香 港 大 學
THE UNIVERSITY OF HONG KONG

Centre of Buddhist Studies

CCCH9044 Dunhuang and the Silk Road: Art, Culture and Trade

Essay Topic:	(Topic 19) Explore how AI can help and harm the preservation of endangered Buddhist heritage, using the Dunhuang Grottoes as a case study.
Student Name:	SHING, Zhan Ho Jacob
UID:	3036228892
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1 Introduction

Since its discovery, the Dunhuang Grottoes have been an important site for the study of Buddhist art and several important aspects of Chinese history, including the trade events via the Silk Road, etc. While a large quantity of artefacts like the murals and sculptures have survived thousands of years to be presented in this modern age, the artefacts are facing significant threats from various factors. A study of X. Jiang et al. (2023) has shown that the despite the lack of immediate risk of preservation due to the drastic climate change in the past few decades, the artefacts are still prone to deterioration due to the weathering effects of the natural environment. Therefore, the preservation of the Dunhuang treasures is of utmost importance and a race against time (Yu et al., 2022). Measures with high efficiency are needed to ensure the survival of the cultural heritage.

In view of the above, the Dunhuang Research Academy (DHA) was established in 1944 and is now devoted to applying modern technologies to the preservation of the Dunhuang Grottoes. While one takes advantage of the efficiency and convenience of modern technologies, such as Artificial Intelligence (AI), one must also be careful about the potential damages that may be imposed on the cultural heritage. This essay aims to explore the current applications of the AI technology in the preservation of the Buddhist heritage, using the Dunhuang Caves as a case study. In the Literature Review section, some cutting-edge AI applications in the archaeological field will be briefly explored. Then, in the following two sections, the benefits and potential risks of these applications will be discussed. Finally, a conclusion on the topic will be included, with a hope that the discussion would provide new insights into the process of critically evaluating the use of AI in the preservation of cultural heritage.

1.1 Terminology

Since the topics "cultural heritage", "preservation" and "AI" are all broad, it may be helpful if these terms are defined before the discussion commences.

1.1.1 Buddhist Heritage and Cultural Heritage

In the context and the scope of discussion of this essay, the term "Buddhist heritage" and "cultural heritage" are treated as the same, and they refer to both the artefacts and sites of the Dunhuang Grottoes. The "artefacts" include the mural paintings, sculptures, and manuscripts. This definition is consistent with that of the current standard as suggested by United Nations Educational, Scientific and Cultural Organization [UNESCO] (2024b).

1.1.2 Preservation

As suggested by UNESCO (2024a), the conservation and preservation of cultural heritage are means taken to elongate the lifespan of the heritage and to convey its significance to the future generations. Therefore, the term "preservation" would imply two aspects: the technical aspect of protecting the existence of the artefacts and sites, and the human aspect of public education and raising awareness.

1.1.3 Artificial Intelligence

Contrary to the common generic definition of AI as "the simple theory of human intelligence being exhibited by machines" (Helm et al., 2020, p. 69), this essay will refer to AI simply as a set of tools utilising Machine Learning (ML), Convolutional Neural Networks (CNNs), Large Language Models (LLMs), and Natural Language Processing (NLP) technologies dedicated to the analysis and processing of images and texts for the purpose of preserving cultural heritage.

2 Literature Review

Current AI applications in the study and preservation of Dunhuang Grottoes can be roughly categorised into image-related techniques and text-related techniques.

2.1 Computer Vision and Image Processing

Algorithms specialised in computer vision and image processing, such as CNNs, Revolutional Neural Networks (RNNs), and Generative Adversarial Networks (GANs), and hybrids of these algorithms are most prominently used in the handling the murals of the Dunhuang Grottoes (Fu et al., 2025; Yu et al., 2022).

For the restoration of damaged murals, conventional patch-based methods (Ballester et al., 2001; Bertalmio et al., 2000) allowed automatic inpainting of small and simple damaged areas. Their inability to handle larger and more complex missing areas have been overcome by modern use of CNNs (Pathak et al., 2016; Yang et al., 2017). In recent years, Song et al. (2018), as cited in Yu et al. (2022) proposed a more modern approach, allowing the restoration and inpainting be context-aware, i.e. the algorithm would reconstruct the missing parts by considering the surrounding context, rather than simply predicting pixels mathematically. Similar means include systems built on CNNs and the ResNet-50 architecture, which are employed by the British Museum and Le Musée du Louvre (the Louvre Museum) for damage recognition (Fu et al., 2025). Recent studies carried out by Chen et al. (2024) proposed a hybrid approach of joint learning, further improving the errors produced by the AI models by allowing the models to learn from the global context of the murals, rather than just the local context.

