

Integrating Geochemical Assessment and Social-Media Analytics to Evaluate Heritage Stone Decay at Lahore Fort: Evidence from Instagram Data

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ABSTRACT

Sites of cultural heritage, such as Lahore Fort (a UNESCO World Heritage site), are under increasing danger from environmental and human caused factors resulting stone structures deterioration. This study on the deteriorating stone of Lahore Fort is complex—integrating a geochemical analysis and social media data mining approach to environmental degradation incidents caused by tourism in relation to cultural heritage preservation. The Continues below Exploring the fort: The study uses state-of-the-art geochemical tests to study the disintegration of stone surfaces at the fort, and harnesses data from Instagram to measure how often tourists visit the structure. By using machine learning, we learn useful information from Instagram images to help relate human activities with stone deterioration. The effects of tourist traffic on various types of stone damages are exacerbated by certain aspects, and coupled with those environmental factors, make it increasingly difficult for the conservation. The work presented here is part of a larger movement toward the growth and expansion of partnerships that combine scientific analysis with digital humanities for improved heritage management. The results offer policy makers important insights on how to better manage heritage sites under pressure from flooding and tourism in the context of climate change.

Keywords: Heritage preservation, stone decay, Lahore Fort, geochemical assay, Instagram data mining, tourism impact, machine learning

INTRODUCTION

Heritage conservation is well known as a key challenge for the protection and preservation of historical and cultural sites worldwide. Being very important not only for historical and architectural reasons, but also for tourism interest and local economy development, cultural heritage sites should be preserved. Lahore Fort in Pakistan is a UNESCO World Heritage Site. It was inscribed in 1981 for its outstanding repertoire of Mughal monuments dating from the era when it was the capital of the Mughal Empire between 1556 and 1612. The fort, however, is a UNESCO World Heritage site and one of the most visited nontourist spots in South Asia. It contains beautiful specimens of Mughal architecture, stone carving and has a fine facade inlaid with marble and slate work. Lahore Fort is becoming a victim of the perils faced by numerous heritage sites the world over such as environmental pollution, urban decay and increasing footfalls of tourism.

Lahore Fort's stone features, integral to the character of the site have suffered considerable loss over time. It has been recently learned that the stone decay is a major problem, enhanced by pollutants like acid rain, nitrogen dioxide and sulphur compounds (Ali 2022). Pollution in the largely urbanized heart of Lahore has increased, and this has hastened eroding stone used to build the fort, which, combined with water damage and age, is making the carvings less detailed while also compromising structural stability. The fort is also a major tourist destination, which though this will boost the economy; it too presents its own challenges for preservation. Higher foot traffic by tourists coupled with contact with the monument and even photography produces additional abrasion on the monument which continually exacerbate its decay (Krause & Green, 2020).

The use of cutting-edge scientific methods combined with digital means, such as Instagram mining, holds great potential for examining and managing those challenges in a new way. The integration of geochemical analysis with social media investigation, especially using formats such as Instagram, provides a novel tool for monitoring not just the physical status of monuments but also human (e.g., visitors') impact in the field. This article seeks to investigate: the extent to which the imaging and sharing of

heritage influences a structure's physical condition through the tourist experience of these sites. Social media, of which Instagram is one of the biggest tourism-related platforms, offers valuable insights into visitation patterns and their association with heritage site damage (Smith et al., 2023). The variety of content creation on Instagram has enabled researchers to gather large-scale data on tourist behavior and preferences, shedding light on the impacts human activities have in inducing heritage decay.

In the field of cultural heritage studies, heritage conservation is considered to be a legacy whose study for ages aims at environmental factors, comprising pollution and weathering till physical degradation. It has been reported that air pollution such as industrial and vehicular emissions are the most significant causes of decay of stone-built monuments, including historic buildings, statues e.t.c. Stone surfaces can react with the sulphuric and nitrogenous compounds present in the atmosphere, causing chemical attack on representative works or constituent parts of a medieval building (Krause & Green, 2020). But although these pressures on the environment are still important, there is an increasing awareness of how human activities (and tourism in particular) are contributing to the accelerated decay of heritage sites. Tourists who visit the sites commonly physically touch, climb or stand near the monuments for taking photographs which can cause stone degradations (Li & Zhang, 2022).

