hinder interoperability and long-term data integration. The sustainability of digital projects over time is also a challenge, particularly in terms of data storage and maintenance [175].

Limited interoperability among digital platforms and data formats, together with the absence of systematic methodologies for archaeological documentation and reconstruction, hinders progress toward sustainable and replicable standards. Technical issues are also evident in three-dimensional visualization and rendering latency [46].

Accuracy and Realism

The accuracy of digital models can be an issue, particularly when the data recovered are insufficient for a complete and precise reconstruction.

Achieving a realistic representation of three-dimensional models also remains a challenge, which may affect both the interpretation and the educational value of the reconstructions [175].

Technical limitations directly affect the fidelity of digital reconstructions, as they may lead to errors in volumetric capture and in the accurate representation of textures and shadows. In particular, inadequate shadow management can obscure relevant geometric details or introduce visual distortions, thereby hindering the precise interpretation of the shape and surface of artifacts. Furthermore, reliance on historical data to compensate for these limitations may increase uncertainty and subjectivity in the final outcome, ultimately reducing the level of realism achieved [46,47].

4.4.2. Challenges

Multiple challenges are associated with the implementation of technologies for the digitization of archaeological evidence, as the adoption of digital approaches in archaeology has not always been successful, particularly in real fieldwork contexts. A recurrent example of unsuccessful application can be observed in the digitization of large-scale or highly complex sites, where the combination of indoor and outdoor scenes, together with inadequate selection of technologies and post-processing strategies, results in loss of accuracy and cumulative errors [176]. Likewise, large-scale digitization often generates an overload of information that is difficult to manage, which in many cases leads to problems related to analysis, storage, or even the partial abandonment of the generated data [177]. In addition, errors in the collection and handling of intermediate data are common; these processes are tedious and prone to failure, thereby compromising the continuity and reliability of the entire digital workflow [178]. From an organizational and infrastructural perspective, one of the main obstacles is the lack of adequate equipment, trained personnel, and sufficient financial resources, a situation commonly encountered in both field projects and archaeological museums and offices [179]. In practice, many archaeologists do not have access to hardware with the computational power required to process large volumes of digital data and typically work with basic computers intended for routine administrative tasks. This limitation is further exacerbated by issues related to standardization, long-term compatibility, and insufficient storage systems [180], as well as by an increased workload and the risk of losing interpretative insights obtained directly in situ due to an excessive reliance on digital tools.

Accessibility and Public Participation

Despite the advantages of digital technologies, their potential for communicating and engaging with archaeological knowledge has not yet been fully exploited [17]. Access to digital technologies and public participation remain limited, which may negatively affect the dissemination and impact of cultural heritage [181]. Accessibility to these technologies is constrained by the need for user-friendly interfaces and platforms that are not always designed for general or non-specialist audiences. Furthermore, skepticism regarding the authenticity of digital representations may negatively influence their acceptance by the public [46].

Interdisciplinary Integration

The effective implementation of digital technologies requires the collaboration of professionals from various disciplines, which can present organizational and logistical challenges [7]. The establishment of clear criteria for the application of these technologies in archaeological practice is essential to ensure their effectiveness and relevance [182].

Interdisciplinary collaboration remains a significant challenge, particularly with regard to the effective integration of data, methodologies, and conceptual frameworks from diverse fields such as archaeology, computer science, and design [46]. This is also reflected in the difficulty of achieving convergence between advanced computational models, such as GANs, and semantic reconstruction.

Incorporating a transdisciplinary perspective under an epistemological framework will make it possible to acquire holistic knowledge that can preserve the authenticity of archaeological studies. This authenticity will, in turn, allow future generations of researchers to access data untainted by the limitations of current technological paradigms.

Impact on Research and Conservation

Digitization can influence and alter the relationship with archaeological data, from its creation and storage to the construction of archaeological knowledge. It is crucial to reflect on how these technologies affect archaeological practice and the conservation of cultural heritage [183].

In archaeological research, the lack of complete documentation and the reliance on manual intervention to adjust models can limit the analytical scope of digital technologies [46]. Moreover, excessive use of resolution or non-contextualized visualization can create confusion in the interpretation of heritage [52].

Emerging Technologies and Adaptation

The rapid evolution of digital technologies requires constant adaptation and the continuous updating of skills and knowledge by professionals. The integration of technologies, such as virtual and augmented reality, presents opportunities but also challenges in terms of implementation and effective use [184].