For creating arts in the visual style of the Dunhuang murals through AI, specialised algorithms referred to as the "style transfer" algorithms are used (Sun and Gao, 2023; Yu et al., 2022). While Yu et al. (2022) mentioned certain limitations of the algorithms built on the CNNs, such as lack of flexibility and optimisation, an experiment carried out by Sun and Gao, 2023. Apart from application on Dunhuang murals, a recent study by Zhang et al. (2023) also mentioned advanced techniques for generating cultural and creative products by replicating visual styles from the input.

As deep learning and AI technologies rely heavily on large datasets, the demand of labelling imagery data, especially for the research of Dunhuang Grottoes, is high (Fu et al., 2025). Seeming to be paradoxical, the use of deep learning itself is the de facto solution for training deep learning models for labelling images and objects automatically. X. Jiang et al. (2019) introduced some of the commonly used state-of-the-art models for object detection, including R-CNN and Fast R-CNN (two-stage detectors), and You Only

Look Once (YOLO) and Single Shot Detector (SSD) (one-stage detectors), all of which are achieving satisfactory results in terms of accuracy and speed. These models are now widely employed by renowned museums for archaeological research and preservation, such as the Metropolitan Museum of Art (Villaespesa and Crider, 2021), Emperor Qin Shihuang's Mausoleum Site Museum (Bevan et al., 2014), and, most importantly, the Dunhuang Research Academy (Yu et al., 2022).

2.2 Natural Language Processing and Large Language Models

Text-related technologies, such as NLP and LLMs, are predominantly used in both research and humanity aspects. As these technologies are often used in collaboration with computer vision technologies, they are only briefly introduced in this section.

In the archaeological research aspect, NLP technology is often used to transcribing and analysing the transcripts of orally told history (Fu et al., 2025). Fu et al. (2025) also mentioned the use of LLMs in generating documentations for the artefacts, while Manovich (2017), as cited in Fu et al. (2025) mentioned providing commentaries for artefacts from innovative perspectives. In Dunhuang's case, the DHA has been leveraged the capabilities of AI to recover and identify characters from excavated manuscripts from the Library Cave (Gansu Cultural Heritage Bureau, 2025).

In the humanity aspect, popular LLMs, such as ChatGPT, are used for interactive chatbots for public education and addressing public enquiries (Dunhuang Research Academy [DHA], n.d.; N. Jiang, 2024; Shen et al., 2024), and also smart search engines allowing users to look for specific artefacts with natural language (DHA, n.d.).

3 AI Technologies Benefiting Buddhist Heritage Preservation

3.1 Automated Object Detection Accelerating Research

The current advancements in computer vision and deep learning technologies plays a catalytic role in the research of the Dunhuang Grottoes. As Resler et al. (2021) mentioned, the fundamental step for researchers in the archaeological field is to fit the excavated artefacts into their appropriate categories according to their features and attributes. It is not uncommon that this process relies heavily on the workers' mastery of knowledge, personal preferences over certain styles (Barcelo, 1995; Yu et al., 2022), and time dedicated to repetitive tasks.

Prior to the emergence of computer vision, the process of classification relied completely on researchers' manual efforts. An experiment carried out by Verschoof-van der Vaart and Lambers (2021) studying the integration of deep learning models in the classification of archaeological artefacts has shown that the speed of work can be increased by 8 times. They also mentioned that the time of the researchers can be reallocated to other steps in the analysis process, further enhancing the efficiency of the research.

In terms of applications in the preservation of Dunhuang Grottoes, the experiment by Yu et al. (2022), employing multiple models and analysis metrics, has given varied results

in terms of accuracy. The result showed that the YOLO v5-S model performed the best, with the mean Average Precision (mAP[2]) of 0.6809.

However, these methods are not without flaws. The performance of object detection models solely depends on the dataset on which that they were trained, which implies that the number of already identified items directly dictates the accuracy in identifying objects of the same kind. As Yu et al. (2022) pointed out, there lacks a balance in the number of readily available labelled images of the artefacts in the e-Dunhuang dataset, which may have resulted in the worst performance of the model when identifying non-Buddhist figures, with accuracy of 0.6293 (while other categories reaching around 0.80).

