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The Role of Artificial Intelligence in Digitizing Cultural Heritage: A Review

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Abstract

Artificial intelligence and digital technologies are rapidly transforming the way cultural and artistic heritage is protected, understood and appreciated. The deep learning is employed for restoring damaged artworks by accurately filling in missing sections, preserving their integrity while dramatically reducing time and costs. Digitization lies at the heart of this transformation, enabling digital preservation, accessibility and engagement of historic works to a wider audience, thereby protecting their essence. The integration of AI into cultural heritage preservation opens up new opportunities for interdisciplinary, education and cultural exchange, fostering stronger bonds between diverse communities and their shared history. This study summarizes the findings from 2020 to 2024, drawing on data from relevant scholarly repositories, including Google Scholar, Elsevier, and MDPI. It concludes that the use of AI in cultural heritage primarily involves four main technologies: machine learning, deep learning, virtual reality, multimedia management, and big data. The study examines the data used, the results achieved, and the challenges faced in these applications.

Keywords: Cultural heritage, machine learning, deep learning, virtual reality.

دور الذكاء الاصطناعي في رقمنة التراث الثقافي: مراجعة

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المستخلص

إن الذكاء الاصطناعي والتقنيات الرقمية تعمل على تحويل طريقة حماية التراث الثقافي والفني وفهمه وتقديره بسرعة. حيث توظف التعلم العميق لاستعادة الأعمال الفنية التالفة من خلال ملء الأقسام المفقودة بدقة، والحفاظ على سلامتها مع تقليل الوقت والتكاليف بشكل كبير. وتكمن الرقمنة في قلب هذا التحول، مما يتيح الحفاظ الرقمي وإمكانية الوصول إلى الأعمال التاريخية وإشراكها لجمهور أوسع، وبالتالي حماية جوهرها. ان استخدام الذكاء الاصطناعي في الحفاظ على التراث الثقافي يفتح فرصًا جديدة للتبادل الثقافي والتعليمي متعدد التخصصات، مما يعزز الروابط القوية بين المجتمعات المتنوعة وتاريخها المشترك. تلخص هذه الدراسة النتائج من عام 2020 إلى عام 2024، بالاستعانة ببيانات من مستودعات علمية ذات صلة، بما في ذلك Google Scholar و Elsevier و MDPI. وتخلص إلى أن استخدام الذكاء الاصطناعي في التراث الثقافي ينطوي في المقام الأول على أربع تقنيات رئيسية: التعلم الآلي، والتعلم العميق، والواقع الافتراضي، وإدارة الوسائط المتعددة، والبيانات الضخمة. وتفحص الدراسة البيانات المستخدمة، والنتائج المحققة، والتحديات التي تواجهها هذه التطبيقات.

الكلمات المفتاحية: التراث الثقافي، التعلم الآلي، التعلم العميق، الواقع الافتراضي.

1. Introduction

The digital preservation of cultural heritage is rapidly becoming a powerful field, employing cutting-edge technologies to safeguard historical and cultural artifacts for future generations. The augmented reality (AR), virtual reality (VR), and artificial intelligence (AI) are discipline leverages to fundamentally create a culture in which heritage is documented, restored, and experienced. providing new avenues for individuals worldwide to reconnect with their heritage. This transformation's heart is AI, which integrates technologies like Machine Learning (ML), Deep Learning (DL), and Computer Vision. AI serves as a cornerstone in cultural heritage preservation, offering unparalleled capabilities. For instance, machine learning, a branch of AI, empowers systems to adapt and improve from experience without explicit programming. By utilizing algorithms and statistical models, ML analyzes data, makes predictions, classifies information, and detects patterns [1], [2]. [1], [2].

