

Cultural Saharan Heritage in the Age of AI: Potential, Risks, and Innovation

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ARTICLE INFO	ABSTRACT
Received: 12 Nov 2024 Revised: 17 Dec 2024 Accepted: 25 Dec 2024	Saharan heritage, encompassing archaeological sites, rock art, and cultural traditions, represents an invaluable treasure but faces multiple threats such as climate change, erosion, urbanization, and looting. Recent developments in artificial intelligence (AI) offer promising solutions to protect and enhance this unique heritage. This article explores the main applications of AI in this field. Machine learning and computer vision technologies facilitate the analysis and classification of data from rock paintings, engravings, and artifacts. Image recognition enables the detection of degradation and real-time monitoring of sites. AI-powered 3D modeling allows for the virtual restoration of endangered or destroyed sites, providing tools for conservation and immersive experiences for the public. Case studies demonstrate the effectiveness of these technologies. For instance, drones equipped with smart sensors assist in mapping inaccessible sites, while supervised learning algorithms automatically classify engravings based on their style and period. These innovations complement traditional methods, which are often constrained by limited human and financial resources. However, integrating AI in Saharan regions remains challenging. Obstacles include the lack of local technological infrastructure, the high cost of equipment, and the need for training local stakeholders. Furthermore, ethical concerns surround the use of cultural data and its potential for commercial exploitation. The study concludes that AI, when used collaboratively and inclusively, can transform the management of Saharan heritage. By involving local communities in data collection and analysis and disseminating results through accessible platforms, these technologies enhance the conservation and valorization of this heritage while promoting sustainable development in the region. Keywords: Saharan heritage; artificial intelligence; machine learning; 3D modeling; conservation; drones.

Introduction:

Desert heritage, which encompasses archaeological sites and cultural traditions, serves as a living testimony to a rich history and ancient civilizations. However, this valuable heritage faces increasing threats due to climate change, urban expansion, and illegal activities, among other factors. These challenges necessitate the adoption of innovative methods to document, monitor, and safeguard this cultural legacy.

In this context, artificial intelligence (AI) emerges as a powerful tool providing advanced solutions for preserving unique heritage. AI technologies, including machine learning and computer vision, enable the analysis and classification of rock inscriptions, artifacts, and environmental conditions. Image recognition facilitates real-time monitoring of heritage sites, while AI-supported 3D modeling aids in the virtual restoration of endangered or damaged sites. Despite these advancements, integrating AI into desert regions faces significant challenges, such as weak technological infrastructure, high implementation costs, and the need for specialized training.

This research aims to explore the role of AI in preserving and enhancing desert heritage within the framework of international conservation efforts. Key research questions include: How can AI contribute to documenting and protecting desert cultural sites? What are the main challenges hindering its adoption in these regions? To address these questions, this study will analyze case studies where AI applications have been successfully implemented in cultural heritage preservation, focusing on best practices and international standards.

The central hypothesis of this research is that AI, when combined with local expertise and community participation, can significantly enhance the management and preservation of desert heritage. By engaging local stakeholders in data collection and analysis, AI-driven solutions can become more sustainable and contextually relevant. The primary goal of this study is to assess the feasibility of AI-based approaches in heritage preservation, propose strategies for their effective implementation in desert contexts, and contribute to the global discussion on digital heritage conservation.

1. Research methodology

This study is based on a qualitative literature review that analyzes peer-reviewed journal articles, case studies, and reports from international organizations such as UNESCO and ICOMOS. Sources were selected based on their relevance to AI and heritage conservation, with a focus on studies addressing desert environments. This review aims to identify the key AI technologies used in this field, including satellite image analysis, 3D modeling, and machine learning, and assess their effectiveness in tackling conservation challenges. The chosen methodology helps in identifying key trends in AI adoption as an effective strategy for preserving desert heritage.