To argue, it is important to recognise that the use of AI does not intend to substitute the researchers, but rather to act as a complementary tool to assist the current works (Verschoof-van der Vaart and Lambers, 2021). An ideal workflow would be to use the AI models for a rough classification and tagging of the artefacts, and then to employ the researchers' intervention to further sample and verify the results. While human intervention is still required, the efficiency of the research is indeed enhanced. Therefore, it is reasonable to conclude that the use of computer vision and deep learning technologies has high potential in accelerating the research of the Dunhuang artefacts, thereby benefiting the preservation work.

3.2 Image Inpainting Assisting Restoration of Artefacts

Endeavours have been made by several parties to restore the damaged murals and manuscripts in the Dunhuang Grottoes. Historically, the restoration of the murals was done by hand, whose biggest risk is the potential of secondary damage to the original artefacts (Lian et al., 2025).

As discussed in Section 2.1, the performance of AI models and frameworks in image inpainting is closely related to the complexity of the image to be restored. Easier cases, such as small, repetitive decorative patterns (caisson paintings, for example) can be restored with high accuracy, while more complex cases, such as the portraits of the Buddhas and Bodhisattvas, tend to be more challenging. This variation of restoration accuracy is a result from the models' inability in extracting valid semantic information from the murals (Lian et al., 2025), therefore not being able to preserve the artistic features of the murals. The experiments by Yu et al. (2022) have also demonstrated this limitation.

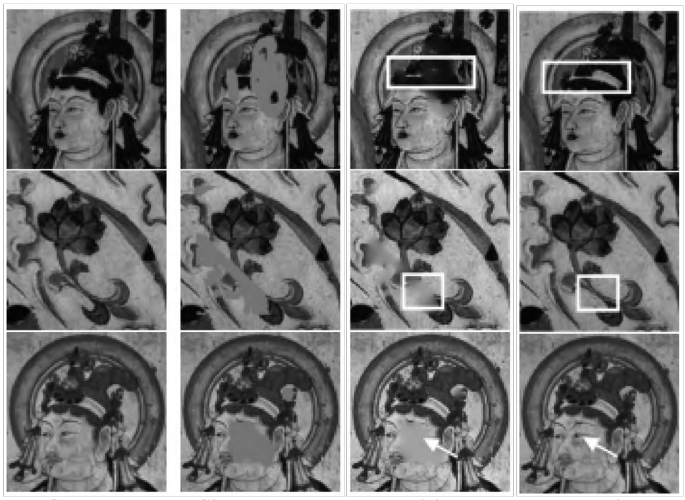
In the latest developments, however, researchers have been able to overcome this issue through the use of adversarial diffusion networks (Lian et al., 2025) and hybrid approaches (Chen et al., 2024). The improvements and outcomes of these methods are significantly better than the traditional methods, as shown in Figure 1 and Figure 2.

Apart from the murals, important milestones have also been achieved in the restoration of the manuscripts from the Library Cave. The DHA has been working in collaboration with technology companies to leverage generative artificial intelligence (GenAI) to restore and generate the missing parts of excavated manuscripts (H. Li, 2024). While the technical details of the algorithms are not disclosed, it is not difficult to imagine that the

[2]The mAP is a metric measuring the model's capabilities in correctly detecting and locating objects in images. The higher the value, the better the model's performance.

Figure 1

Results of the hybrid image inpainting algorithms on simulated damaged murals of complex patterns



Note. Results of the hybrid image inpainting method showed satisfactory results in restoring complex patterns, such as the facial features of the Bodhisattva, when compared to the traditional method. Adapted from "Mural Inpainting Algorithm Based on Semantic Reasoning and Joint Learning", by Chen et al., 2024, *Journal of Beijing University of Posts and Telecommunications*, *47*(5), 73–80.

approach has made use of image and text processing technologies built on deep learning and NLP, and also the use of large datasets of calligraphy for the purpose of identifying variants of the same Chinese characters. H. Li (2024) has remarked that the generated contents are of promising quality and reliability. Whereas this application is still in an immature state, it is reasonable to expect that AI technologies will gain more attention in this area.

The discussions made above focused on restoration of two-dimensional artefacts, namely the murals and manuscripts. For three-dimensional artefacts, such as sculptures, while the use of GenAI is still in its infancy and remains at a theoretical stage, further research on proposed methods such as that of Ge et al. (2019) may allow GenAI to be used for restoring damaged, if not lost, sculptures in the Dunhuang Grottoes in the future.