The adoption of emerging technologies, such as artificial intelligence and semantic modeling, continues to pose significant challenges due to the sensitivity of results to technical parameters and the lack of infrastructure capable of supporting their large-scale application in archaeological contexts [46].

4.5. Future Directions

Technologies are significantly transforming the reconstruction of archaeological artifacts (Figure 26), offering new opportunities and innovative methodologies. Below are some of the most notable future perspectives presented in Table 8.

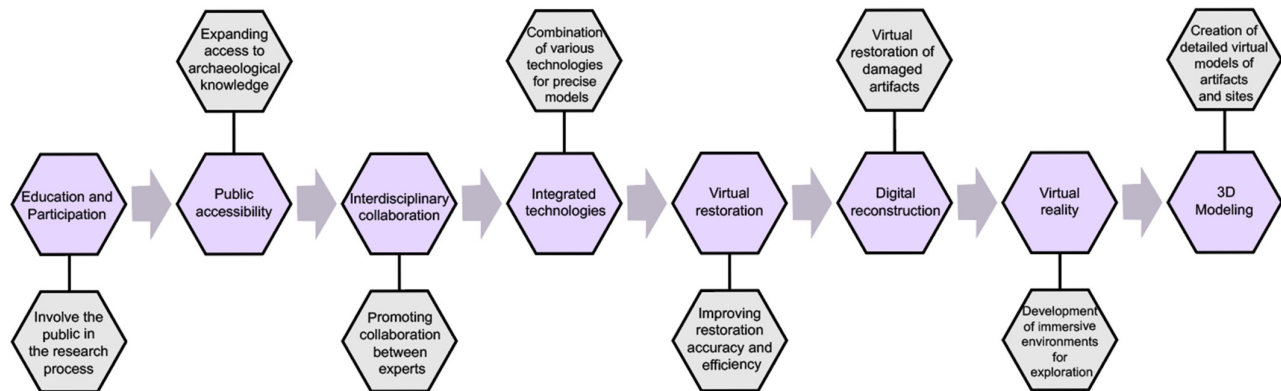


Figure 26. Future perspectives on technologies used for the reconstruction of archaeological artifacts.

Table 8. Future Perspectives on Digital Technologies for the Reconstruction of Archaeological Artifacts.

Aspect	Details
Innovative Methods and Tools	3D Modelling and VR: Creation of detailed digital reconstructions for research and public engagement. Digital Refitting: Enhanced accuracy and efficiency in reconstructing fragments using software tools.
Applications and Benefits	Preservation and Conservation: Digital documentation and restoration mitigate risks of physical handling. Public Engagement and Education: Interactive tools enhance user experience and accessibility to heritage pieces.
Challenges and Considerations	- Accuracy and Realism: Balancing realistic representations with the authenticity of underlying data. - Ethical and Political Dimensions: Navigating the complexities of cultural heritage politics and the implications of digital reconstructions.
Future Directions	- Interdisciplinary Collaboration: Integrating expertise from various fields to develop sophisticated tools with transdisciplinary vision. - Enhanced Data Integration: Using advanced techniques like CT scans and photogrammetry for improved detail and precision.

4.5.1. 3D Modeling and Virtual Reality

Current projections point toward the intensive use of 3D modeling in combination with immersive technologies such as Virtual Reality (VR) and Augmented Reality (AR). The integration of these tools into virtual museums, immersive exhibitions, and educational environments accessible via web-based platforms is emerging as a dominant trend, as it facilitates remote access and interaction with heritage in geographically dispersed or unconventional contexts [46]. This projection responds to the growing need to democratize knowledge and expand learning opportunities, particularly in communities that lack physical access to cultural assets.

The direct use of point clouds in virtual and augmented reality environments represents another key advancement, as it enables the creation of more realistic and immersive experiences. However, this trend introduces the challenge of optimizing digital workflows through simulation and specialized analytical tools aimed at the three-dimensional study of human and animal remains within their archaeological context. The increasing complexity of 3D datasets, together with the associated computational costs, can significantly limit process efficiency if not properly managed.

