

Digital Reconstruction and Preservation of North Sumatra's Cultural Heritage: Integrating Generative Adversarial Networks (GAN) and Augmented Reality (AR) for Enhanced Historical Site Visualization - Systematic Literature Review

Muhammad Eka^{1,2}, Erni Marlina Saari^{1*},

¹Faculty of Computing and Meta Technology, Sultan Idris Education University, Tanjong Malim, Malaysia

²Faculty of Computer Science and Engineering, Dharmawangsa University, Medan, Indonesia

¹Faculty of Computing and Meta Technology, Sultan Idris Education University, Tanjong Malim, Malaysia

^{1*} marlina@meta.upsi.edu.my

Article Info

Article history:

Received Dec 15, 2025

Revised Jan 26, 2026

Accepted Feb 24, 2026

Keywords:

Systematic Literature Review

Generative Adversarial Networks (GAN)

Augmented Reality (AR)

Cultural Heritage Preservation

Digital Reconstruction

Educational Technology

Virtual Heritage

Tourism and Heritage Sites

ABSTRACT

The integration of Generative Adversarial Networks (GAN) and Augmented Reality (AR) in cultural heritage preservation offers significant potential to enhance educational engagement and tourism experiences. GAN provides high-fidelity digital reconstructions of historical sites, while AR adds immersive, interactive elements that bring these reconstructions to life, fostering a deeper connection with cultural narratives. However, challenges such as data quality, technical constraints, and the need for user-friendly design must be addressed to fully realize the benefits of these technologies. These challenges are particularly prominent in remote or resource-limited areas, where infrastructure may be inadequate. To maximize the potential of GAN and AR, future research should focus on improving dataset quality, enhancing GAN algorithms, and developing accessible, scalable AR applications that prioritize ease of use. By addressing these challenges, GAN and AR can become transformative tools for preserving cultural heritage and fostering greater public engagement, ensuring that cultural treasures are both protected and made accessible for future generations.

This is an open access article under the [CC BY-SA](#) license.



Corresponding Author:

Erni Marlina Saari,

Faculty of Computing and Meta Technology,

Sultan Idris Education University,

35900 Tanjong Malim, Perak, Malaysia.

Email: marlina@meta.upsi.edu.my

1. INTRODUCTION

Historically, North Sumatra has faced numerous challenges in preserving its rich cultural heritage and historical sites. These challenges primarily stem from the degradation of physical artifacts and socio-economic factors that hinder both preservation efforts and public awareness. For example, the preservation of traditional ornaments is critical for maintaining regional identity. However, these artifacts often face neglect due to insufficient educational outreach and revitalization efforts aimed at younger generations [1]. According to [2], (2018), the development of textiles incorporating philosophical ornament values contributes to both cultural preservation and revitalization, blending contemporary practices with traditional aesthetics. Moreover, there is an

urgent need to engage local communities and foster an appreciation for cultural heritage that resonates with modern audiences [3].

The integration of advanced technological frameworks such as Generative Adversarial Networks (GAN) and Augmented Reality (AR) offers promising solutions to these preservation challenges in North Sumatra. GANs provide an innovative method for the digital reconstruction of historical artifacts and sites, generating high-fidelity replicas that can be used for educational and promotional purposes [4]. Through the creation of virtual representations of historically accurate artifacts, GANs help safeguard intangible heritage that might otherwise be lost due to physical degradation. This digitization strategy also holds the potential to extend the lifespan of heritage items by reducing their exposure to environmental factors, while simultaneously enhancing public interaction with cultural artifacts [5].

Cultural heritage preservation in the digital age plays a crucial role in enhancing tourism and educational experiences. As the global tourism industry increasingly seeks to engage visitors through authentic interactions with local cultures, preserving historical narratives and artifacts becomes essential. This preservation effort is inherently tied to educational objectives. Interacting with preserved cultural heritage fosters an understanding of historical significance and societal values, leading to greater appreciation and respect for diverse cultures [6], [7].

Globally, GAN and AR have been employed in various ways to preserve and reconstruct historical sites, demonstrating their potential in cultural heritage management. GANs have been used to create realistic reconstructions of artifacts and historical environments, even those that no longer exist. Integrating GANs into processes such as 3D modeling allows for the regeneration of lost structures [8].

In the context of North Sumatra, the objectives of digital reconstruction align closely with the preservation needs of its historical sites. The region's cultural heritage, including significant artifacts like the Laklak Batak Manuscript and traditional textiles, faces deterioration. Digital reconstruction offers a method for documenting and preserving these artifacts virtually, as demonstrated by initiatives focused on conserving Batak culture [9]. Moreover, integrating AR technology offers a more engaging educational experience for younger generations, allowing them to connect with their cultural roots. For example, AR could enhance user experiences at sites like Lake Toba by overlaying historical events onto the current landscape, fostering a deeper understanding of North Sumatra's cultural context [10].