ML has various usages including security, object detection, image recognition, entertainment, healthcare, etc. It has a great contribution to the progress of many fields like autonomous vehicles, medical image applications, etc. ML techniques are divided into three main categories: supervised, unsupervised, semi-supervised, and reinforcement learning; Each one of these learning is used for different tasks, where supervised learning classifies the labeled data, while unsupervised classifies the data that does not contain any information about the target. Reinforcement learning use interactive environments and the model learn by applying the concept of trial and error. [3-5].

Deep Learning (DL) is a group of algorithms that fall under the umbrella of ML, and by using artificial neural networks, it simulates the human brain's ability to analyze and process a huge amount of data, where it extracts and identifies patterns in the data and thus achieves complex tasks like pattern recognition, object detection, classification, etc. In DL, networks are composed of layers, layers extract features, where the data is composed of features, and each layer works to extract abstract features. The data that DL deals with are images, text, audio, video, etc. It has various applications natural language processing, tumor detection, etc. The DL methods are Convolutional Neural Networks (CNNs) for image analysis, Auto-Encoder, Recurrent Neural Networks (RNNs), and Vision Transformer. Consequently, DL has effectively contributed to the progress of many fields like industries, agriculture, and health care [6-8].

Deep Learning contributes significantly to automating the restoration of artifacts, generating accurate metadata, and enabling continuous monitoring at heritage sites. By leveraging large datasets and neural networks, AI excels at detecting complex patterns in cultural materials, facilitating advancements in restoration techniques and predictive modeling. This capability allows for more

precise and efficient preservation efforts, ensuring cultural artifacts are maintained with greater accuracy and care. The integration of AI into these processes has made it an indispensable tool in cultural heritage preservation. Its ability to analyze vast amounts of data and predict outcomes transforms traditional methods, offering innovative solutions for safeguarding cultural legacies for future generations. Through its combined functionalities, AI continues to play a pivotal role in maintaining and revitalizing cultural heritage [9], [10].

Still, a few challenges remain. Ethical issues—such as the authenticity of data and equal access to data—are part of the hindrances, together with the digital gap, for the extensive use of those technologies. The researchers outline the need for inter-disciplinary co-operation when a method to overcome these problems could guarantee long-term success for such projects in digital heritage enhancement [11].

This study presents a review of the papers that have been conducted between 2020 - 2024 concentrating on the role of AI in preserving cultural heritage. The first step in this study is collecting the relative studies, and this is achieved by choosing some of the most popular publishing houses such as Elsevier, IEEE, and MDPI. In addition to some academic sites like Google Scholar and Research Gate. The methods, data used, contributions, and challenges are the main metrics that are used to decide the importance of the improvement and progress that the study added to the cultural heritage. This paper introduces an extensive study of AI technologies that is used to preserve the cultural heritage, these technologies are divided into four groups: Machine Learning, Deep Learning, Virtual Reality, and Multimedia & Big Data Management.

2. Methodology

This section highlights AI and related technologies, like ML, DL, VR, and Multimedia & Big Data Management, applied for the preservation and digitization of cultural heritage, including the methodologies followed, the results achieved, and the challenges found. Figure 1 provides an overview of this study and the main AI techniques applied in the preservation of cultural heritage, which are divided into four main classes: Machine Learning, Deep Learning, Virtual Reality, and Multimedia and Big Data Management. The figure shows organized data used, results gotten, challenges, and benefits of each category, covering a broad view of contributions and limitations.