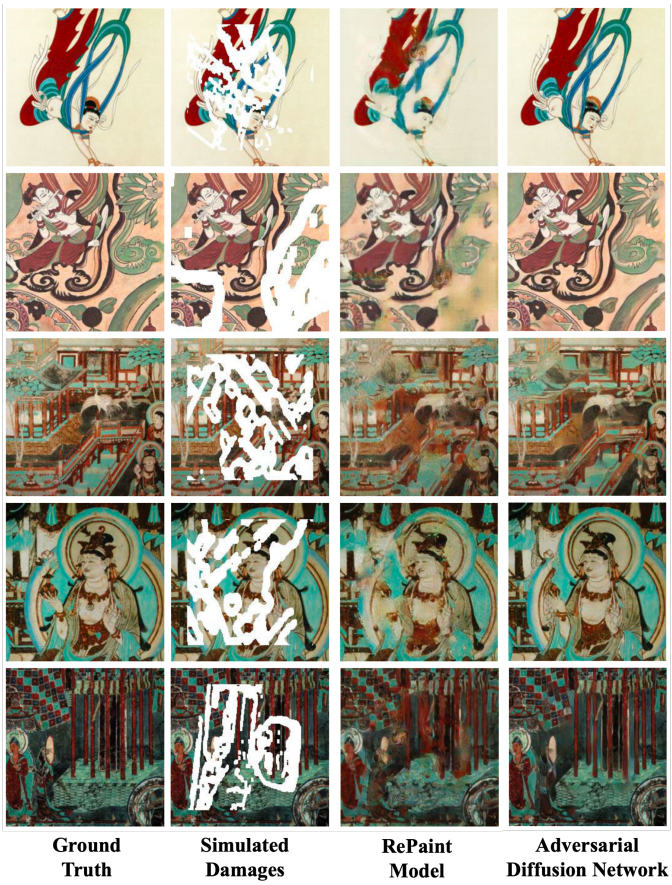
Having discussed the latest advancements in the use of image inpainting and related technologies, it is conceivable that the use of AI technologies can benefit the preservation of Dunhuang Grottoes by helping the restoration of artefacts.

3.3 Raising Public Awareness and Interest Through Artistic Style Transfer

The focus of Section 3.1 and Section 3.2 was on the technical aspects of the preservation of Dunhuang's cultural heritage. However, as defined in Section 1.1.2, the humanity aspect of preservation is equally important. The key to raising public awareness and in-

Figure 2

Results of the adversarial diffusion network on simulated damaged murals of complex patterns



Note. Results of the ADN model proposed by Lian et al. (2025) displayed advanced capabilities in restoring complex murals. Adapted from "Adversarial Diffusion Network for Dunhuang Mural Inpainting", by Lian et al., 2025, *IEEE Transactions on Circuits and Systems for Video Technology*, *35*(7), 6561–6574.

terest so as to ensure the survival of the cultural heritage is the next generation of people. Measures for educating and inspiring the domestic (Chinese) adolescents are distinct from those for the international audience, as they have different backgrounds. This section will draw its focus on the former.

A new consumerism phenomenon advocating cultural identity and cultural confidence, known as the "National Trend" (*Guochao*), has emerged in China, especially amongst the younger generation. According to Liu (2021), relevant queries on the Chinese search engines have increased by four times, peaking in 2019 at 26 billion queries. Leveraging this trend is a way to promote the vibrant cultures of the Dunhuang Grottoes, and such leverage would be made possible easily by the use of GenAI.

On the technical side, Sun and Gao (2023) discussed that the use of style transfer has long been a dominant trend in the field of artistic creation. They further stated that, however, the use of such technology in the context of Dunhuang Arts is insufficiently explored. Trained models already exist and are capable of producing promising results, as shown in both Figure 3 and Figure 4.

On the public acceptance side, while no major use of GenAI in the context of Dunhuang Grottoes has been reported, similar cases can be looked at as a reference. Zhang et al. (2023) have conducted a study of the public's perception of the sustainability of intangible cultural heritage on AI-generated New Year products. The results showed that the public is generally engaged and supportive of the attractive products, revealing a positive correlation between younger generation's cultural identity and economic boost.