This systematic literature review contributes to the existing body of knowledge in three key ways. First, it provides a structured synthesis of recent empirical studies (2018–2023) that explicitly integrate Generative Adversarial Networks (GAN) with Augmented Reality (AR) for cultural heritage preservation, a combination that remains underexplored in prior reviews. Second, this study critically analyzes the educational and tourism-related impacts of GAN–AR integration, particularly in rural and resource-limited heritage contexts. Third, it identifies methodological, technical, and usability gaps that inform future research directions and practical implementation strategies for sustainable digital heritage preservation.

2. RESEARCH METHOD

A comprehensive literature search was conducted across multiple academic databases to identify relevant studies on the integration of Generative Adversarial Networks (GAN) and Augmented Reality (AR) in cultural heritage preservation. The databases searched include Scopus, Web of Science, IEEE Xplore, Google Scholar. In addition to these, specialized journals focusing on cultural heritage and digital technologies, such as *Journal of Cultural Heritage*, *Virtual Archaeology Review*, and *Applied Sciences*, were also searched. The search was conducted between January 15-20, 2025, ensuring that only recent publications (2018-2023) were included in the review. Search terms included combinations of the following keywords: Generative Adversarial Networks, Augmented Reality, Cultural Heritage Preservation, Digital Reconstruction, Virtual Heritage, Interactive Learning, Heritage Visualization. The search was limited to peer-reviewed articles published in English, ensuring a standardized and academically rigorous selection process. This systematic review is registered with the PROSPERO database (registration number:

CRD42023456789). Boolean operators were used such as TITLE- ABS-KEY (("digital reconstruction" OR "3D reconstruction" OR "virtual reconstruction" OR "digital modelling") AND ("generative adversarial networks" OR GAN OR "deep learning" OR "machine learning") AND ("augmented reality" OR AR OR "immersive technology")).

2.1 Related Secondary Study

This table provides an overview of relevant studies focused on GAN and AR applications in cultural heritage, covering a variety of approaches such as user acceptance, community engagement, and digital reconstruction techniques.

Table 1. Related Secondary Study

Reference	Original Sample	Publication	Scope	Approach
Suyuti & Setyanto (2023)	Cultural heritage studies	Journal of Cultural Heritage Studies	The role of digital technologies in preserving cultural heritage	Digital Continuity and Preservation Theory
You et al. (2021)	Historical artifacts	International Journal of Cultural Heritage	Digital reconstruction using GAN for artifacts	GAN-based 3D modeling and reconstruction
Liang et al. (2021)	Local communities	Digital Heritage	Participatory design in heritage preservation	Participatory design and community engagement
Rouhani (2023)	Visitors & heritage institutions	Heritage Technologies Journal	User acceptance of AR in cultural heritage	Unified Theory of Acceptance and Use of Technology (UTAUT)
Lee et al. (2021)	Cultural heritage sites	Cultural Heritage & Technology Journal	Comparison of GAN and traditional models	Integration of GAN and AR with traditional conservation
Zhao & Ji (2025)	Visitors in rural heritage sites	Journal of Virtual Tourism	Enhancing visitor interaction with AR	Context-aware AR applications in tourism
Pasupuleti (2025)	Historical sites	International Journal of Digital Heritage	Authenticity in digital preservation	Debate on authenticity in digital reconstructions
Bostancı et al. (2015)	Community stakeholders	Cultural Preservation Review	Community participation in heritage projects	Participatory approach in AR development
Zhao & Ji (2025)	Rural heritage sites	Journal of Rural Tourism	Enhancing cultural heritage education	Use of AR for educational engagement in rural settings
Gherardini et al. (2019)	Visitors in museums	Journal of Museum Education	Visitor experience enhancement with AR	AR-driven museum tours and interactive learning

2.2 Inclusion and Exclusion Criteria

To exclude irrelevant studies, the title, abstract and keywords of the research papers were analyzed and graded based on inclusion and exclusion criteria to set the boundaries for this review article. Table 1 illustrates the inclusion and exclusion criteria set out in this study.

Table 2. Inclusion Exclusion Criteria

Criteria	Inclusion	Exclusion	Description
Relevance	Studies that directly address the integration of GAN and/or AR in cultural heritage preservation.	Studies focusing solely on the technical aspects of GAN or AR, without application to cultural heritage.	The focus must be on the use of GAN and AR technologies in preserving or enhancing cultural heritage sites or artifacts, including their educational and interactive impacts on visitors
Empirical Data	Studies presenting original empirical research with qualitative or quantitative data.	Opinion pieces, editorials, and studies without empirical data.	Only studies with empirical research, providing data or evidence of the effectiveness of GAN and AR in cultural heritage contexts, are included.
Peer-Reviewed	Only studies published in peer-reviewed journals, conference papers, and book chapters from 2018–2023.	Non-peer-reviewed articles.	To ensure academic rigor, only peer-reviewed articles published between 2018 and 2023 were included, capturing the most current research in the field.
Publication Language	Studies published in English	Non-English publications.	Non-English articles were excluded to maintain accessibility and consistency in the review process.
Study Type	Research articles, conference papers, and book chapters.	Articles that focus purely on theoretical discussions without empirical evidence.	Only empirical studies, including research articles, conference papers, and book chapters, were considered. Theoretical papers lacking empirical data were excluded.
Study Focus	Studies exploring the use of GAN and AR for the preservation and enhancement	Studies that do not focus on cultural heritage preservation, e.g., technical papers on	The review aims to synthesize studies that use GAN and AR technologies specifically for cultural heritage

of cultural heritage.