With regard to 3D modeling and three-dimensional digitization technologies have become an essential foundation for the documentation and preservation of cultural

heritage. Their ability to enable the virtual manipulation and recreation of objects in different historical contexts provides a significant advantage in research and dissemination projects [171,185,186]. Tools such as Agisoft Photoscan and Unity v6.0 stand out in this field for their versatility in transforming images into 3D models and developing immersive visualization environments [187,188]. Nonetheless, although these platforms allow for precise and detailed reconstructions, the learning curve and the need for advanced technical resources may constitute barriers for institutions with limited capacities.

4.5.2. Digital Reconstruction and Restoration

Digital reconstruction is projected to evolve toward a more efficient reuse of 3D models through the creation of component libraries adapted to different heritage contexts [46]. This strategy aims to optimize resources and streamline documentation, restoration, and visualization processes, particularly in large-scale projects. Complementarily, the integration of data obtained through LiDAR systems and unmanned aerial vehicles (UAVs) will enable high-precision archaeological monitoring, enhancing the ability to record and analyze temporal changes in heritage sites and objects.

An emerging trend is the exploration of immersive reconstructions that integrate not only the visual dimension but also other sensory experiences, such as soundscapes. This multisensory approach has the potential to enrich the understanding of cultural heritage, although it presents the challenge of ensuring the historical accuracy of such reconstructions [3].

With regard to digital reconstruction, techniques such as photogrammetry and laser scanning have proven to be essential tools for the virtual restoration of damaged or incomplete artifacts [189]. These methodologies offer the advantage of enabling the recreation of missing pieces with high precision and in a non-invasive manner, which is fundamental for complex projects where the physical handling of objects could compromise their integrity. However, the quality of the results depends largely on the resolution of the data captured and the availability of specialized equipment, which may limit their application in institutions with restricted resources.

On the other hand, virtual restoration, which incorporates advanced algorithms and texture synthesis techniques, is emerging as a more efficient and alternative to traditional methods [109]. This modality is particularly relevant for the conservation of fragile or non-renewable objects, as it enables their visual recovery without the risk of physical damage. Nevertheless, there remain opposing viewpoints regarding the subjective interpretation that the use of automated algorithms can introduce in the recreation of missing details, which could affect the scientific accuracy of the results.

4.5.3. Integration of Technologies and Interdisciplinary Collaboration

The future of digital reconstruction of cultural heritage is envisioned as being oriented toward the consolidation of archaeological data on collaborative platforms that facilitate interoperability between systems through the use of international standards and advanced visualization technologies [46]. This approach will not only allow for the centralization of large volumes of information but also improve its accessibility for a wide range of stakeholders and disciplines. Integration with urban Geographic Information Systems (GISs) and the adaptation of Heritage Building Information Modeling (HBIM) models are emerging as key elements for the development of applications with pedagogical, scientific, and educational purposes.

The automation of processes through intelligent interfaces will play a central role in this ecosystem by enabling more efficient data processing and analysis. However, this advancement poses the challenge of ensuring the quality of the integrated data and avoiding potential biases resulting from the use of automated algorithms in the interpretation of archaeological information.

Within the field of integrated technologies, the use of tools such as spherical photogrammetry, which enables comprehensive 360° spatial capture in complex environments, has proven to be fundamental for obtaining metrically accurate models of complex archaeological structures [190]. This technological integration not only enhances the geometric fidelity of digital models but also enables the recreation of missing elements and the generation of more comprehensive representations of the studied contexts. Nevertheless, the reliance on multiple systems and methodologies can hinder process standardization, which represents a contradiction to the need for interoperability.

On the other hand, interdisciplinary collaboration has become an essential component of digital reconstruction projects. The coordinated participation of archaeologists, architects, designers, and computer scientists ensures that the generated models are not only technically robust but also historically and scientifically relevant [191]. This collaboration, however, faces challenges associated with terminological and methodological differences between disciplines, which at times can hinder the effective integration of knowledge and tools.

4.5.4. Accessibility and Knowledge Dissemination

Future projections of digital technologies in archaeology point toward the democratization of access to knowledge, fostering broader public participation in the understanding and appreciation of cultural heritage. The expansion of mixed reality environments for educational purposes and the widespread dissemination of 3D models through open-access platforms are dominant trends that aim to reduce geographical and socioeconomic barriers to accessing heritage information [46,52,163]. These tools not only bring cultural assets closer to communities traditionally excluded from museum circuits but also promote greater interaction with heritage through innovative and engaging formats.