Additionally, the review method ensures that only rigorous and credible sources are considered, thereby enhancing the reliability of the findings. By focusing on peer-reviewed and institutional reports, the study maintains a high standard of academic integrity. The inclusion of detailed case studies offers practical insights into how AI is applied in real-world conservation efforts. This approach systematically categorizes the AI techniques, highlighting their roles in overcoming specific challenges in harsh desert settings. It provides a clear evaluation of the technologies' effectiveness in improving heritage documentation and risk assessment. Ultimately, the qualitative review lays a solid foundation for future research and strategic development in the field of desert heritage preservation.

2. The Role of Artificial Intelligence in Heritage Preservation

2.1 AI in Documentation and Digitization

AI plays an increasingly important role in protecting cultural heritage, particularly in desert environments where harsh conditions pose additional challenges. AI-powered technologies analyze large datasets and high-resolution images to monitor changes in archaeological sites and detect potential threats before they worsen. For example, deep learning is used to identify erosion patterns in rock sites, while 3D modeling techniques contribute to restoring and reconstructing deteriorated or destroyed landmarks.

Additionally, AI-enhanced smart sensors and drone-based imaging facilitate the surveying of remote areas that are difficult to access, enabling precise documentation of heritage sites without extensive human intervention. AI algorithms also assist in analyzing historical and archival images to restore lost information about archaeological sites, thereby strengthening conservation strategies and digital heritage restoration.

Thus, documentation and digitization have become among the most important AI applications in desert heritage preservation. These technologies enable the creation of highly accurate digital replicas of archaeological sites and artifacts, ensuring their preservation for future generations and facilitating research and study. This section will focus on 3D scanning and modeling of landmarks and artifacts, as well as the digitization of ancient texts and manuscripts for long-term conservation.

- **3D Scanning and Modeling:**

3D scanning is an advanced technique used to create high-resolution digital models, aiding in virtual restoration and academic research. This approach employs structured light scanning devices and point cloud processing software such as MeshLab, alongside 3D modeling software like Blender, to produce highly accurate digital replicas that enhance archaeological studies. This technology achieves precision levels of up to less than 1mm and allows for the transformation of digital models into physical replicas through 3D printing.

Furthermore, 3D scanning captures intricate details of artifacts that may be overlooked by traditional documentation methods. It involves acquiring thousands of data points from various angles, which are then processed into a comprehensive digital model. The high level of detail provided by this technique is critical for monitoring minute changes in archaeological sites over time. This method not only supports restoration efforts by providing accurate references for damaged structures but also enables researchers to perform virtual analyses remotely. Additionally, the resulting digital replicas can be shared globally, allowing experts from different regions to collaborate on conservation projects. The integration of 3D scanning with other AI-powered tools further enhances data analysis and interpretation. By enabling the creation of physical models through 3D printing, this technology also facilitates educational outreach and public engagement. Overall, 3D scanning stands as a vital tool in the preservation and study of cultural heritage, bridging the gap between digital technology and historical conservation.

- **Comparison of 3D Documentation Techniques:**

Table 1. Comparison of 3D Documentation Techniques for Desert Heritage Preservation

Feature	LiDAR	SLS	Photogrammetry
Accuracy	Very High ($\leq 1\text{mm}$)	Medium ($\leq 2\text{mm}$)	Low (2-5mm)
Cost	High	Medium	Low
Applications	Archaeological buildings	Small artifacts	Open spaces
Ease of Use	Complex	Moderate	Easy
Need for Specialized Equipment	Yes	Yes	No

3D documentation of desert heritage faces several challenges, primarily high costs and the complexity of data processing, which requires advanced software for analyzing digital models. However, these challenges can be mitigated using low-cost techniques like photogrammetry and AI-enhanced image analysis, as well as open-source tools. Additionally, securing digital data is crucial, requiring cloud storage and encryption technologies to ensure data security and sustainability.