It is predicted that the DHA could take advantage of the current National Trend and the cutting-edge technologies, with proper online and offline marketing strategies, to promote the Dunhuang Grottoes, as its nature of being a valuable traditional Chinese cultural heritage is in line with the values of the National Trend and aligns with the contemporary Chinese government's policies of promoting cultural confidence among its citizens (Liu, 2021). Furthermore, the DHA can borrow the experience of Shao (2023) to gain economic benefits from the market of intellectual property, which can be used to fund the preservation work, creating a positive feedback loop.

To conclude, the use of AI technologies in artistic style transfer can be beneficial to the preservation of the Dunhuang Buddhist heritage by raising public awareness and interest.

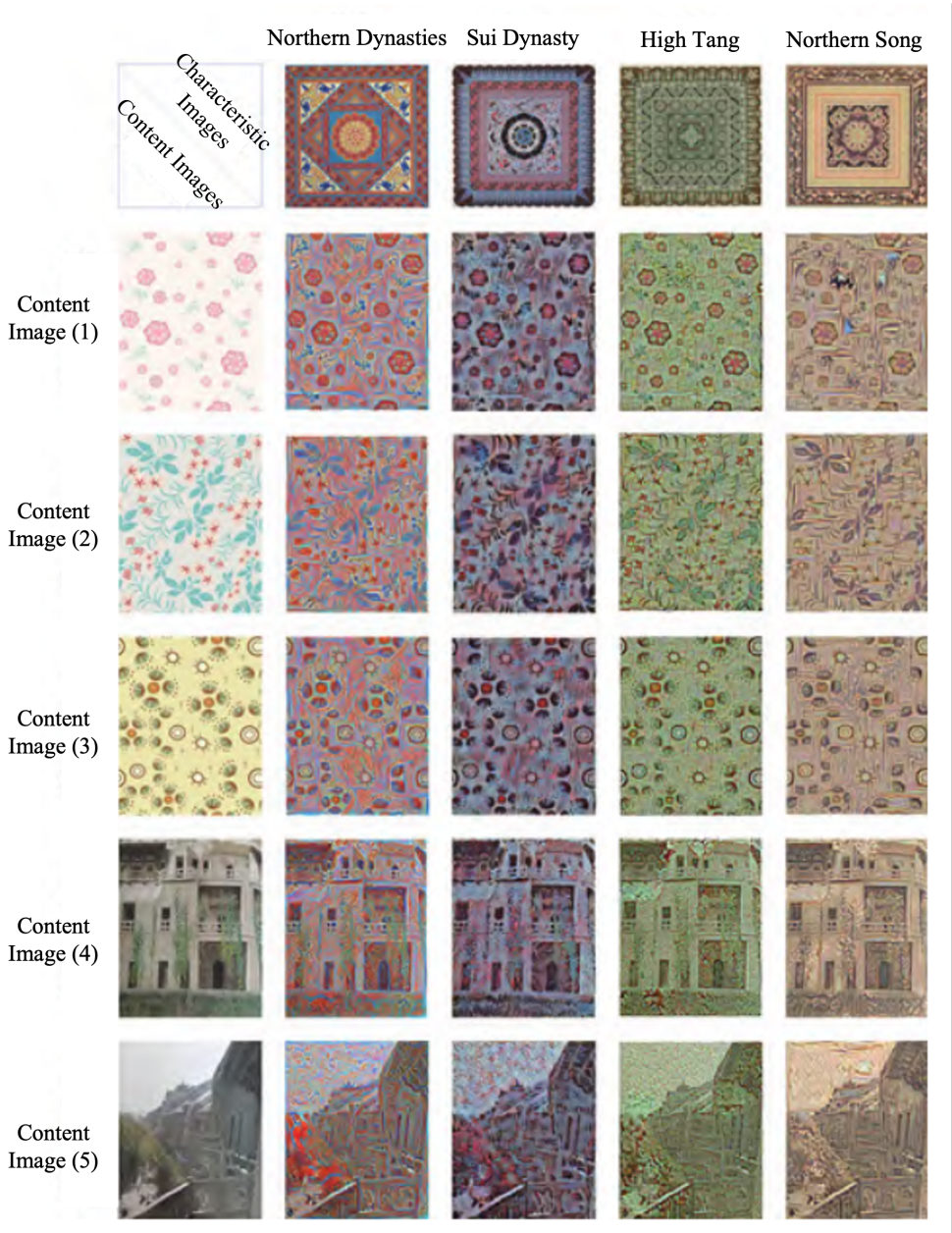
4 Concerns Raised Against AI Technologies in Buddhist Heritage Preservation

4.1 Forfeited Authenticity and Originality in AI-Restored Artefacts

While the algorithms and models discussed earlier have shown remarkable accuracy in the restoration of artefacts, one must bear in mind that by no means can the AI-generated artefacts be "authentic" howsoever they resemble the original. Regarding generated arts, Tiribelli et al. (2024) posed two critical questions regarding the authorship and whether the generated art is eligible to be claimed as "original" or "authentic".