Besides, impact of tourism is not confined to a direct physical contact. The number of people circulating can augment the risks relating to pollution, particularly in cities with poor air quality. It is increased by environmental degradation, which means that it becomes even more essential to study the combined effect of tourism and pollution on heritage preservation. In the last couple of years, with the rise of social media in platforms such as Instagram, tourism has established a new ground in which it is approached and studied. On Instagram, millions of visitors document their outings – which content can be revealing about the way people engage with cultural icons. The visual data recorded by these systems can then be compared to monitor visitor behavior, determine which areas within a site are more popular and how high traffic may lead to greater damage from human activity Smith et al. (2023). Through using

such new methods, researchers may better comprehend the intricate relationship between tourism and heritage conservation.

Significance

Similar to other cultural icon, Lahore Fort too is facing rapid environmental and anthropogenic transformations which require immediate focus and integrated preservation measures for safeguarding its value. The fort is not only national treasure of Pakistan; it is also an invaluable asset to the patrimony the whole world. It has monumental architecture and historic value, so it is important to conserve. Yet the twin challenges of environmental destruction and tourist-related erosion suggest that conservation should involve more than a single strategy.

The project will fill a void in heritage conservation by taking an interdisciplinary approach to the analysis of nature and how it is perceived, adding much-needed social and environmental context to the subject. The contribution of this work is important as it represents the first time that geochemical assays and digital data mining techniques have been combined together to provide a complete study of heritage decay. While geochemical analysis provides key information on the physical state of the stone, as well as the level of environmental damage, social media analysis leads to understanding tourist activities patterns and their involvement in this degradation. In combining these approaches, this research is not only able to deal with the direct environmental factors but also takes into account the indirect effects of human activity, mainly tourism, on the conservation of heritage sites.

The results of this study are believed to give a better insight into the association of tourism and heritage deterioration that can contribute substantially towards future conservation policies, as well as toward the formulation of strategies for controlling tourism impact on cultural monuments. Against the backdrop of macro-scene-becoming and encroaching forces on the heritage, it is crucial to utilize cutting-edge methods underpinned by a scientific (see above) as well as digital-based approach to preserve cultural heritage into future time scales. Finally, the study may provide a model for other heritage sites around the world that have similar issues, providing new concepts of sustainable tourism and heritage preservation.

Research Objectives & Hypotheses

The main aims of this study are:

Geochemical Studies to Determine the Extent of Stone Decay in Lahore Fort.

To study tourist visitation patterns and their relation to stone erosion in Meoto Iwa island by using Instagram data.

To offer advice on how the negative effects of tourism could be managed to protect the site's iconic heritage.

We have been suspected that human activities (tourism) on the one hand combined with environmental influence, has played a crucial role to accelerate the decay of stone structures.

LITERATURE REVIEW

Early studies on heritage preservation largely aimed to protect against environmental factors such as air pollutants, acid rain or weathering that were identified as the primary causes of monument deterioration (Hagerty et al., 2018). Yet, increasingly the very human interventions – especially tourism – that further aggravates the decline of heritage sites are making headlines. Nowadays, (inter)national conservation of heritage is associated with an interdisciplinary response that implements classical forms of preservation in combination with latest technologies to cope with aspects of both natural and human-induced changes (Sharifi & Yusof, 2020).

Conservation of heritage has matured rapidly throughout the last decades, and it is thanks to this development in scientific methodologies that today we are able to more accurately measure and limit the impact from environmental as well as human actions on historical sites. Geochemical study is one of the most frequently used methodologies to investigate stone decay. The chemical composition of stone materials and the reasons for their deterioration have often been studied through the use of techniques such as X-ray diffraction (XRD) or scanning electron microscopy (SEM). For example, XRD is able to be used for crystallite structures analysis with more effective (Cheng et al., 2019) and could make it possible to identify the chemical weathering and other possibly compounds generated by the environmental pollution. SEM can be used to obtain high-resolution images from stone surfaces,

aiding in the characterization of microstructural damage and physical alterations that results from pollutant action.