One major obstacle is the significant initial investment in high-precision scanning equipment, which can strain budgets. The complexity of handling and processing vast amounts of data demands specialized expertise and robust computational power. Photogrammetry offers a cost-effective alternative by capturing multiple images that can be stitched together to create detailed 3D models. AI-enhanced image analysis automates many processing steps, reducing manual effort and error. Open-source software provides accessible and customizable solutions that lower overall costs. Cloud

storage not only safeguards the digital archives but also facilitates collaborative work among researchers worldwide. Encryption ensures that sensitive cultural data remains protected against unauthorized access. These integrated approaches create a more sustainable and scalable framework for heritage preservation. Continued research and investment in these technologies will further streamline processes and expand their application across diverse heritage sites.

- **Digitization of Ancient Texts and Manuscripts:**

The digitization of historical documents and manuscripts is a fundamental AI application in desert heritage preservation, enabling the creation of accurate digital archives for long-term conservation. These techniques help reconstruct lost monuments, analyze historical images, and integrate AI with 3D scanning, paving the way for new methods in archaeological data analysis. AI-driven digital heritage platforms also enhance research accessibility and facilitate interactive exploration of cultural sites.

Furthermore, this process allows for the preservation of fragile texts that are otherwise at risk of deterioration due to environmental factors and time. By converting physical documents into digital formats, researchers can safeguard invaluable historical information from being permanently lost. The digitization process also supports advanced data analysis techniques, enabling the extraction of hidden patterns and details that might be overlooked in manual examinations. These digital archives serve as critical resources for comparative studies and interdisciplinary research across the fields of history, linguistics, and archaeology. Additionally, the availability of digital manuscripts democratizes access to heritage materials, allowing scholars and enthusiasts worldwide to engage with primary sources. This enhanced accessibility can lead to new insights and collaborative research projects that further our understanding of ancient cultures. Moreover, integrating AI into the digitization process accelerates the restoration of deteriorated documents, ensuring that their content is preserved with high fidelity. The synergy between digitization and AI not only bolsters the conservation of heritage but also drives innovation in archival research methods. As these technologies evolve, they promise to open new avenues for preserving and interpreting the cultural legacy of desert regions.

Ultimately, AI has proven to be a transformative tool in preserving desert heritage by enabling precise documentation, risk assessment, and restoration of archaeological sites. Through advanced techniques such as deep learning for erosion detection, 3D scanning for virtual restoration, and digitization of ancient texts, AI enhances our ability to monitor and safeguard cultural artifacts. These technologies not only improve the accuracy and speed of heritage recording but also facilitate global access to invaluable historical data. Despite challenges like high costs and complex data processing, the adoption of cost-effective methods and open-source tools offers promising solutions. Continued investment and interdisciplinary collaboration will be essential to ensure that technological advancements align with sustainable cultural preservation for future generations.

2.2 AI in Risk Assessment and Environmental Monitoring

AI plays a crucial role in assessing environmental risks and enhancing monitoring systems. Modern technologies rely on 3D scanning and remote sensing to track environmental impacts on heritage sites, enabling proactive conservation measures (D'Errico et al., 2024). Key techniques include:

- **Remote Sensing Using Satellites and Drones:**

AI-powered remote sensing analyzes geospatial data and aerial imagery to detect environmental changes such as desertification, site erosion, and extreme climatic conditions. This technique improves conservation and restoration efforts by providing precise data for real-time decision-making (Vousdoulas & Ranasinghe, 2022).

- **Predictive Models:**

AI and machine learning create analytical models that predict the impact of environmental changes on heritage sites, such as temperature fluctuations, humidity levels, and wind strength, helping develop preventive conservation strategies (Laguna-Palma & Palacios, 2023).

By integrating digital scanning and AI, researchers can compare historical data with recent images captured by drones or LiDAR systems. These technologies not only improve digital restoration but also create predictive models that allow researchers to understand the long-term environmental effects on cultural heritage (D'Errico et al., 2024).

2.3 AI in Reviving Language and Cultural Knowledge

Given the increasing challenges facing cultural knowledge, especially endangered languages, AI has become a key tool in documenting oral traditions and reviving cultural knowledge, ensuring their preservation for future generations.