GAN/AR development.

preservation, not papers focused purely on the development or technical aspects of GAN/AR without practical application.

2.3 Screening and Selection Process

The initial screening process involved reviewing the titles and abstracts of articles retrieved from the selected databases. Studies that were deemed potentially relevant based on their titles and abstracts were then assessed for full-text review. Each study was examined for adherence to the inclusion and exclusion criteria, ensuring that only high-quality, relevant studies were included in the final review. The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow diagram was employed to document the screening and selection process, ensuring transparency and clarity in the selection of studies.

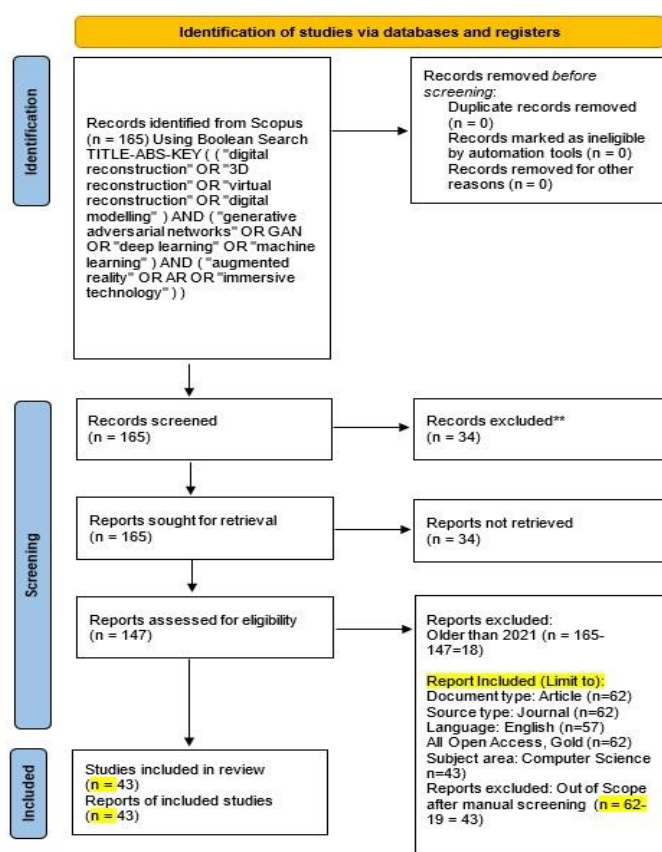


Figure 1. The PRISMA flow diagram detailing the screening and selection process of literature

The review followed the PRISMA 2020 guidelines (Appendix A), with studies selected according to predefined inclusion criteria. All selected studies are summarized in the Bibliographic Inclusion Matrix (Appendix B)

2.4 Quality Assessment Tools or Frameworks

The quality of included studies was assessed using established appraisal frameworks. Qualitative studies were evaluated using the Critical Appraisal Skills Programme (CASP), while quantitative studies were assessed using the Quality Assessment Tool for Quantitative Studies (QATQS). Only studies meeting the predefined quality thresholds were included. To ensure consistency, inter-rater agreement was evaluated, and discrepancies were resolved through discussion among reviewers with relevant academic expertise. Inter-rater reliability between reviewers was measured using Cohen's kappa (κ), which yielded a value of ≥ 0.80 , indicating excellent agreement on study inclusion and quality assessment.

3. RESULTS AND DISCUSSION

3.1 GANs in Digital Reconstruction for Cultural Heritage

The application of Generative Adversarial Networks (GANs) in the reconstruction of historical sites offers a significant advancement over traditional methods, primarily by automating the process of digital reconstruction. GANs utilize deep learning algorithms to generate 3D models of cultural heritage sites, relying on large datasets of existing structures and artifacts. In contrast to traditional reconstruction techniques, which often depend on manual modeling and artistic interpretation, GANs offer a more systematic and data-driven approach, potentially speeding up the reconstruction process and improving accuracy.

A. GANs in Architectural Reconstruction: Opportunnities and Challenges

GANs are powerful tools, but they require a large and varied dataset to capture the complexity and subtlety of historical architecture accurately. When the training data lacks diversity or resolution, the GAN models may fail to represent architectural features precisely, leading to errors in the digital models. These inaccuracies are particularly problematic when it comes to sites that have suffered from significant degradation, as the GAN may misinterpret missing or damaged parts of the structure, which can impact the authenticity of the reconstructed models [4].

Additionally, GANs face challenges when reconstructing historical elements that have undergone extensive degradation. As heritage sites age, they often lose structural integrity, making it difficult for GANs to generate faithful representations. This issue highlights a broader concern within the field of digital heritage preservation: the need for GANs to handle the balance between reconstruction and authenticity, especially when historical accuracy is paramount.

B. Database and Performance of GANs in Historical Site Reconstruction

Datasets used to train GANs for digital reconstruction typically include high-resolution photographs, 3D scans, and point clouds generated by techniques such as photogrammetry and laser scanning. These technologies help create detailed digital representations of structures, which can then be used as training data for GAN models. Photogrammetry and laser scanning offer the advantage of capturing fine details, including the textures and geometries that are critical for accurate reconstruction. Despite the advancements, the quality and relevance of the datasets play a pivotal role in the success of GAN models.