Besides traditional geochemical methods, interest has emerged during the last years on the application of new digital techniques to monitor and analyze degradation of heritage sites. A more creative use of social media, especially Instagram, is to monitor tourist behavior at cultural heritage sites. Instagram is increasingly recognized as a precious tool to study the impact of tourism on heritage sites, thanks to its potential to access large quantity of data from tourists sharing images, videos and contents that can be location-tagged. Utilization of machine learning algorithms and image recognition tools to analyse these data sets has only recently emerged, allowing patterns to be recognized in tourist behaviour by spatial visitation (Zhang & Wang, 2021). For instance, social media data make the most visited spots of a heritage site known so that it is possible to pinpoint what portions are at the greatest risk of physical risk being affected by excessive tourist activity. The amalgamation of digital and geochemical analysis, here mediated through Instagram data mining, is here proposed as an innovative interdisciplinarity approach that can allow for new understandings to be developed concerning conservation practices relative to heritage sites.

A number of other advanced methods have been utilized to assess environmental factors affecting the degradation of heritage sites. Remote sensing, including satellite images and drones, has been used to evaluate environmental changes affecting cultural sites. 4.2 Example applications 1) Urbanization, air pollution and deforestation near heritage site may affect the long-term stability of monuments (Li et al., 2021). Furthermore, sensors for environmental monitoring can be set in/on or near heritage sites to monitor air quality, humidity and temperature and other useful environment factors responsible for cultural heritage decay as well (Hagerty et al., 2018). These advances are allowing the characterization and preservation of heritage sites to be more complete and in real time.

The effect tourism has on heritage sites has long been a subject of investigation, with growing interest in recent decades, as many investigators have concluded that tourism

represents one of the most destructive forces to culture monuments. In its early days, research into tourism's impact on heritage concentrated largely on visitor behaviour and management measures against the wear and tear of monuments. For instance, Anderson & Rich (2019) assessed tourists' physical interactions with monuments - including foot traffic and direct contact with stone surfaces. They also highlighted that visitor management measures, including restricting access to high-risk areas and regulating the number of people entering at peak times, could help mitigate some of the physical effects tourism creates on heritage sites. Besides that, the investigations of Durmaz & Mutlu (2020) further explored how physical behaviour observed from visitors, including contact, climbing and picture-taking process, lead to increased degradation due to wear on the surfaces of historic buildings.

Yet the majority of these were more qualitative in nature, looking at visitor use and how to control damage. These typically draw on direct observations, surveys and interviews with tourists—valuable resources—but not amounting to the kind of comprehensive data that would allow a more complete analysis of impacts over time by tourism. Moreover, despite the well-established impact of tourism on physical degradation, to date no attempts have been made to combine digital data from social media with scientific methods for the purpose of quantifying and monitoring such an impact on heritage by tourism.

This lack in the literatures creates space for original research that uses both established scientific methods and recent digital instruments. For instance, an innovative approach of using Instagram data with machine learning algorithms can enable one to explore who are the visitors and where they go in a heritage site due to tourism. When this information is combined with geochemical factors for the decay of stonework, it can expand our knowledge of how tourism and elements in the environment contribute to historic deterioration. There are few studies on this interdisciplinary, and so it has an important research space.

Additionally, although this social media data analysis contributes to understanding tourist visitation patterns, research on the medium-long term impacts of social media tourism in heritage conservation is still called for. Among the recognition of less

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famous are those that have had a boom based on social networks and lead to subsequent overexploitation in number of visits and consequent deterioration (Smith et al., 2023). This trend, as it has been called – also dubbed “Instagram able tourism” – has generated worries about the sustainable development of cultural heritage. Yet little is known about the long-term effects of this process on physical decay and its broader implications for heritage conservation.

Also, beyond the direct consequences of tourism, further research should extend its gaze to the larger impact of digital platforms on heritage management and conservation. Using the scientific and digital data to combine into a singular method, researchers may measure not only direct physical impacts for tourism but also have an understanding of underlying trends and behaviors that contribute in damaging heritage. This kind of studies is crucial to design more efficient solutions for a sustainable protection of cultural heritage sites, which are under increasing pressure because of the development of tourism.

METHODOLOGY

This research used a mixed-methods design, which combined qualitative and quantitative methodologies to provide multi-dimensional understanding of causes of deterioration in heritage stones at Lahore Fort. Mixed-methods approaches are highly applicable to conducting exactly these kinds of research because they provide the means to capture a wide array of data forms – quantitative geochemical and Instagram-mined assaying data, qualitative exploratory interviews with tourists and conservationists. By integrating both, the research is able to examine not only the physical effect of environmental elements and tourism on the site but also human activity and perceptions that may contribute to site degradation. This design allows for a comprehensive examination of the topic, where both scientific and social perspectives are needed in heritage conservation (Creswell & Poth, 2017). It also offers a solid basis for monitoring the effects of environmental pollution, human activities and the physical degradation of cultural heritage.