- **Generative AI Models:**

AI models contribute to protecting endangered languages by documenting and revitalizing oral traditions. Using natural language processing and deep learning, AI analyzes spoken texts and converts them into digital data for translation and machine learning. This supports the creation of digital dictionaries and linguistic databases, making these languages more accessible (Ajuzieogu, 2024).

- **Community Participation in Language Preservation:**

Engaging local communities is essential for ensuring the success of these initiatives. By involving native speakers in digital content creation and linguistic database development, AI can accurately capture cultural expressions and oral traditions, ensuring precise documentation and digital sustainability.

3. Ethical and Practical Challenges

3.1 Data Sovereignty

Artificial intelligence is one of the most effective tools for documenting cultural and environmental heritage in desert regions. However, it raises significant issues regarding data ownership and usage rights. In many cases, information about archaeological sites, oral traditions, and ecological systems is collected by external entities without the active involvement of local communities. This increases concerns about digital sovereignty (Khouadjiya, S. H, 2016).

The primary challenge lies in determining the ownership of cultural and environmental data—whether indigenous communities hold exclusive rights to their data or if research institutions and technology companies are the actual owners. Additionally, fair use of this data necessitates policies that prevent commercial exploitation without benefiting the original communities. Digital ethics also require addressing technical biases in AI models, as some systems may reflect external perspectives that do not align with local cultural contexts.

To ensure respect for local communities' sovereignty, strategies must include engaging local experts in managing their data, enacting legal policies that protect digital heritage from exploitation, and enhancing transparency through regulations that grant desert communities control over their data (Swissinfo, 2024).

Thus, while AI presents a promising opportunity for desert heritage preservation, its success depends on ensuring digital justice and respecting the rights of indigenous communities, striking a balance between technological advancement and the preservation of desert culture for future generations.

3.2 Ethics of AI Adoption

Integrating AI technologies into cultural heritage preservation presents a complex ethical challenge, requiring a balance between technological progress and cultural identity preservation. Unregulated use of these technologies may distort original meanings or cause the loss of crucial historical contexts, thereby affecting cultural continuity. This issue is particularly relevant when dealing with endangered languages, as some concepts may lose their deep significance when converted into digital data. Thus, policies must be established to ensure cultural sensitivities are respected, with strict ethical standards governing the development and deployment of AI technologies.

In this regard, the "Ubuntu" philosophy, which emphasizes collaboration and mutual respect, offers an ethical framework ensuring that AI enhances cultural heritage authenticity rather than reshaping it according to external standards. This philosophy underscores the importance of involving local communities in decisions regarding their linguistic and cultural data. By doing so, "Ubuntu" contributes to balancing technological innovation with the preservation of original meanings and cultural contexts.

Therefore, clear policies must be established to safeguard local communities' rights to control their linguistic and cultural data, preserving their identity and authenticity. These policies should include guidelines on data collection, processing, and usage to prevent misuse. Furthermore, promoting transparency in AI development fosters trust between communities and institutions involved in heritage preservation. Accountability is also crucial to ensuring the fair and equitable use of these technologies, thereby protecting cultural diversity. Through these measures, a balance can be achieved between technological innovation and respect for cultural values.

3.3 Infrastructure Challenges

Limited access to technology and weak internet connectivity in remote desert areas are among the main obstacles AI faces in cultural heritage preservation. These challenges directly or indirectly impact the ability of local communities and researchers to collect and analyze data, necessitating sustainable investments in improving digital infrastructure, such as enhancing communication networks and adopting renewable energy solutions to power intelligent systems in harsh desert environments. Additionally, building local capacities is essential to ensure effective use of these technologies without excessive reliance on external entities. This can be achieved through training programs targeting researchers and community members interested in cultural heritage preservation.