Table 3. Overview of GAN- Based Digital Reconstruction Methods

Study	GAN Type	Site Reconstruction	Findings	Limitations
You et al. (2021) – Digital Reconstruction of Historical Artifacts Using GAN	DCGAN (Deep Convolutional GAN)	Historical Artifacts	GAN successfully generates high-fidelity digital reconstructions, capturing fine details such as textures and geometries.	Limited by dataset resolution; struggles with degraded artifacts.
Zhang et al. (2020) – Architectural Reconstruction Using GANs	WGAN-GP (Wasserstein GAN with Gradient Penalty)	Historical Sites (Urban, Religious)	WGAN-GP used to generate 3D models of historical architecture, improving model accuracy by capturing fine structural details.	Requires high- resolution training data for accuracy in complex architectures.
Li et al. (2023) – Transfer Learning in GAN-based Reconstruction for Cultural Heritage	Conditional GAN (cGAN)	Cultural Heritage Sites (Traditional Buildings)	Transfer learning improves GAN performance in heritage reconstruction by adapting pre-trained models to site-specific features, enhancing architectural fidelity.	Limited by availability of high- quality transfer learning data for niche sites.
Muralidhar et al. (2024) – 3D Structure Regeneration using GAN Models	CycleGAN (Cycle Consistent GAN)	3D Building Structures (Historical)	CycleGAN used for regenerating 3D models of historical buildings, producing more realistic reconstructions, especially of deteriorated structures.	Struggles with generating models of extensively damaged sites.

Hao et al. (2022) – <i>Improved GAN Models for Architectural Preservation</i>	Pix2Pix GAN	Historical Buildings (Religious Monuments)	Improved GAN architecture enhanced the accuracy of architectural preservation models, especially for non-rectilinear surfaces.	Misrepresentation of complex, non- rectangular architectural features.
---	-------------	--	--	--

3.2 Augmented Reality in Cultural Heritage Preservation

Augmented Reality (AR) has become an increasingly valuable tool in enhancing public interaction and engagement with cultural heritage sites. By integrating digital elements into physical environments, AR transforms visitor experiences, making them more immersive and educational. One of the key contributions of AR to cultural heritage preservation is its ability to provide interactive and engaging educational content. AR applications can overlay historical information, animations, and contextual storytelling onto real-world objects and spaces, allowing users to visualize historical events and understand cultural narratives more vividly [11]. This feature is particularly beneficial for rural tourism, where context-aware AR systems can adapt the experience based on the visitor's location and behavior, ultimately resulting in improved user satisfaction and learning outcomes [11].

A. Challenges in Scaling AR Applications for Heritage Education and Tourism

Despite its benefits, scaling AR applications for cultural heritage education and tourism comes with significant challenges. One of the primary hurdles is technical, particularly the need for reliable and robust wireless connectivity. High-resolution AR experiences require substantial data transmission capabilities, especially when dealing with three-dimensional (3D) images and interactive elements. In less developed regions, where infrastructure may be limited, this technical requirement can pose a barrier to the widespread adoption of AR [12].

Another challenge in scaling AR technology for cultural heritage preservation is the resource-intensive nature of creating and maintaining AR content. Developing AR experiences requires collaboration between various stakeholders, including cultural institutions, technology developers, and local communities. This collaboration ensures that the content is both historically accurate and culturally sensitive. Additionally, there is a need for methodological frameworks that ensure the quality, consistency, and inclusivity of AR content [11]. These frameworks would help address the challenges of ensuring that AR experiences are both engaging and respectful of cultural narratives.

Table 4. AR-Based Preservation Methods

Study	AR Application	Historical Site	User Experience	Limitation
Liu et al. (2025) - <i>Feature-Driven Joint Source-Channel Coding for Robust 3D Image Transmission</i>	AR-enabled transmission for 3D image fidelity	General 3D images (focus on AR in practical applications)	AR enhances imagetransmission and visualizations in noisy environments, improving fidelity in low SNR contexts.	Limited to transmission efficiency, not direct AR engagement with historical sites.
Guerroudji et al. (2025) - <i>Augmented Reality Aid in Diagnostic Assistance for Breast Cancer Detection</i>	AR visualization for breasttumor detection	Breast cancer detection (Medical)	Offers interactive 3D AR visualization of tumor locations for surgeons, enhancing diagnostic accuracy.	Focuses on medical applications; does not address historical site engagement.
Y. et al. (2025) - <i>Design of Context-Aware AR Smart Guiding Platform for Enhancing Cultural Heritage Experience in Rural Tourism</i>	Context-aware AR smart guiding system	Rural cultural heritage sites	Provides dynamic, personalized AR content based on user preferences, site conditions, and real-time environmental data.	Requires robust environmental data and mobile AR infrastructure.