Efficiency in communicating heritage values and the incorporation of integrated digital narratives into museum experiences are emerging as central objectives of this approach. However, there is a counterpoint regarding the risk of oversimplifying content to make it more accessible, which could compromise the academic depth and scientific accuracy of the information conveyed.

In terms of public accessibility, the development of virtual platforms and open databases has strengthened the dissemination of archaeological knowledge [17,182,192]. This open access allows anyone to explore high-quality digital information and models, increasing social appreciation of cultural heritage. Nevertheless, the sustainability of these platforms depends on continuous investments in technological infrastructure and content update policies, which poses a challenge for their long-term maintenance.

Education and public participation are becoming key dimensions in dissemination strategies. The creation of interactive virtual environments and educational activities based on digital reconstructions not only improves the understanding of heritage but also allows the public to actively engage in the archaeological research process [17]. This participatory approach contributes to strengthening the sense of belonging to cultural heritage, although it raises the challenge of ensuring that the information is transmitted with the necessary academic rigor to avoid distortions in its interpretation.

4.5.5. Strategic Recommendations for Practical Implementation

Future improvements in the implementation of these technologies may benefit from progressive deployment approaches, starting with accessible and scalable solutions before incorporating more complex or computationally demanding ones. Technological selection should be directly aligned with project objectives (documentation, conservation, dissemination, or monitoring), avoiding oversized strategies that exceed the technical, organizational, or economic capacities of archaeological institutions [193].

From a prospective perspective, the most relevant future technical solutions are not focused solely on technological sophistication, but rather on operational feasibility and sustainability. These include the use of cloud-based processing and storage platforms to compensate for limited local hardware capacity, the partial automation of workflows through artificial intelligence for tasks such as classification, segmentation, and preliminary reconstruction, and the adoption of open standards to ensure interoperability and long-term preservation of digital data. Complementarily, it is strategic to strengthen staff training in decision-making, critical evaluation of digital results, and data management, rather than in highly specialized technical skills alone. Finally, the development of institutional guidelines and best-practice frameworks may help balance the use of digital technologies with in situ archaeological observation, promoting a more realistic, efficient, and scientifically robust integration of these tools into contemporary archaeological practice.

4.6. Artificial Intelligence in the Reconstruction of Archaeological Evidence

Artificial Intelligence (AI) and Machine Learning (ML) are revolutionizing the field of archaeology by providing innovative tools and methodologies for the reconstruction of archaeological artifacts. Figure 27 describes the most representative contributions of AI to archaeological research, specifically for the digital reconstruction of evidence.

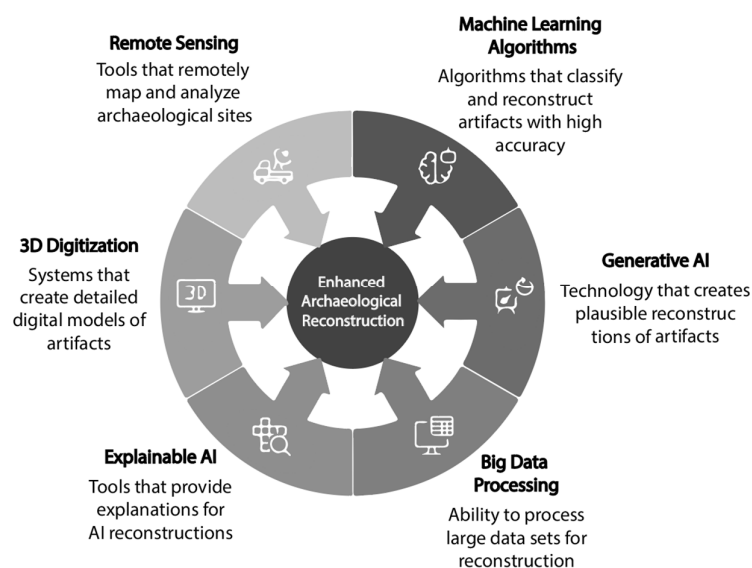


Figure 27. Contribution of AI in the Digital Reconstruction of Archaeological Evidence.

4.6.1. Artifact Classification and Reconstruction

The use of Artificial Intelligence (AI) algorithms, particularly Machine Learning (ML), has emerged as a growing trend in the classification and reconstruction of archaeological artifacts. Convolutional Neural Networks (CNNs) stand out for their high accuracy, achieving classification rates close to 88% and F1-scores of 89% in artifact classification tasks [194]. These architectures not only enable the identification of fragments but also predict how they fit together, facilitating the reconstruction of broken objects in a more efficient and systematic manner [187]. Similarly, ML is beginning to play a crucial role in the semantic segmentation of archaeological scenes, allowing for the automatic classification of structures and artifacts. This advancement accelerates complex tasks such as the detection of architectural or decorative elements, significantly reducing interpretation and analysis times [46].