Geochemical Studies Stone samples were taken from around the different parts of Lahore Fort especially the stations with apparent damage and tourist overload. These

locations were chosen through initial experience and literature that indicated these are highly susceptible to degradation (Ali, 2022). The stones and lithics were analyzed for mineral composition and the state of their crystal lattice using modern geochemical methods such as X-ray diffraction (XRD) and scanning electron microscopy (SEM). Inductively Coupled Plasma Mass Spectrometry (ICP-MS) was also used to determine the content of elements in stone samples, and such move helps the reuse or the sources of micropollutants including sulphone's, nitrogen compounds and metals that are recorded into decayed stones. Quantitative information on the level of environmental damage and the composition of these pollutants affecting the stones was given by the outcomes in these assays (Cheng et al., 2019).

Instagram Data Crawling: Instagram data was captured by means of custom machine learning-based algorithms developed to scrape publicly available posts tagged with relevant keywords including #LahoreFort, #VisitPakistan and other similar hashtags. This process of mining data allowed me to assemble a sizable sample of fort-related images and metadata. The study of these Instagram posts was primarily aimed at identifying space and time patterns in tourist visits, with a specific focus on which part of the fort were most visited. Location and tourist interactiveness (eg, having been photographed in a given location) of the posts were categorized using image recognition and natural language processing (NLP). This allowed quantitative analysis to determine what parts of the fort were most highly trafficked and visually attended, leading to site damage (Zhang and Wang 2021).

There were two types of sampling for this study in which quantitative data from social media were paired with qualitative interviews. 2. Results 2.1 Dataset A sample of 2000 Instagram images were selected, based on a wide range of users who posted contents for Lahore Fort, with respect to the number of hashtags used by them. The sample size was considered enough to capture a variety of tourist interactions and trends in visitation. In addition, 40 semi-structured interviews were performed with a wide range of other individuals (local guides, conservationists and tourists). These interviews yielded qualitative data on the attitudes and actions associated with conserving the fort, as well as social and economic forces underpinning tourism. By

triangulating information from these two distinct informants, the research was able to gain a more sophisticated understanding of the continued despoilment of heritage taking place as a result of tourism (Anderson & Rich, 2019).

In the context of Instagram data analysis, machine learning models such as deep learning were used to analyze and categorize images according to their content and associated metadata. To gain a sense of what was happening, the research team used NLP protocols to extract hashtags, location data and captions from the posts—context that would add rich nuance and help identify the particular parts of fort most photographed by tourists. The frequency of interactions (comments and likes) was also used as a measure of popularity for various parts of the site.

On the geochemical side, elements in stone samples were analyzed using ICP-MS. That made it possible to measure trace elements that can provide evidence for pollution levels that lead to stone decay. Cross-referencing these findings with the geolocations of high tourist activity recorded in the Instagram data allowed us to associate levels of deterioration with distinct tourism behaviours and environmental exposures (Li et al., 2021).

Ethical issues The ethical components of the research were based on informed consent obtained during interviews, and all interviewees remained anonymous. Community workers explained the purpose of the study to participants, and participation was strictly voluntary. Publicly available Instagram data was examined with particular concerns for privacy, and no personally identifiable information was leveraged without consent.

rigorous cross-validation techniques were used to validate the accuracy of data in the study. The result of the Instagram photos was crossverified with the geochemical analysis to check for uniformity and correctness. Furthermore, the qualitative findings in the interviews were compared with quantitative results to ascertain consistent patterns and validate the findings. Literature review had added both credibility and validating an enriched meaning of the complex multidimensional issues around Lahore fort (Creswell, 2014).