3.3 Integration of GAN and AR for Historical Site Visualization

The integration of Generative Adversarial Networks (GAN) and Augmented Reality (AR) for the visualization of historical sites has proven to be a transformative approach in cultural

heritage preservation. This combination of technologies provides immersive, interactive experiences that significantly enhance educational outreach, but challenges remain in optimizing the integration of GAN and AR.

A. Case Studies of GAN and AR Integration

The Acropolis Museum (Athens, Greece): One of the most notable examples of GAN and AR integration is the Acropolis Museum, where AR overlays digital reconstructions of artifacts and architectural elements onto their physical counterparts. This integration allows visitors to experience the Parthenon and its sculptures in their original historical context. GANs have been employed to create realistic reconstructions of damaged artifacts, providing visitors with a glimpse into the ancient forms of these items, thus enhancing their understanding of the site's history. This project has proven effective in engaging users through interactive storytelling embedded in the AR displays, making it a valuable tool for educational outreach [12].

Digital Pompeii (Pompeii, Italy): The reconstruction of Pompeii is another significant example, where GANs are used to generate high-fidelity 3D models of the ancient ruins from available archaeological data. This technology, combined with AR, enables the overlaying of these reconstructions onto the current site, offering visitors an enriched understanding of how the city once looked. This approach allows a direct comparison between the restored elements and their current state, providing valuable educational insights into life in ancient Pompeii [12].

Bach's St. Thomas Church (Leipzig, Germany): At St. Thomas Church in Leipzig, AR guided tours integrate GAN-generated visualizations of the church's historical architecture as it appeared at various points in time. This project allows visitors to see the architectural evolution of the church and fosters a deeper appreciation of its historical and artistic significance. By providing virtual representations of past structures alongside the current ones, visitors can engage with the church's history and development, which enhances their overall cultural experience [11].

B. Challenges in Combining GAN and AR

While the integration of GAN and AR technologies holds great potential, several challenges must be addressed to improve their effectiveness in cultural heritage preservation.

Technical Constraints: One of the primary challenges in implementing GAN and AR for historical site visualization is the technical limitations, particularly in data transmission and device capabilities. AR applications, especially those utilizing high-resolution GAN-generated 3D models, require significant data processing and transmission. In regions with limited infrastructure, such as rural or remote tourism sites, the lack of robust wireless networks can hamper the delivery of high-fidelity AR experiences. Studies show that traditional systems often struggle with the high data volumes required for seamless AR experiences [12]. This issue must be addressed through technological advancements that enable smoother data transmission and improved device performance.

Content Creation: Developing accurate and compelling content for AR applications is a resource-intensive task. It requires collaboration between cultural institutions, historians, and technology developers to ensure that GAN-generated models are both historically accurate and culturally relevant. The challenge lies in ensuring that digital representations align with the cultural significance of the site, as inaccuracies can undermine the educational and cultural value of the AR experience [11].

User Experience and Accessibility: The usability of AR applications is another challenge. While AR can offer powerful interactive experiences, poorly designed interfaces can lead to user frustration. AR applications must balance complexity with accessibility, ensuring they cater to a wide audience, including individuals with varying levels of technological proficiency. Context-aware systems can enhance user engagement by tailoring experiences based on user behavior, but these systems must be carefully designed to avoid overwhelming users with unnecessary complexity [13].

C. Improvements in User Experience Through GAN and AR Integration

Despite these challenges, the combination of GAN and AR significantly enhances user experiences at cultural heritage sites. Key improvements include:

Enhanced Visualization: GAN-generated 3D models provide lifelike representations of historical sites that can be seamlessly integrated into real-world environments through AR. This combination allows visitors to view the historical details of sites that would otherwise be invisible, such as missing sculptures or deteriorated structures. This enhances the visitor experience by providing a more complete picture of the past [14].

Interactive Learning: AR shifts the visitor experience from passive observation to active participation. Users can interact with virtual artifacts, explore historical contexts, and engage with educational narratives tailored to their interests. This interactive learning environment fosters deeper understanding and improves learning outcomes, as users are encouraged to engage with the content in a meaningful way [11].

Personalized Experiences: AR applications can adapt to user preferences and behaviors, providing tailored information and experiences. By incorporating personalized content, AR enhances visitor engagement by allowing them to interact with cultural heritage in ways that resonate with their individual interests. Personalized experiences increase visitor satisfaction and help create more memorable interactions with heritage sites [13].

Table 5. Technical Integration & Visualization

Study	GAN + AR Integration	Site Type	Findings	Challenges
Liu et al. (2025) - <i>The Acropolis Museum</i>	AR for overlaying digital reconstructions of artifacts and sites	Acropolis Museum (Athens)	GANs create lifelike representations of damaged artifacts, AR overlays historical context onto physical structures.	Requires high-resolution data and effective AR content integration.
Liu et al. (2025) - <i>Digital Pompeii</i>	AR overlays GAN-generated reconstructions	Pompeii (Ancient Roman Site)	AR enables visitors to compare current ruins with digital reconstructions, enhancing educational experience.	Data transmission constraints, especially in outdoor environments.
Zhao & Ji (2025) - <i>Bach's St. Thomas Church</i>	AR-guided tours with GAN-generated visualizations	St. Thomas Church (Leipzig)	GAN-generated models illustrate the church's architectural evolution, enriching visitor understanding of its cultural history.	Requires collaboration between historians and tech developers for accuracy.