In parallel, Generative Artificial Intelligence (Generative AI) technologies open a new horizon in digital reconstruction. Tools such as Generative Adversarial Networks (GANs) offer the ability to generate multiple plausible reconstructions of ancient environments and artifacts, providing innovative solutions to the inherent uncertainty of archaeological data [195]. This approach makes it possible to virtually recreate missing pieces from existing fragments or patterns, broadening the possibilities of visual restitution in cases of damage or partial loss [46]. The flexibility of generative techniques also allows for the exploration of different reconstruction scenarios, enriching dynamic interpretations and scholarly debate about the past.

Nevertheless, these technologies also raise significant counterpoints. While ML and Generative AI algorithms increase the efficiency and accuracy of classification and reconstruction processes, their intensive use may introduce biases derived from training datasets. Additionally, the ability to generate multiple plausible reconstructions could create tensions regarding the scientific validity of each interpretation, especially when material evidence is limited. The automation of key tasks in archaeological research also poses the challenge of maintaining human oversight in decision-making to prevent algorithmic models from replacing the specialist's contextual expertise.

4.6.2. 3D Data Acquisition and Processing

The exponential increase in data generated by digital archaeology has made it essential to use advanced tools capable of managing and analyzing large volumes of information. Artificial Intelligence (AI) has become a central pillar for optimizing the acquisition and processing of 3D data, enabling the extraction of patterns and relationships that might go unnoticed through traditional methods [196,197]. This capability is particularly relevant in complex contexts, such as urban archaeological sites or monumental structures, where data density and heterogeneity hinder conventional processing [46].

Big Data processing through AI not only accelerates the creation of high-fidelity 3D models but also facilitates the reconstruction of artifacts from fragmentary information [197]. However, this trend poses the challenge of ensuring that the use of algorithms does not lead to the blind automation of processes, thereby compromising human oversight and methodological rigor.

In this context, developments in Explainable AI (XAI) are gaining prominence by providing tools that allow archaeologists to use machine learning models without requiring advanced programming skills. Platforms such as IArch not only facilitate access to technology but also offer clear explanations of their predictions, contributing to the validation of results and the generation of new hypotheses regarding artifact reconstruction [110]. The incorporation of interpretability techniques will become increasingly important as AI is integrated into critical decision-making processes in restoration and conservation [46]. Nonetheless, there remain counterpoints regarding the level of trust placed in intelligent systems. While XAI increases transparency, its implementation still faces limitations when explaining complex deep learning models. This could hinder the full adoption of these tools in disciplines such as archaeology, where decision-making traceability is essential for scientific validity.

4.6.3. Automated Analysis and Interpretation

Advanced 2D and 3D digitization has become a central component in the generation of detailed digital models of archaeological artifacts, which are essential for their reconstruction and virtual analysis [187,188]. Data acquisition systems, combined with signal processing techniques, enable the creation of precise representations that facilitate morphological and structural studies. In this context, Artificial Intelligence (AI) plays a key role by automating processes such as segmentation, annotation, and semantic labeling of

three-dimensional models [46]. This automation significantly reduces the need for manual intervention, increasing workflow efficiency and allowing large volumes of information to be managed with less time and human resource investment.

AI-powered remote sensing and LiDAR tools represent another expanding trend. These technologies make it possible to map and analyze archaeological sites with unprecedented precision, facilitating the identification and reconstruction of the spatial layout of structures and archaeological contexts [194,198]. AI's ability to process and segment data collected by remote sensors is particularly valuable for detecting buried or degraded structures, often invisible to the human eye [46]. This approach has proven crucial for improving the understanding of the context in which artifacts are found, providing key information for their scientific interpretation.

However, these innovations present significant counterpoints. While the automation of analytical tasks accelerates processes and reduces errors derived from manual work, it also entails the risk of excessive dependence on algorithms that may incorporate biases in data interpretation. Furthermore, the accuracy of the results depends on the quality of the data captured, which could limit the applicability of these systems in contexts with adverse conservation conditions or in sites with limited remote sensing coverage.