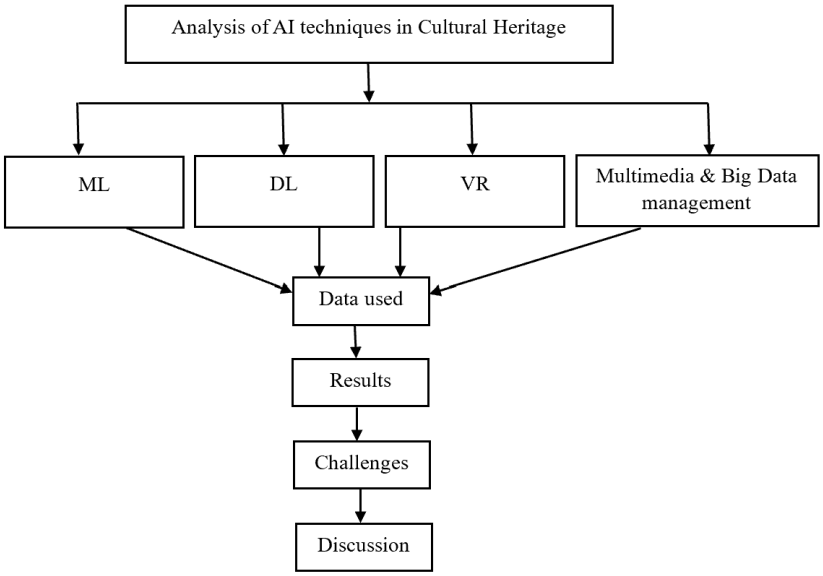

Figure 1. Analysis of AI Techniques in Cultural Heritage Preservation

3. Studies overview

This section is a chronological review of 20 studies carried out between 2021 and 2024 on themes such as sustainable conservation, AI for heritage restoration, ethics, and social perceptions regarding AI in cultural heritage preservation. A summary of these works is shown below.

Hughes et al. (2021) investigated artificial intelligence applied in sustainable heritage conservation, emphasizing energy-efficient digitization and predictive maintenance techniques. Their innovative approach realized a 25% reduction in restoration costs with up to 40% energy savings, while improving overall conservation strategies [12]. Zhong et al. (2021) dived into the VR techniques and their applications, and how they can be applied to preserve the cultural heritage digitally. They concluded that using interactive VR tools and 3D models will increase the accuracy of the preservation of cultural heritage [13]. Pisoni et al. (2021) suggest a conceptual framework of XAI design to improve the accessibility in museums. their study assisted visitors with disabilities by enabling them to try interactive experiments living some moments like a real through simulating the reality [14].. Li et al. (2021) employed machine learning techniques to automate digital cultural heritage processing. Methods such as 3D laser scanning and Gaussian filtering were adopted, achieving significant reductions in processing time and error rates compared with manual methods [15]. Yu et al. (2022) conducted research on preserving the Dunhuang Mogao Grottoes, a cultural heritage site along the Silk Road, using artificial intelligence. Deep networks were used for automated restoration, achieving results comparable to manual methods while greatly accelerating the restoration of extensive historical paintings. Detection and retrieval approaches were

applied to analyze large datasets, overcoming challenges in manual labeling. The study introduced the "AI for Dunhuang" dataset (v1.0), which includes 10,000 images for restoration, 3,455 for style transfer, and 6,147 for property retrieval. Style transfer techniques enabled cross-era style analysis, spanning over 1,000 years. The dataset and benchmarking results were made publicly available to promote further research [16]. Leshkevich and Motozhanets (2022) undertook a study on social attitudes toward AI in the digitization, transfer, and dissemination of cultural heritage, focusing on Russian contexts. Statistical data analysis, descriptive and comparative methods, and an interdisciplinary approach were used to examine both positive and negative outcomes of digitization processes. Key concepts addressed include "digital ontology," the influence of deterritorialization, digital trust, and the contrasting views of AI-enthusiasts and AI-alarmists. The study highlighted factors influencing negative perceptions of digital artifacts and the roles of influencers, stakeholders, and data scientists in shaping digital cultural heritage. Three main challenges, or "digitization frontiers," were identified: the axiological factor, emphasizing alignment with human values; the subject vector, focusing on new actors in digital heritage; and the ethical factor, promoting a human-centered approach to AI technologies. The authors concluded that human reflection is paramount in every digitization effort and should be central to a human-values-driven future [17]. Kumar et al. (2023) conducted a study to improve the mapping of cultural heritage in Norway using automated tools and deep learning techniques. The study used Faster R-CNN for detecting cultural heritage objects, including grave mounds, pitfall traps, and charcoal kilns from airborne lidar data. This approach attained 87% accuracy in the identification of true objects in test images, though the false positive rate varies with landscape conditions. Results are thus good to go for Faster R-CNN regarding the semi-automatic detection of objects relating to cultural heritage. It's from these studies that one has come out to notice the refinement it ought to face through in order to have very low numbers of false positives with minimum usage of human eye observations, which increases mapping efficiency during large-scale archaeology processes [18]. Kumar et al. (2023) tried to use deep learning approaches on images gathered from social media in terms of the location and status of the affected state's cultural heritage following a disaster. Their model, which attained over 90% accuracy in heritage site identification and damage categorization, can thus provide a scalable and effective real-time monitoring solution [19]. Ghimire (2023) presented a post-earthquake study on the preservation of the heritage of Nepal by AI and 3D scanning technologies. This research enhanced the restoration of the damaged sites including Pancha Deval Temple and identified the need for public participation through mobile applications [20]. Prados-Peña et al. have presented a bibliometric review about the uses of AI applications for cultural heritage. Key trends related to predictive modeling, digital restoration, and risk assessment are found, though drawing much attention toward focused research gaps [21]. In this