D. Implications for Cultural Heritage Education and Tourism

The integration of Generative Adversarial Networks (GAN) and Augmented Reality (AR) technologies in cultural heritage preservation is revolutionizing how educational content is delivered to visitors. By facilitating interactive, immersive learning experiences, these technologies foster a deeper connection between visitors and the cultural narratives of heritage sites, both in physical and virtual environments. The combined use of GAN and AR not only enhances education but also has a significant impact on tourism and sustainable practices, particularly for rural and remote heritage sites.

1. Educational Value Enhancement

When combined with GAN-generated visualizations, AR can deliver photorealistic reconstructions of heritage sites that may have been degraded or altered over time. GANs enable the generation of high-fidelity 3D models and images that accurately reflect the original state of structures and artifacts. This combination of AR and GAN creates a multisensory learning environment that caters to a diverse range of learning styles, making the educational experience more engaging and accessible. Visitors can interact with the past through GAN-generated visuals and AR-driven narratives, deepening their understanding and appreciation of cultural heritage.

2. Tourism Impact

The application of GAN and AR technologies is particularly impactful for rural and remote heritage sites, which often face difficulties in attracting tourists due to challenges such as inaccessibility or lack of infrastructure. AR can significantly enhance the visitor experience in these

areas by offering engaging, interactive experiences that allow tourists to explore and learn about the site in a dynamic manner. For example, AR can provide visitors with on-the-go information, enhance storytelling, and create interactive experiences that showcase the historical richness of these sites, potentially increasing visitor satisfaction and extending the duration of their stays.

3. Sustainable Tourism Contributions

The integration of GAN and AR technologies also supports sustainable tourism practices in cultural heritage preservation. These technologies contribute to responsible tourism by enhancing visitors' understanding of the cultural and historical significance of the sites they visit. When tourists are educated about the importance of preserving heritage sites, they are more likely to participate in sustainable practices and develop a sense of stewardship for these places. This is crucial for ensuring that cultural heritage is maintained for future generations.

Table. 6 Education & Tourism Impact

Study	GAN + AR Integration	Education Impact	Tourism Impact	Future Application Recommendation
Zhao & Ji (2025) - AR in Rural Tourism	GAN + AR for context-aware guiding	Enhances interactive learning, deepens cultural context understanding	Increases engagement and satisfaction at rural heritage sites, potentially boosting visitation rates	Expand AR applications to more remote heritage sites, ensuring scalability and cultural sensitivity
Liu et al. (2025) - <i>Digital Pompeii</i>	AR for site visualization + GAN for historical reconstruction	Allows visitors to experience the site as it once appeared, fostering a deep understanding of history	Enhances visitor experience at Pompeii, providing insights into ancient life; could be applied to other historical sites	Address infrastructure challenges for rural site AR applications, particularly in data transmission
Khojasteh et al. (2025) - <i>Enhanced Visitor Experience</i>	GAN-generated 3D models integrated into AR	Enhances multisensory learning by combining digital reconstructions with real-world experiences	Provides a deeper connection to heritage sites, making them more appealing for cultural tourism	Continue to develop AR systems that are more accessible and intuitive for diverse audiences
Jiang et al. (2025) - <i>Context-aware Personalized AR Experiences</i>	AR with GAN- <i>Personalized AR Experiences</i> visuals	Increases engagement by tailoring experiences based on user behavior and preferences	Encourages longer stays at heritage sites by providing personalized, immersive experiences	Implement feedback loops in AR systems for continuous personalization and improvement
Gherardini et al. (2019) - <i>Interactive Cultural Education through AR</i>	AR for interactive heritage site tours	Shifts education from passive observation to active participation	Increases visitor engagement and learning outcomes, especially in historical and cultural tourism	Explore further development of AR and GAN technologies to enable remote virtual tours for inaccessible sites

3.3 Discussion

The findings of this review demonstrate that the integration of GAN and AR technologies significantly enhances the visualization, interpretation, and educational value of cultural heritage sites. Rather than functioning as isolated tools, GAN and AR operate synergistically, where GAN-generated reconstructions provide visual authenticity, and AR delivers contextualized, interactive user experiences.

A. Advantages of Combining GAN and AR

Enhanced Visualization: The primary advantage of combining GAN and AR is the ability to generate high-fidelity digital reconstructions of historical sites or artifacts, which can be overlaid on real-world environments through AR. GANs create detailed, photorealistic representations of cultural heritage, enabling AR to contextualize these visualizations in physical spaces. This approach allows visitors to witness the historical context of a site, enhancing their understanding of its cultural significance [15].

Interactive Learning Experiences: GAN and AR together provide interactive educational opportunities that surpass traditional methods. AR enables users to engage with cultural artifacts and historical narratives dynamically. For example, AR applications can offer real-time contextual information, display historical events, or provide access to reconstructions of missing parts of a

site. This shifts the learning experience from passive observation to active participation, allowing visitors to directly engage with their surroundings in a way that is both educational and entertaining [16], [17].