However, AI tools often struggle to adapt to resource-constrained environments. Therefore, it is crucial to develop solutions to overcome these challenges in remote areas. Implementing data compression techniques and optimizing machine learning algorithms can reduce computational requirements, making AI systems more feasible in regions with limited infrastructure. Strengthening collaborations between research institutions and tech companies can also help develop tailored solutions that address the needs of desert communities.

Moreover, documenting traditional knowledge and converting it into digital models contributes to cultural heritage preservation while ensuring community participation in this process. Finally, national policies should be established to support AI applications in heritage conservation, along with securing necessary funding for digital transformation projects in this field.

4. Interpretation of results

4.1 Case Studies and Success Stories

• Documenting Rock Art in Algeria Using AI

Rock art in Algeria represents a unique cultural heritage that documents human life in prehistoric times, particularly in the Tassili and Hoggar regions. These areas contain thousands of paintings reflecting the evolution of ancient societies. However, these artworks face challenges related to erosion and vandalism, making their documentation and preservation essential.

AI has played a crucial role in preserving rock art through image recognition and machine learning techniques, which allow researchers to analyze and classify these paintings based on their artistic styles and historical periods. This has led to:

- ✓ Improved accuracy in analysis and classification, as AI algorithms offer advanced capabilities in identifying ancient patterns and symbols.
- ✓ Faster documentation processes, compared to traditional methods that take significantly more time.
- ✓ Enhanced accessibility to information, by converting rock paintings into digital data available to researchers worldwide.

This technology has contributed to creating a digital database that facilitates the study of rock art in Algeria and understanding the evolution of life and culture in the region. However, challenges remain, including insufficient funding and the lack of adequate efforts to analyze these artworks, as some researchers have noted since the 1970s.

• Digitization of Timbuktu Manuscripts

The Timbuktu manuscripts are a cultural treasure that reflects the history of Islamic sciences and culture in West Africa. However, these manuscripts face severe threats due to conflicts and environmental factors. To protect them, a digitization project employing AI and machine learning techniques was launched.

AI applications in digitization included:

- ✓ Analyzing and categorizing ancient texts, using advanced algorithms to extract and classify information based on subject matter.
- ✓ Converting manuscripts into searchable digital texts, allowing researchers to study them without accessing the original copies.
- ✓ Enhancing image quality, through techniques that improve resolution and correct distortions caused by manuscript deterioration.

Despite its success, the project faced challenges such as political instability in the region and difficulties in maintaining high-quality digital images of fragile manuscripts. However, future AI advancements are expected to improve digitization processes and expand access to these texts through stronger academic and community collaborations.

• Using Remote Sensing to Protect Archaeological Sites in Chad

Heritage sites in Chad, such as the Ennedi Plateau and the ruins of Wara, are threatened by environmental factors, particularly desertification. To protect them, remote sensing technologies—including drones and satellite imagery—were adopted to monitor these sites and assess the risks they face. Applications of technology in heritage protection included:

- ✓ Monitoring environmental changes, by analyzing satellite images to identify areas most vulnerable to desertification.
- ✓ Assessing the condition of archaeological sites, using AI to analyze data collected by drones.
- ✓ Improving conservation strategies, by developing sustainable plans based on digital data.

Despite the significance of these technologies, limited resources and funding hinder their widespread application. Strengthening collaboration between research institutions and local governments is essential to sustaining these efforts. Future AI and data analysis advancements are expected to improve environmental forecasting, aiding in the development of more efficient strategies for cultural heritage preservation in Chad.

The case studies illustrate the transformative potential of AI in cultural heritage preservation across diverse contexts. In Algeria, AI-driven documentation of rock art has significantly improved the accuracy and speed of recording ancient cultural expressions, enhancing global access to invaluable historical data despite ongoing challenges such as funding constraints and limited analytical efforts. In Timbuktu, the digitization of manuscripts using AI has enabled the preservation of fragile texts by converting them into searchable digital formats, although political instability and image quality issues persist. In Chad, remote sensing technologies have proven effective in monitoring environmental threats like desertification, thereby informing sustainable conservation strategies; yet, resource limitations and funding remain key obstacles to widespread implementation. Overall, these findings underscore that while AI offers innovative solutions for heritage preservation, its successful application requires continuous investment, interdisciplinary collaboration, and the development of robust support systems to address technical and contextual challenges.