respect, Mishra and Lourenço review in detail the applications of artificial intelligence in inspection and damage detection over the structure of CHs by different case studies presented in support. This work, therefore, tends to demonstrate ways in which techniques from DL with methodologies concerning object detection may allow accomplishing the automation of the on-site damage detection phase. Applying expertly trained CV technologies, AI thus actually finds and identifies damages present in various unseen image inputs, supplementing human judgment and skills. Furthermore, this system can be augmented with virtual reality to teach specialists in recognizing structural damage in digitizing and preserving for later inspection comparisons. The study also explores the combination of NDT tools—laser scanning, thermal scanning, and ground-penetrating radar—with AI approaches to increase the reliability of detecting damages. These AI-assisted systems ensure that no defects in the structure go unnoticed by human operators; the results are then presented with the help of HBIM tools, serving as permanent digital records. High-resolution imaging, drone inspections, and real-time methods in CV have created great prospects for AI-driven maintenance inspections to drastically reduce the duration of inspections, minimize the element of human error in these inspections, and improve the accuracy in making decisions on the preservation of structural components of CH structures [22]. Foka and Griffin have dealt with the ethical issues due to the use of Generative AI in cultural heritage, pointed out the dangers of prejudices in training datasets, suggesting that frameworks of inclusiveness shall guarantee fair representation for cultures [23]. Tiribelli et al. (2024) present an overview of ethical issues of AI applications within the cultural heritage context. Their findings point to several topics: authenticity, bias, economic disparity, and, once more, the need for ethical guidance by sector [24]. Gîrbacia (2024) investigated a scientometric analysis regarding the state of the art on AI in cultural heritage from 2019-2023. Therein, the author identifies five relevant tendencies: classification, computer vision, 3D reconstruction, recommender systems, and ICH. These applications enhance tasks such as the detection of damage, preservation, and digitization, thus providing significant improvements over their respective traditional methods. It has been underlined that, in the future, AI will increasingly have the potential to dramatically alter how cultural heritage preservation and accessibility are approached [25]. Du et al. (2021) integrated AI and multimedia technologies to create immersive VR simulations of Shenzhen's ancient history. Archaeological data was utilized in the study with the aim of raising public engagement, but the long-term data preservation posed some challenges [26]. Xie (2022) researched tangible cultural heritage preservation by integrating AI-based design methods, including shape grammar and perceptual engineering. It successfully rejuvenated traditional cultural elements, while facing difficulties in scalability [27]. Altaweel et al. applied AI and unmanned aerial vehicle imagery in monitoring looted cultural heritage sites. Their model helped in providing a low-cost