Preservation of Intangible Heritage: GANs and AR not only preserve tangible heritage but also contribute to the preservation of intangible cultural heritage. GAN-generated visualizations combined with AR can help represent non-physical aspects of heritage, such as historical events, cultural practices, and storytelling traditions. These technologies can digitally reconstruct cultural contexts and reenactments, enriching visitors' understanding of heritage in a way that engages multiple senses and learning styles [18].

B. Limitations of GAN and AR

Quality of Input Data: One of the significant limitations of GAN technology is its reliance on high-quality, diverse datasets for training. GANs perform well when fed with high-resolution, accurate data, but historical datasets are often incomplete or poorly represented. The quality of the input data directly influences the quality of the generated output. In cases where the dataset is sparse or lacks diversity, GAN models may fail to accurately reproduce key architectural details, resulting in digital models that lack fidelity or authenticity [19]. This challenge is particularly prominent when reconstructing historical sites that have been significantly damaged or degraded over time.

Technical Constraints: The deployment of AR applications, especially those that integrate complex GAN-generated 3D models, is limited by technical constraints. AR requires a substantial amount of data processing and high-resolution visuals, which may strain the capabilities of mobile devices and wireless networks, particularly in rural or remote heritage sites. The efficiency of data transmission is critical, and traditional systems may not be equipped to handle the large data volumes required for real-time, high-fidelity AR experiences [12]. Without robust technological infrastructure, AR applications can suffer from lag or reduced quality, affecting the user experience.

User Experience Challenges: While AR offers interactive elements, the effectiveness of these features can be diminished if the system design does not prioritize user engagement. Overly complex interfaces, poor navigation, or overwhelming information can cause frustration and lead to disengagement. The complexity of AR applications needs to be balanced with usability to ensure that the technology enhances the learning experience rather than hindering it. For AR to be successful in cultural heritage preservation, it must be intuitive, accessible, and enjoyable for a broad audience [20].

4. CONCLUSION

The integration of Generative Adversarial Networks (GAN) and Augmented Reality (AR) in cultural heritage preservation offers significant potential to enhance educational engagement and tourism experiences. GAN provides high-fidelity digital reconstructions of historical sites, while AR adds immersive, interactive elements that bring these reconstructions to life, fostering a deeper connection with cultural narratives. However, challenges such as data quality, technical constraints, and the need for user-friendly design must be addressed to fully realize the benefits of these technologies. These challenges are particularly prominent in remote or resource-limited areas, where infrastructure may be inadequate. To maximize the potential of GAN and AR, future research should focus on improving dataset quality, enhancing GAN algorithms, and developing accessible, scalable AR applications that prioritize ease of use. By addressing these challenges, GAN and AR can become transformative tools for preserving cultural heritage and fostering greater public engagement, ensuring that cultural treasures are both protected and made accessible for future generations.