5. Recommendations for Sustainable Implementation

To ensure the sustainable use of AI in cultural heritage preservation, a comprehensive approach integrating technical, legal, and social aspects is required. The following steps are recommended:

5.1 Policy and Legislation Development

- Enhancing international cooperation: Establish global ethical guidelines regulating AI use in heritage preservation, emphasizing transparency, accountability, and privacy protection.
- Standardizing data management protocols: Develop guidelines for storing, sharing, and archiving archaeological data to ensure accessibility and sustainability.
- Protecting intellectual property: Enforce laws safeguarding the rights of local communities and original owners of cultural and linguistic data.

5.2 Capacity Building and Skill Development

- Empowering local communities through AI training programs for effective participation in heritage preservation.
- Integrating AI in archaeological education to prepare future researchers with smart analytical tools.
- Organizing workshops and conferences to facilitate knowledge exchange among academics, tech experts, and local communities.

5.3 Sustainable Funding and Infrastructure

- Securing sustainable funding sources through partnerships between governments, private sectors, and international organizations.

- Developing advanced digital infrastructure, including cloud databases and AI-powered processing tools.
- Establishing regional data centers for cultural heritage preservation.

By implementing these strategies, AI can play a crucial role in safeguarding desert heritage and ensuring its sustainability while aligning technological advancements with cultural preservation needs. The integration of AI in heritage documentation, risk assessment, and linguistic revival has demonstrated its potential in preserving the cultural identity of desert communities. However, the success of these efforts depends on overcoming challenges related to digital infrastructure, establishing clear regulatory frameworks, and actively involving local communities in preservation and digitization processes. Future research should explore emerging technologies such as augmented and virtual reality to enhance visitor experiences and predictive AI models to assess environmental risks. Additionally, addressing climate change and desertification through AI-driven solutions is essential to ensure the long-term preservation of desert heritage.

Conclusion

The integration of AI in preserving desert heritage emerges as an innovative solution to address challenges related to documentation, protection, and the revival of endangered cultural elements. Studies have shown that these technologies provide effective tools for recording historical landmarks, analyzing environmental risks, and reviving extinct languages, thereby strengthening the cultural identity of desert communities. However, the success of these efforts requires overcoming digital infrastructure challenges, establishing clear regulatory policies, and enhancing local community engagement in preservation and digitization processes. Field studies have led to several recommendations, including investing in the development of communication networks in desert areas, offering specialized training programs for local populations, and promoting collaboration between research institutions and government agencies to ensure the sustainability of these initiatives. Furthermore, it is crucial to formulate legal frameworks that protect intellectual property rights related to cultural heritage and ensure the ethical use of AI in this domain.

The integration of AI-driven tools, such as machine learning algorithms and automated image recognition, can significantly enhance the accuracy and efficiency of heritage documentation. Additionally, AI-powered chatbots and virtual assistants can facilitate interactive storytelling, allowing users to engage with cultural narratives in innovative ways. The use of big data analytics can also support decision-making processes related to heritage conservation by predicting potential risks and suggesting preventive measures. Moreover, AI can aid in the restoration of damaged artifacts through digital reconstruction techniques, preserving their historical value for future generations. Interdisciplinary collaborations between AI experts, archaeologists, and cultural historians are essential to developing sustainable and context-sensitive preservation strategies.

Regarding research prospects, while this study has explored the role of AI in preserving desert heritage, several areas still require deeper investigation, such as the impact of augmented and virtual reality technologies on visitor experiences and the role of AI in predictive analysis for changes in archaeological sites. Additionally, environmental challenges, such as climate change and desertification, call for further research on how AI can be utilized to mitigate these effects and ensure the long-term sustainability of desert heritage.

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