Based on the information from the previous sections, Table 9 summarizes and describes the contributions of AI across multiple aspects, highlighting the technologies employed to enhance the reconstruction of digital evidence.

Table 9. Emerging Technologies Used for the Reconstruction of Archaeological Artifacts.

Aspect	Description
Detection and Classification	Advanced Algorithms: Use of sophisticated algorithms like Convolutional Neural Networks (CNN) for artifact classification. Ceramic Recognition: Tools like ArchAIDE for recognizing archaeological ceramics based on shapes and decorations.
Reconstruction of Fragmented Objects	3D Modeling: AI enables reconstruction of fragmented objects using 2D and 3D data acquisition techniques. Simulation Generation: AI generative models create simulations for interpreting archaeological data.
Data Analysis and Validation	Explainable AI: Tools like IArch allow archaeologists to analyze data without programming skills, validating existing hypotheses. False Positive Reduction: Techniques like LiDAR help reduce false positives in site identification.
Preservation and Documentation	3D Digitization: Creation of digital twins for detailed preservation and documentation of artifacts. Data Availability: Ensures archaeological data is accessible for future research.

4.6.4. Challenges and Considerations

The implementation of Artificial Intelligence (AI) in archaeology introduces a set of challenges that have a direct impact on scientific validity, result reliability, and the historical interpretation of cultural heritage. Beyond technical aspects, one of the most significant impacts concerns ethical implications, particularly with regard to data protection and the fidelity of digital reconstructions. Algorithmic biases arising from incomplete or non-representative training datasets can substantially affect the accuracy, objectivity, and fairness of the results obtained [194,199]. Although this impact is rarely addressed explicitly in existing studies, it has the potential to compromise both the scientific validity of analyses and the historical interpretation of heritage assets, and therefore should be considered a priority in future developments.

The impact of algorithmic bias becomes even more pronounced when automated models are applied in contexts where archaeological evidence is fragmentary. While AI can accelerate classification and reconstruction processes, the absence of robust validation mechanisms may lead to the incorporation of erroneous or subjective inferences, directly affecting the reliability of reconstructions and the strength of archaeological conclusions. This situation highlights the need to balance the benefits of automation with expert human oversight as a key factor in preserving scientific rigor and minimizing interpretative errors.

Furthermore, insufficient interdisciplinary collaboration has a significant impact on the applicability, sustainability, and overall quality of AI-based solutions in archaeology. The development of scientifically robust and practically useful tools requires the integration of expertise from archaeologists, engineers, computer scientists, designers, and ethics specialists [197]. Several studies already demonstrate that this interdisciplinary approach can tangibly enhance the technical and conceptual robustness of heritage projects by incorporating computational models grounded in well-defined methodological frameworks [46]. Nevertheless, the positive impact of these initiatives could be further strengthened by advancing toward a transdisciplinary perspective, in which shared conceptual frameworks transcend traditional disciplinary boundaries, enabling more comprehensive solutions that are better adapted to the complexity of cultural heritage.

4.6.5. Case Studies and Applications

A notable example is the reconstruction of sites and artifacts, which includes projects such as the recreation of a necropolis in Crete, a Gallo-Roman sanctuary in Belgium, and the partial reconstruction of a fragmented stone sculpture in Brussels [187]. These experiences demonstrate how AI can improve the prediction of original forms and enhance the visual realism of digital models [46]. Furthermore, its integration into simulations of movement, structural behavior, and architectural evolution allows for the dynamic exploration of construction processes and the historical development of heritage sites.

In parallel, applications aimed at more specialized tasks, such as pottery recognition, have been developed. The ArchAIDE project is a paradigmatic example, having created AI-based tools for the automatic recognition and classification of ceramic forms, significantly accelerating analytical processes and improving their accuracy [200]. These techniques, which combine computer vision and machine learning algorithms, are not only applicable to the archaeological study of material culture but can also be adapted to broader museological and research contexts [46].

These cases illustrate a clear trend toward the diversification of AI applications in archaeology, ranging from large-scale virtual reconstruction to the detailed analysis of artifacts. However, counterpoints remain, particularly concerning the dependence on high-quality data to ensure the reliability of results. Likewise, the emphasis on automation presents the challenge of maintaining expert oversight in the final interpretation of findings.