RESULTS AND EVALUATION

The chemical analysis of stone samples collected from Lahore Fort indicated a great deal of decay, mainly due to the influence of high tourist traffic. The X-ray diffraction (XRD) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) analyses showed that the levels of pollutants, for example sulfur and nitrogen-based compounds, were increased in the stone. These pollutants, typically associated with urban pollution, were also discovered to be particularly concentrated in the areas of the fort visited by large numbers of visitors. This implies that environmental factors, such as air pollution, promote the faster deterioration of the stone in these high traffic areas (Cheng et al., 2019). The high contents of sulfur-containing compounds, for example, are characteristic of acid rain and atmospheric pollution that have been identified as promoters of chemical weathering of stone materials (Hagerty et al., 2018). In addition, plots with visible loss of soil had significantly more NO₂ and SO₄ attributed to vehicular emissions and industrial pollution (Li et al., 2021). This information highlights the importance of environmental pollutants in the deterioration of monuments such as Lahore Fort.

The Instagram study, however, found distinct patterns of tourist engagement with different areas of the fort. The most visited places of tourists such as the Sheesh Mahal and the Alamgir Gate were among the most prominently displayed in Instagram posts. These territories showed more frequently posts, likes and comments, although they are more valuable tourist places. These results correspond well with Instagram findings; in the most posted areas there were also geochemically signs of more severe stone decay. Maybe you can even try to combine with these, because it also confirmed that the more human interactions (unlike/Instagram talking about) we have the worst are their physical conditions of each site (Zhang & Wang, 2021).

The information was complemented with locals guides through informal interviews which are qualitative oriented and brought out the dynamics of tourism toward conservation of Lahore Fort. The guides stressed the need for control of tourist traffic, especially in historically sensitive or architecturally fragile regions. They wrote: 'Tourism is of major importance for the local economy, but it also implies large

challenges to conservation efforts.' Tourists, particularly those not fully aware of the significance of the site, would do things that accelerate wear and tear such as climbing walls, feeling on gentle stone carvings and even sitting on some architectural elements to take photographs.

Conservationists concurred, while also pointing out this erosion is exacerbated by the higher number of visitors and ongoing exposure to pollutants. The guides also observed that some of the most visited attractions, like the main entrance and courtyard of the fort are already wearing down from constant human interaction and exposure to environmental elements. This knowledge highlights the importance of approaches in visitor management that mitigate against further degradation of the site (Anderson & Rich, 2019).

Combining the geochemical with Instagram analysis provides a holistic perception of the decay of stone infrastructure of Lahore fort, due to tourism and environmental factors collectively. The evidence thus reveals a complicated interplay between human and natural action, which the two conditions conspire to amplify stone degradation. Posted by Hipwell Supplied Air pollutants such as sulfur and nitrogen are major contributors to chemical weathering, but social media foot traffic, and thus physical contact with the site (based on Instagram data), adds to the rate of degradation.

This interdisciplinary methodology, mixing scientific with social media data, offers a detailed insight into the problem of preserving heritage. The findings indicate that, besides incidence of environmental pollution, influence of tourism should also not be neglected. Integrated with scientific assays and digital analytics, this research provides a broader perspective of the impact of modern tourism on cultural heritage decay, offering important implications for future conservation practise. These findings strengthen the argument for a conservationist approach in managing tourism, wherein conservation efforts run parallel with sustainable tourism development towards protecting these vulnerable heritage sites (Sharifi & Yusof, 2020).

DISCUSSION

This research has helped to elucidate what are the causes of accelerated decay for Lahore Fort stone faces due to human activities and environmental pollutants being major culprits. The geochemical analyses also indicated a striking decay in high-traffic scenes, influenced by pollutants, especially of sulfur and nitrogen compounds intensity influence on the chemical weathering. The process is accelerated by the contact of tourists with such surfaces and their activities (as touching or photography). These behaviors not only physically erode the monuments, they deposit oils and contaminants that promote further deterioration of the stone (Hagerty et al., 2018). The cooperation of environmental pollutants including acid rain and air pollution, along with human impact due to the increased visitation speeds up in deploying of stone as well as its vulnerability for decay (Li et al., 2021).

Instagram post data corroborate this finding, and show that tourist traffic occurs at spatially concentrated regions corresponding to the most impaired sub-areas. Crowded contemporary destinations, Sheesh Mahal and Alamgiri Gate, reflected more wear and tear compared to other sites, providing the proof that human intervention also has a role in destruction. Data also yielded patterns of increased use in these hotspots, including the frequency of photos and social media postings to be found there (with popularity on social media mirroring likeliness for physical decay). This convergence of digital and physical information also highlights the requirement to develop management strategies for both natural and anthropogenic sources causing heritage loss (Zhang & Wang, 2021).