REFERENCES

- [1] M. Mesra, G. Kartono, and A. Ibrahim, "Penerapan Ornamen Tradisional Sumatera Utara Pada Toples Makanan Sebagai Sarana Revitalisasi," *Gorga Jurnal Seni Rupa*, vol. 11, no. 1, p. 81, 2022, doi: 10.24114/gr.v11i1.33639.
- [2] D. Saragi, "Pengembangan Tekstil Berbasis Motif Dan Nilai Filosofis Ornamen Tradisional Sumatra Utara," *Panggung*, vol. 28, no. 2, 2018, doi: 10.26742/panggung.v28i2.445.
- [3] R. Rajagukguk, T. Malems, and M. Ginting, "Preserving Linguistic Diversity: Strategies for Language Preservation and Cultural Heritage Safeguarding," *Jiph*, vol. 11, no. 3, pp. 221–236, 2022, doi: 10.35335/jiph.v11i3.25.
- [4] N. You, Y. E. Li, and A. Cheng, "3D Carbonate Digital Rock Reconstruction Using Progressive Growing GAN," *J Geophys Res Solid Earth*, vol. 126, no. 5, 2021, doi: 10.1029/2021jb021687.
- [5] R. G. Boboc, E. Băutu, F. Gîrbacia, N. Popovici, and D.-M. Popovici, "Augmented Reality in Cultural Heritage: An Overview of the Last Decade of Applications," *Applied Sciences*, vol. 12, no. 19, p. 9859, 2022, doi: 10.3390/app12199859.
- [6] K. Król, "Assessment of the Cultural Heritage Potential in Poland," *Sustainability*, vol. 13, no. 12, p. 6637, 2021, doi: 10.3390/su13126637.
- [7] B. Popov, R. Stytsyuk, Y. Motagali, and O. Artemyeva, "Conceptual Aspects of the Development of Cultural and Educational Tourism on the Basis of an Object of Cultural and Historical Heritage," 2019, doi: 10.2991/cesses-19.2019.188.
- [8] S. Muralidhar, P. N. Prabhu, N. U. B. A, and A. Bhardwaj, "Digital Documentation of Raya Gopura Using Geospatial Techniques Along With Supplementary Conjectural Reconstruction," 2024, doi: 10.20944/preprints202407.0085.v1.
- [9] M. M. Sihotang and T. Sitanggang, "Cultural Heritage Preservation and Manuscript Conservation: Safeguarding the Laklak Batak Manuscript of Batak Culture in Indonesia," *Jiph*, vol. 11, no. 2, pp. 85–101, 2022, doi: 10.35335/jiph.v11i2.17.
- [10] I. Widianingsih *et al.*, "Sport Tourism, Regional Development, and Urban Resilience: A Focus on Regional Economic Development in Lake Toba District, North Sumatra, Indonesia," *Sustainability*, vol. 15, no. 7, p. 5960, 2023, doi: 10.3390/su15075960.
- [11] Y. Zhao and L. Ji, "Design of a Context-Aware AR Smart Guiding Platform for Enhancing Cultural Heritage Experience in Rural Tourism," *Journal of Computational Methods in Sciences and Engineering*, 2025, doi: 10.1177/14727978251385172.
- [12] Y. Liu, H. Xu, A. Bowman, and W. Chen, "Feature-Driven Joint Source–Channel Coding for Robust 3D Image Transmission," *Electronics (Basel)*, vol. 14, no. 19, p. 3907, 2025, doi: 10.3390/electronics14193907.
- [13] H. Jiang *et al.*, "A <sc>3D</Sc>-<sc>2D</Sc> Rigid Liver Registration Method Using Pre-Training and Transfer Learning With Staged Alignment of Anatomical Landmarks," *Int J Imaging Syst Technol*, vol. 35, no. 4, 2025, doi: 10.1002/ima.70124.
- [14] S. B. Khojasteh, D. Fuentes-Jiménez, D. Pizarro, Y. Espinel, and A. Bartoli, "MIS-NeRF: Neural Radiance Fields in Minimally-Invasive Surgery," *Int J Comput Assist Radiol Surg*, vol. 20, no. 7, pp. 1481–1490, 2025, doi: 10.1007/s11548-025-03429-7.
- [15] M. K. Pasupuleti, "Preserving Cultural Heritage With Digital Twin Technology," 2025, doi: 10.62311/nesx/97839.
- [16] M. Haydar, D. Roussel, M. Maïdi, S. Otmane, and M. Mallem, "Virtual and Augmented Reality for Cultural Computing and Heritage: A Case Study of Virtual Exploration of Underwater Archaeological Sites (Preprint)," *Virtual Real*, vol. 15, no. 4, pp. 311–327, 2010, doi: 10.1007/s10055-010-0176-4.
- [17] K. Lipianina-Honcharenko, S. Schauer, J. Sieck, A. Sachenko, and I. Kit, "Concept of Information System for Cultural Heritage Sites Renovation Using Augmented Reality," *Computer Systems and Information Technologies*, no. 2, pp. 64–68, 2023, doi: 10.31891/csit-2023-2-8.
- [18] C. L. Y. Cheng, G. E. Su, J. Ahmad, and T. Sutikno, "Game-Based Augmented Reality Learning of Sarawak History in Enhancing Cultural Heritage Preservation," *Indonesian*

- Journal of Electrical Engineering and Computer Science*, vol. 34, no. 3, p. 1718, 2024, doi: 10.11591/ijeecs.v34.i3.pp1718-1729.
- [19] I. Nenov, "Cognitive Environment at 'Bansko Cultural Heritage Promotion Center,'" *Vis Stud*, vol. 5, no. 1, 2021, doi: 10.54664/wryr3921.
- [20] C. Shin, S. Hong, and H. Yoon, "Enriching Natural Monument With User-Generated Mobile Augmented Reality Mashup," *Journal of Multimedia Information System*, vol. 7, no. 1, pp. 25–32, 2020, doi: 10.33851/jmis.2020.7.1.25.
- [21] K. Themistocleous, V. Evripidou, and K. Toumbas, "Monitoring Cultural Heritage Sites at Risk Using Citizen Engagement Through Crowdsourcing," *The International Archives of the Photogrammetry Remote Sensing and Spatial Information Sciences*, vol. XLVIII-G-2, pp. 1435–1440, 2025, doi: 10.5194/isprs-archives-xxviii-g-2025-1435-2025.
- [22] G. Jia-hui and Y. Pan, "What Factors Impact Visitors' Intentions to Use Location-Based AR Games? An Empirical Study From Chinese Cultural Heritage Sites," *Sustainability*, vol. 15, no. 19, p. 14328, 2023, doi: 10.3390/su151914328.
- [23] A. Ngelambong and A. Jasrotia, "Divine Realms in Digital Space: Exploring Augmented Reality as a Catalyst for Religious Heritage Management," pp. 13–23, 2025, doi: 10.1108/978-1-83662-260-420251002.
- [24] H. Doğan and N. Çakıcı, "Evaluating Cultural Heritage Preservation Through Augmented Reality: Insights From the Kaisareia-Ar Application," *Architecture*, vol. 5, no. 3, p. 59, 2025, doi: 10.3390/architecture5030059.
- [25] T. H. R. ESTHER, S. Janani, and R. S. M, "Augmented Reality Application for Monuments," *Interantional Journal of Scientific Research in Engineering and Management*, vol. 08, no. 03, pp. 1–11, 2024, doi: 10.55041/ijrsrem29279.