5. Discussion

The implementation of digital technologies in the reconstruction of archaeological artifacts has not only transformed the technical processes of documentation and restoration but has also introduced a series of conceptual, social, and methodological challenges that must be addressed from a critical and interdisciplinary perspective. This section discusses four fundamental axes identified throughout the analysis: interdisciplinary collaboration, technological inequalities, digital authenticity, and the participatory potential of immersive technologies.

5.1. Interdisciplinarity as a Driver and Challenge of Digital Reconstruction

One of the main findings of this research is the growing need for collaboration among various disciplines—archaeology, anthropology, geomatics, geodesy, industrial design, computer science, art history, and conservation—to achieve robust and culturally meaningful digital reconstructions. This integration not only enables greater technical accuracy but also allows heritage to be approached from narrative, educational, and sensory perspectives [46,182]. However, the effective implementation of such collaborations faces organizational, methodological, and epistemic challenges. The development of methodological frameworks is necessary to ensure coherence between archaeological data and digital visualizations, in which industrial design can play a pivotal role through user-centered heritage methodologies.

5.2. Access and Infrastructure Gaps as Conditions for Use

Despite technological advances, structural limitations regarding access to specialized hardware, technical knowledge, and advanced computational resources persist, particularly in Latin American contexts [18,163]. The implementation of technologies such as 3D scanning, parametric modeling, or artificial intelligence often depends on institutions with significant technical and financial capacity. This poses the risk of generating new heritage inequalities, where certain cultural assets may not be adequately digitized or disseminated. It is therefore crucial to promote low-cost solutions, such as the use of open-source software, photogrammetry with conventional cameras, or the creation of open collaborative platforms for the modeling and documentation of cultural heritage.

5.3. Authenticity, Fidelity, and Paradata in the Digital Era

Digital reconstruction, especially when involving technologies such as generative artificial intelligence or deep learning, raises questions about the authenticity of virtual artifacts. The accuracy of 3D models may be compromised by the lack of complete archaeological data or by interpretations that are not always made explicit [46,52]. In this regard, the discussion surrounding the use of paradata—information that documents the process and decisions behind a reconstruction—becomes essential to ensure scientific transparency and academic reproducibility. From a narrative design perspective, there is also the possibility of visually integrating these processes into the interfaces themselves, allowing users to explore not only the final result but also the technical and conceptual history of the reconstructed object.

5.4. Immersive, Educational, and Participatory Potential of Digital Technologies

Immersive technologies such as Virtual Reality (VR) and Augmented Reality (AR) are expanding the horizons of access, participation, and communication of archaeological heritage. These tools not only facilitate the remote and interactive visualization of artifacts but also foster meaningful experiences in educational and museum environments [52]. Initiatives such as the implementation of semantic visualization systems, game engines for virtual tours, and interactive environments for artifact restoration encourage a closer and more emotional relationship with heritage, even among non-specialist audiences. This suggests that digital reconstruction should not be viewed solely as a technical tool but as a cultural practice with enormous potential to democratize access to archaeological knowledge and revalue heritage identities through visual and sensory narratives.

6. Conclusions

The implementation of technologies such as photogrammetry, three-dimensional (3D) scanning, and virtual reality has significantly transformed traditional approaches to

archaeological documentation, preservation, and restoration. These tools enable highly accurate and non-invasive virtual reconstructions, supporting the conservation of fragile artifacts and the creation of digital replicas for research, dissemination, and educational purposes.

Despite these technological advances, substantial challenges remain, particularly with respect to infrastructure limitations, implementation costs, and the lack of interoperable standards. Moreover, tensions persist between traditional archaeological practices and digital methodologies, alongside risks related to information loss—often referred to as the ‘Digital Dark Age’—and concerns regarding the authenticity and transparency of reconstructions. Addressing these challenges requires sustained interdisciplinary collaboration among archaeologists, designers, engineers, and other specialists to develop sustainable, interoperable, and ethically responsible solutions.

Looking ahead, future perspectives emphasize the expanded integration of immersive technologies, artificial intelligence, and open collaborative platforms aimed at democratizing access to cultural heritage and enhancing user engagement. Equally important is the systematic incorporation of metadata, including paradata, reconstruction traceability, and the development of interactive educational environments that promote the social appropriation and critical understanding of archaeological knowledge.