The findings also propose that the process of erosion at Lahore Fort is not necessarily time or age-bound, but rather a dynamic relationship between the physical environment of the site and human interventions. The study adds further weight to the idea that there is, then, a degree of unprecedented pressure mounted on heritage sites in the contemporary assemblage due to environmental change and mass tourism that labours world cultural heritage sites into an accelerated decay (Anderson & Rich, 2019).

Based on the results, this study has significant implications for heritage management. First, it is important to operationalize visitor management measures that minimize the physical intrusion of tourism in delicate areas of the fort.

There should also be a public information campaign to teach tourists about the historical consequences of their actions in these sorts of historical sites. Educating visitors on the value of maintaining cultural landmarks and providing the proper behavior, such as not climbing or touching the stone would be an effective way to diminish physical toll on the fort. Strict regulations for the control of pollution, in addition would be helpful to reduce the exocrine factors for durability of stone. This could be done, for example by vehicle emission policies and industrial pollution (around areas with heritage sites) or higher surveillance of air quality to preserve the fort's construction material (Cheng et al., 2019).

Lastly, the use of digital technologies including scraping Instagram data could also give useful information into visitor's behavior and help to target conservation strategies. Using social media analytics, tourist patterns can be learned in order to help authorities predict where there will be high foot traffic and deploy conservation efforts ahead of time (Smith et al., 2023). "This is the future for heritage conservation," added Prof. Andras, "where you can have instant feed back which will enlight not only policy but also the way down to ground science."

Although this study provides many insights, there are several limitations to be borne in mind. A major drawback is the difficulty in accounting for all environmental factors, which may affect stone decay at Lahore Fort. Although the analyses were directed at the high use areas and specific pollutants, other environmental factors of temperature changes, humidity levels or the even presence of micro-organisms on stone surfaces also influence deterioration (Krause & Green, 2020). However, such a phenomenon was not considered in our research and it might to affect very much the erosion as well so that future work should be proceeded.

Another potential limitation pertains to the use of publicly available Instagram data than may be not reflective for (on) the entire tourists population. Although Instagram is a useful platform through which to gain insight into visitor patterns, it may

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overestimate some categories of tourist (e.g. tourists who are more social media active) and attract more visitors in the site for its Ample evidence for observing this effect can be found online^{50–52}. This may lead to biased data that does not reflect the behavior of all tourists, especially those who are not active in social media (Zong & Zhao, 2022). Additionally, the data are observational and derived from public-facing posts—these do not always have exact location information or may account only for visitors who choose to post pictures online.

CONCLUSION

This research has important implications for the development of holistic approaches to heritage protection, particularly in locales such as Lahore Fort, where the twin pressures of tourism and environmental decay intersect. “Lahore Fort, the house of Lahore” is faced by natural as well as anthropogenic threats such as vehicular pollution, acid rain, and increasing tourist activities (roof and spamer 2007; Hussain et al. Classical conservation procedures are no longer capable of dealing with the many issues that today contribute to the degradation of culture heritage structures. This research presents a new method by integrating geochemical analysis with social media mining, which could gain insights into the physical deterioration process of heritage sites and catch human behaviors to enhance this process (Cheng et al., 2019). Through combining scientific (stone weathering) data with digital information from platforms such as Instagram, the paper presents an innovative approach to assessing the effects of tourism on heritage preservation. Social media data mining allows for real-time tracking of visitor activity and can determine areas on the site that are more prone to damage, considering user interaction. Moreover, geochemical analyses provide an objective and measurable evidence for environmental degradation which would contribute to more effective conservation strategies (Zhang & Wang, 2021).

Surely, future conservation will have to continue on the cross-disciplinary path that this initiative represents -- calling upon information within environmental science, electronic circles and tourism studies. With growing threats from human force, as well as the effects of climate change, put upon heritage sites across the globe, it is necessary for conservation to continue in this era along with modern technology.

Digital methodologies (e.g., social media data mining) may be able to yield useful insights about visitor trends, and science-based approaches can monitor the state of physical health of monuments so that they continue to contribute to the cultural patrimony for future generations (Smith et al., 2023).

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