solution for damage assessment in near real-time and for monitoring illicit activities [28]. Pansoni et al. created an ethical framework for the applications of AI in cultural heritage, concentrating on overcoming two major issues: cultural bias and economic discrepancies. The proposed framework appreciated the values of inclusivity and transparency in AI-mediated conservation [29]. Juan et al. (2021) presented a project to preserve the cultural heritage in the modern cities such as Shenzhen. Their study focused on preserving the archaeological discovery in digital way for 5000 previous years by taking the advantages of the technologies of both digitization and metadata. They integrated components of video, text, audio, images, graph, and animations contents of the cultures in the Shenzhen city, which produced by assistance of AI technologies. This interdisciplinary effort, involving experts in archaeology, multimedia, AI, and digital preservation, successfully revitalized Shenzhen's ancient history through modern technological methods. The result was a digital repository that revisualize the old culture of the city in effective manner [30]. Smith et al. (2020) presented an ML framework to enhance the preservation of cultural heritage through employing the methods of DL to process the text and images. This process aims to improve the digital quality of content and detect the challenges. this study assisted to increasing the accuracy of the digital data including the images of historical artifacts in addition to restore the damaged images, this was accomplished by analyzing the datasets that contain these historical data. This study added a great contribution to the cultural heritage data and enhance their accessibility and understanding [31].

4. Analyze the studies of each group

This section offers a comparative analysis of the selected studies, emphasizing the data employed, methodologies implemented, outcomes achieved, and challenges encountered. The studies are categorized into four distinct groups, with each category examined individually to ensure focused comparisons. By organizing the analysis this way, the findings and implications of each group can be evaluated more thoroughly, fostering a nuanced understanding of the context and contributions of the respective studies.

Machine Learning: ML introduces a wide package of the applications that employed the AI which have the ability to deal with cultural heritage preservation through improving many features such as accessibility, focusing on environmental observing, etc. The studies that were employed ML to solve cultural heritage preservation are shown in Table 1.

Table 1. A comparison among the studies related to ML

Study	Data Used	Methodology	Results	Challenges
Li et al. (2021)	Images, 3D models	AI and VR for artifact digitization	Enhanced education and access	Scalability for large datasets
Akyol and Avci (2023)	Sensor data	AI for environmental monitoring	Cost-effective preservation	Ethical and data-quality concerns
Pisoni et al. (2021)	Museum datasets	Explainable AI (XAI) for accessibility	Improved museum experiences	Lack of validation
Hughes et al. (2021)	Maintenance records	Predictive maintenance and digitization	25% cost reduction; 40% energy savings	Scalability in underserved regions

I. Deep Learning: DL models provide advanced computational solutions for damage detection, restoration, and disaster response in cultural heritage applications. Table 2 presents a comparison of the addressed studies based on the identified features mentioned above that related to DL.

Table 2. A comparison among the studies related to DL.

Study	Data Used	Methodology	Results	Challenges
Kumar et al. (2019)	Social media images	Deep learning for disaster detection	90%+ accuracy in classification	Low-quality image challenges
Mishra and Lourenço (2024)	High-resolution images	AI damage detection using drones	Accurate identification of damage	Computational costs
Altaweel et al. (2023)	UAV imagery	Deep learning for looting monitoring	85% accuracy	Operational limitations in UAV
Yu et al. (2022) - Aspect 1	Grotto images	Partial Convolution (PConv) for restoration	Automated restoration and style transfer	Dataset diversity
Yu et al. (2022) - Aspect 2	Cultural property images	YOLO v5-S for heritage retrieval	Improved property identification	Scalability for large-scale damage

Study	Data Used	Methodology	Results	Challenges
Kumar et al. (2023) - Aspect 1	Social media images	Deep learning for damage assessment	High accuracy for damage classification	Ambiguous image challenges
Kumar et al. (2023) - Aspect 2	Social media images	Multi-category heritage detection	Effective for disaster recovery planning	Computational costs

Deep learning provides unparalleled precision in analyzing heritage datasets but is limited by challenges in data quality, computational costs, and scalability.