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Abbreviations

The following abbreviations are used in this manuscript:

GIS	Geographic information system
SDG	Sustainable development goal
RQ	Research questions
SfM	Structure from motion
VR	Virtual reality
AR	Augmented reality
UAVs	Unmanned aerial vehicles
HMD	Head-mounted display

Appendix A

Check list PRISMA® for Scoping Review (Prisma-ScR).

Table A1. Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Review (PRISMA-ScR) Checklist.

Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR) Checklist			
Section	Item	PRISMA-ScR Checklist Item	Reported on Page #
TITLE			
Title	1	Identify the report as a scoping review.	1
ABSTRACT			
Structured summary	2	Provide a structured summary that includes (as applicable): background, objectives, eligibility criteria, sources of evidence, charting methods, results, and conclusions that relate to the review questions and objectives.	1
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known. Explain why the review questions/objectives lend themselves to a scoping review approach.	1, 2, 3, 4
Objectives	4	Provide an explicit statement of the questions and objectives being addressed with reference to their key elements (e.g., population or participants, concepts, and context) or other relevant key elements used to conceptualize the review questions and/or objectives.	4
METHODS			
Protocol and registration	5	Indicate whether a review protocol exists; state if and where it can be accessed (e.g., a Web address); and if available, provide registration information, including the registration number.	3, 4
Eligibility criteria	6	Specify characteristics of the sources of evidence used as eligibility criteria (e.g., years considered, language, and publication status), and provide a rationale.	4.5
Information sources *	7	Describe all information sources in the search (e.g., databases with dates of coverage and contact with authors to identify additional sources), as well as the date the most recent search was executed.	5
Search	8	Present the full electronic search strategy for at least 1 database, including any limits used, such that it could be repeated.	5
Selection of sources of evidence †	9	State the process for selecting sources of evidence (i.e., screening and eligibility) included in the scoping review.	5
Data charting process ‡	10	Describe the methods of charting data from the included sources of evidence (e.g., calibrated forms or forms that have been tested by the team before their use, and whether data charting was done independently or in duplicate) and any processes for obtaining and confirming data from investigators.	4
Data items	11	List and define all variables for which data were sought and any assumptions and simplifications made.	4
Critical appraisal of individual sources of evidence §	12	If done, provide a rationale for conducting a critical appraisal of included sources of evidence; describe the methods used and how this information was used in any data synthesis (if appropriate).	4
Synthesis of results	13	Describe the methods of handling and summarizing the data that were charted.	12
RESULTS			

Selection of sources of evidence	14	Give numbers of sources of evidence screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally using a flow diagram.	5–11
Characteristics of sources of evidence	15	For each source of evidence, present characteristics for which data were charted and provide the citations.	-
Critical appraisal within sources of evidence	16	If done, present data on critical appraisal of included sources of evidence (see item 12).	-
Results of individual sources of evidence	17	For each included source of evidence, present the relevant data that were charted that relate to the review questions and objectives.	-
Synthesis of results	18	Summarize and/or present the charting results as they relate to the review questions and objectives.	12, 13
DISCUSSION			
Summary of evidence	19	Summarize the main results (including an overview of concepts, themes, and types of evidence available), link to the review questions and objectives, and consider the relevance to key groups.	12, 13
Limitations	20	Discuss the limitations of the scoping review process.	13
Conclusions	21	Provide a general interpretation of the results with respect to the review questions and objectives, as well as potential implications and/or next steps.	37
FUNDING			
Funding	22	Describe sources of funding for the included sources of evidence, as well as sources of funding for the scoping review. Describe the role of the funders of the scoping review.	38

PRISMA-ScR = Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews. * Where sources of evidence (see second footnote) are compiled from, such as bibliographic databases, social media platforms, and Web sites. † A more inclusive/heterogeneous term used to account for the different types of evidence or data sources (e.g., quantitative and/or qualitative research, expert opinion, and policy documents) that may be eligible in a scoping review as opposed to only studies. This is not to be confused with information sources (see first footnote). ‡ The frameworks by Arksey and O'Malley (6) and Levac and colleagues (7) and the JBI guidance (4, 5) refer to the process of data extraction in a scoping review as data charting. § The process of systematically examining research evidence to assess its validity, results, and relevance before using it to inform a decision. This term is used for items 12 and 19 instead of “risk of bias” (which is more applicable to systematic reviews of interventions) to include and acknowledge the various sources of evidence that may be used in a scoping review (e.g., quantitative and/or qualitative research, expert opinion, and policy document).

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