Figure 3

Examples of results of merging Dunhuang art styles with modern images using different models and algorithms



Note. The original figure were in Chinese. The captions are translted into English by the author. Adapted from "Innovative Design of Dunhuang Decorative Patterns Based on Image Style Transfer Algorithm", by Sun and Gao, 2023, *Color*, *446*(09), 100–103.

Figure 4

Examples of results of tranfering Dunhuang art styles onto new images by different models

Note. The left-most column are the original images, while the others are the results of Dunhuang art styles being transferred on the original images by different models. Adapted from "Artificial Intelligence for Dunhuang Cultural Heritage Protection: The Project and the Dataset", by Yu et al., 2022, *International Journal of Computer Vision*, *130*(11), 2646–2673.

While authorship is not within the scope of discussion of this paper, the authenticity, however, is difficult to guarantee. As discussed earlier, GenAI relies on the datasets on which they were trained. Even if the algorithms were designed to be absolutely neutral, which only exist in an ideal condition, the dataset can already be comprimised with bias of which the developers are not aware of. Plus, since it is inevitable to have an imbalance in the number of available data amongst different categories of data, AI models tend to misinterpret parts on which they were not adequately trained. Fu et al. (2025) mentioned an incident of an AI model empolyed by the Shanghai Digital Heritage Centre misinterpreting Tibetan cultural elements due to the fact that it was trained predominantly on the cultures of the Han dynasty. It is therefore inferred that contemporary AI technologies are not yet reliable in terms of authenticity.

Even if the authenticity can be guaranteed in a hypothetical scenario, one must recognise that "authenticity" and "originality" are two distinct concepts. Y. Li (2022) mentions two types of authenticity – moral authenticity and type authenticity, which asserts the AI models' ability to extract the artist's intentions from the style of the original artefacts. The ability to extract qualifies the AI-generated artefacts to be "authentic", as they were created with the original artist's process of thoughts, however by no means be "original". It comes naturally that one would argue that the AI-generated or -restored artefacts forfeit their authenticity, if not originality.

If such originality issue is not addressed, although the application of AI technologies advantages the technical aspect of preservation, it may undermine the message conveyed by the artefacts, which in turn comprimises the humanity aspect of preservation. As of the case of Dunhuang Grottoes, the restored artefacts proposed by Yu et al. (2022) and Lian et al. (2025) are not currently displayed for the general public, but rather for research purposes only. Therefore, the Dunhuang Grottoes are not in immediate risk of forfeiture of authenticity and originality, but thorough assertions must be made before an official endorsement can be made.

4.2 Misinformation and Hallucination of LLMs

It is of common knowledge that LLMs are prone to generating misinformation, or having hallucinations when they attempt to generate output in a less familiar area. This behaviour is rooted in the way LLMs produce output, thus inevitable (Saha et al., 2025).

In particular, in the context of Dunhuang Grottoes, the LLMs are expected to provide service in a field that is highly specialised and requires expertise. Frankly, as Shen et al. (2024) have shown, despite the unrivalled mastery of languages, LLMs are falling short in terms of knowledge in the field of seconary-education-level history, let alone the specialised knowledge in the field of archaeology and Buddhist history. The research by N. Jiang (2024) also backs this claim, that is, there exists a high potential for LLMs to provide incorrect information when prompted.

While measures have been proposed to combat this issue, such as using multiple layers of LLMs to verify the reliability of the output (Saha et al., 2025; Verspoor, 2024), the application of such error-prone technologies to provide public education remains a concerning risk of comprimising the purpose of preservation.

5 Conclusion

This article endeavoured to critically evaluate the use of AI technologies in the preservation of Buddhist heritage by using the Dunhuang Grottoes as a case study. Through the exploration of the current applications, the importance of AI in archaeological research and preservation is acknowledged. On the contrary, the concerns regarding such technologies and applications are also briefly discussed, from both the ethical and technical perspectives. It is concluded that while the use of AI technologies does indeed benefit the preservation of Buddhist heritage through several means, critical evaluations of the applications are advocated to ensure the sustainability of the preservation work.

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