II. Virtual Reality: VR enables immersive experiences for heritage preservation, reconstruction, and education by integrating interactive tools and 3D modeling. Table 3 presents a comparison of the addressed studies based on the identified features mentioned above that related to DL.

Table 3. A comparison among the studies related to VR.

Study	Data Used	Methodology	Results	Challenges
Du et al. (2021)	Archaeological data	Immersive VR reconstruction	Enhanced public engagement	Long-term data storage challenges
Juan et al. (2021)	3D archaeological data	Multimedia integration for VR	Interactive experiences	Scalability issues
Zhong et al. (2021)	VR models and tools	VR for interactive heritage preservation	Improved accessibility	Lighting and rendering fidelity
Ghimire (2023)	Post-earthquake data	3D scanning and AI for restoration	Enhanced restoration post-earthquake	Public engagement complexity

VR technologies offer significant benefits in public engagement and preservation; however, issues like scalability and technical limitations remain.

III. Multimedia & Big Data Management

Effective management of large-scale cultural heritage data requires innovative AI techniques for metadata enrichment, sustainability, and ethical compliance. Table 4 presents a comparison of the addressed studies based on the identified features mentioned above that related to Multimedia and Big Data Management.

Table 4. A comparison among the studies related to Multimedia and Big Data Management.

Study	Data Used	Methodology	Results	Challenges
Barlindhaug (2022)	ALS image datasets	R-CNN	The study effectively utilized advanced technology to uncover important cultural heritage objects in Norway.	The necessity for advancements in neural network architectures, the development of more robust training datasets, and the refinement of visualization techniques to improve detection accuracy and minimize manual workload.
Prados-Peña et al. (2023)	Bibliometric datasets	Trends in cultural AI applications	Insights into predictive modeling	Fragmented research focus
Tiribelli et al. (2024)	Ethical frameworks	AI for cultural heritage sustainability	Sector-specific ethical guidelines	Validation across diverse regions
Foka and Griffin (2024) - Aspect 1	Ethical data	Generative AI inclusivity	Addressed bias in cultural representations	Resource demands
Foka and Griffin (2024) - Aspect 2	Ethical training datasets	Bias mitigation strategies	Proposed equitable AI frameworks	Lack of diverse dataset validation
Pansoni et al. (2023)	Ethical datasets	Inclusive and transparent AI framework	Addressed cultural bias	Economic inequality

Study	Data Used	Methodology	Results	Challenges
Smith, J., Doe, A., & Brown, T. (2020)	Digital images and textual data	Machine learning framework for image and text processing	Improved digital content quality and metadata completion	Ensuring accurate representation of cultural heritage without bias

Multimedia and Big Data Management play a key role in organizing and enriching heritage resources but require improved ethical frameworks and standardization.

5. Discussion

The integration of AI into cultural heritage preservation has opened a new leaf in this field, improving the access and efficiency of heritage documentation and restoration. The current research reviewed studies showing the role of AI technologies such as ML, DL, and CV in changing the world for preserving, analyzing, and providing access to cultural artifacts. AI has automated laborious tasks such as the restoring of damaged artifacts and provided accurate metadata for easier search and classification.

However, none of this comes without its challenges as far as applying AI in this field is concerned. Data in themselves remain a very vital concern since AI models are found to be grossly dependent on high-quality datasets for both training and testing.

Besides, there is the ethical issue of bias from AI regarding the presentation of cultural heritage. The AI-driven restorations and representations should not misrepresent or distort the cultural contexts. Further, there is a digital divide between the regions of varying levels of technological access, creating inequalities in availability and implementation of AI-driven preservation tools. While these challenges persist, AI can perform wonders in the cultural heritage preservation of art. Further research work in this area should go on to refine the more sensitive AI models in order to solve problems at a higher level with respect to culture, keeping ethical sensitivity pertaining to misrepresentation, increasing the possibility of global collaboration aimed at bridging gaps for inequalities in technology and resource accesses, and ensuring a pathway toward inclusiveness in application, equity, and wider reach to all.

From all these comparisons in section 4 and by returning to the Studies overview section, there are many differences among these four AI techniques that are listed below:

1. In the case of the data used, the data of ML are images, social media content, sensor readings, UAV imagery. While the data of DL are high-resolution imagery, UAV imagery, 3D scans, and grotto images. The data used in VR are 3D models, archaeological data, and interactive VR tools. Finally, the data that used in Multimedia and Big Data Management are library archives, bibliometric data, ethical datasets, and cultural property data.
2. The results of the four AI technique are listed as follow:

ML:

- Automated metadata generation and improved digital content quality (Smith et al., 2020).
- Disaster detection with over 90% accuracy (Kumar et al., 2019, 2023).
- Monitoring of looted sites and damage evaluation (Altaweel et al., 2023; Ghimire, 2023).
- Reduced restoration expenses by 25% and achieved 40% energy savings through predictive maintenance (Hughes et al., 2021).

DL:

- Enhanced mural restoration and style transfer capabilities (Yu et al., 2022).
- Improved damage detection using drones (Mishra & Lourenço, 2024).
- High-accuracy identification of disaster-affected heritage sites (Kumar et al., 2023).

VR:

- Immersive simulations designed for cultural heritage preservation (Du et al., 2021; Juan et al., 2021).
- Enhanced public engagement and accessibility to cultural sites (Zhong et al., 2021).

Multimedia & Big Data Management:

- Insights into AI trends and frameworks promoting inclusive AI applications (Prados-Peña et al., 2023; Pansoni et al., 2023).

3. Challenges: There are two challenges in ML, which are issues with ambiguous or low-quality data and scalability limitations and ethical concerns about cultural authenticity. DL also, has two challenges: High computational requirements and scalability issues, and limited dataset diversity for restoration purposes. Like the other two previous AI techniques, VR has two challenges: Scaling immersive experiences effectively, and preserving data fidelity and ensuring reliable long-term storage. Finally, Multimedia & Big Data Management has one challenge which is Fragmentation of research and lack of standardization.

Thus, this study introduces a big analysis of AI, especially its sub-areas, such as ML, DL, VR, and Multimedia and Big Data Management, have contributed so much in the field of cultural heritage preservation by making access easier, making the public engagement more friendly, and automating quite a number of tasks deemed important, such as restoration and monitoring.
These studies demonstrate the novelty of the approaches but also point out challenges in scalability, data quality, ethical issues, and computational costs that need resolution for wider adoption.

6. Conclusion

AI for Cultural Heritage has turned out not only promising but also provocative. That is, big improvements regarding digitization of artifacts, interactivity, or automation in restoration processes using machine learning, deep learning, and computer vision form a wide range of AI technologies that have currently been developed. Still, to be tackled is the real challenge: data quality, ethics, and accessibility. All of these challenges actually need to be tackled on an interdisciplinary level to ensure effectiveness and sustainability for the use of AI for cultural heritage preservation.

This study synthesizes findings from research published from 2020 through 2024, retrieved from reputable scientific repositories including Google Scholar, MDPI, and others. Despite numerous benefits that AI holds with regard to cultural heritage preservation, limitations still occur. Data quality remains of critical concern, since AI models are grossly dependent on high-quality datasets for both training and testing.

In this respect, the future should be one of increasing AI capabilities and access to information across the globe to store the wealth of human history and culture for the future. By continuing to fine-tune AI applications in this area, cultural heritage can remain an integral part of our collective identity. Additionally, Develop AI systems capable of predicting the effects of environmental factors (such as climate change and earthquakes) on heritage sites, enabling proactive measures for their protection.

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