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INTEGRATING PREVENTIVE CONSERVATION AND CLIMATE CHANGE ADAPTATION: STRATEGIES FOR SUSTAINABLE PROTECTION OF CULTURAL HERITAGE IN EGYPTIAN MUSEUMS

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ABSTRACT

Egypt is renowned country for its vast, unique cultural heritage which testifies its long, diverse history and serves as a source of national pride. The preservation of this treasure in the face of the escalating climate change crisis is challenging and requires a multifaceted strategy that integrates heritage preservation practices with climate change adaptation measures. In Egypt, artefacts are housed in newly built museums, historical museum buildings and older museums, each differing in nature and infrastructure capabilities. This paper selects key Egyptian museums representing these categories and analyses the strategies employed in the selected museums for mitigating the risks posed by climate change-related threats, including rising temperature, increased humidity, and frequent extreme weather events. By surveying the preventive conservation practices implemented during the last years, and exploring the decision-making process for the artefact protection, this study aims to evaluate the effectiveness of these strategies and identify the critical gaps needing further improvement. It offers practical recommendations for policymakers, conservation scientists, and museum professionals based on the challenges encountered in these museums. The findings of this paper not only guide the decision makers but also actively contribute to the global discourse on preserving cultural heritage in the face of climate crisis.

KEYWORDS: preventive conservation, climate crisis responses, sustainability, resilience, Grand Egyptian Museum, Egyptian Museum-Cairo, decision-making, evidence-based conservation strategies.

1. INTRODUCTION

Cultural heritage is an irreplaceable asset that connects communities to their history, fostering a sense of identity and belonging. Egypt, with its unparalleled wealth of archaeological treasures and historical artefacts, serves as a testament to the rich civilisations that have thrived along the Nile for millennia. This heritage holds immense historical, cultural, and economic value. Nowadays, these treasures are increasingly under threat from the multifaceted impacts of climate change.

Located at the crossroads of North Africa and the Middle East (Bahgat, 2023), Egypt experiences a hot desert climate characterised by wide temperature variations and low annual precipitation (Mandour and Ebrahim 2023). Projections indicate that the nation is particularly vulnerable to rising temperatures, increased humidity, and more frequent extreme weather events (Hamed et al., 2023), all of which pose significant risks to cultural heritage. These climatic shifts exacerbate the natural aging of materials, accelerate decay, and compromise the structural integrity of artefacts and buildings alike.

The preservation of Egypt's cultural heritage, therefore, requires a proactive approach that integrates preventive conservation strategies with climate change adaptation measures. Preventive conservation, which focuses on maintaining stable environmental conditions to prevent damage to artefacts, has become a cornerstone of modern museum practices. However, as climate change accelerates, traditional methods alone may no longer suffice. Museums must evolve, employing innovative strategies and leveraging new technologies to mitigate the emerging risks.

This study investigates the potential of developing strategies for sustainable protection of cultural heritage in Egyptian museums in the face of climate change crisis through analysing the conservation practices implemented over the past decade in two pivotal institutions in the country's heritage landscape, the Grand Egyptian Museum (GEM) and the Cairo-Egyptian Museum (EM), in order to assess the effectiveness of current strategies in mitigating climate-related risks, identifying gaps, and proposing actionable recommendations to enhance resilience across Egypt's museum sector.

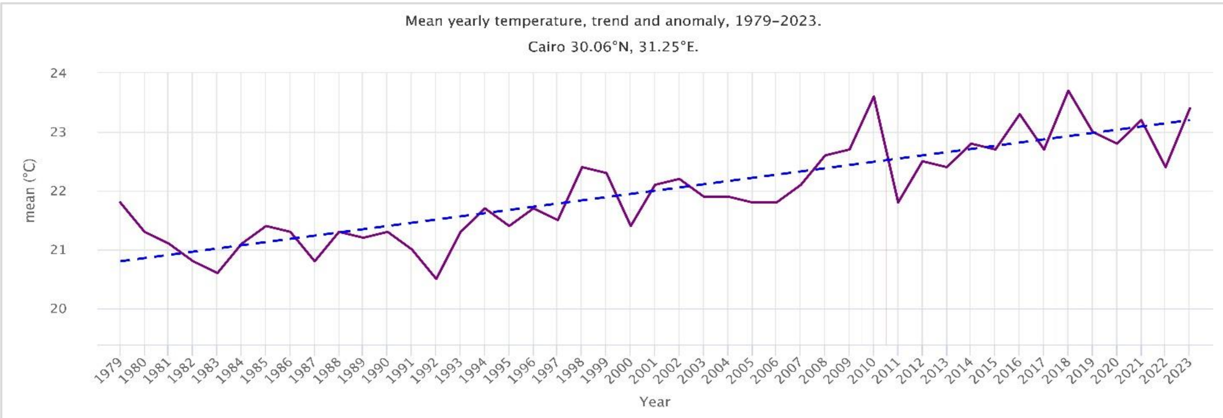
GEM and EM represent two leading institutions in the country's heritage landscape. GEM, the newest and most technologically advanced museum, offers state-of-the-art conservation facilities and showcases a forward-looking approach to artefact care. EM, by contrast, stands as a testament to historical museology, housing a vast collection in a building with over a century of heritage. Together, these museums provide an ideal framework for examining how preventive conservation and climate adaptation strategies can be implemented across differing institutional contexts.

This research is particularly timely as the global cultural heritage community grapples with the implications of climate change. Through a detailed analysis of these two case studies, the findings of this research extend beyond Egypt, contributing to the global discourse on preserving cultural heritage in the face of the climate crisis. The study provides a roadmap for sustainable heritage management by bridging the gap between traditional conservation practices and innovative climate adaptation strategies, ensuring long-term protection of heritage treasures for generations to come.

2. CLIMATE CHANGE: HEIGHTENED RISKS FOR CULTURAL HERITAGE IN EGYPT

Climate change represents one of the most pressing challenges of the 21st century, threatening ecosystems, economies, and cultural heritage alike. Humanity is facing a grave threat from climate change (Goklany, 2012; Randle and Eckersley 2015; John et al., 2023) derived from not only the average temperature increases but also the loss and damage caused by climate change (Effiong et al., 2024), such as increasing sea levels (Friend et al., 2022), coastal erosion (Hamed et al., 2024), extreme weather (Engdaw et al., 2024), shifting wildlife populations and habitats, desertification (Ganzour et al., 2024), and decreased soil fertility (Elemam and Hamam 2024; Ganzour et al., 2024), which results in food and water scarcity (Abou-Ali et al., 2023). While its catastrophic impacts can be felt anywhere in the world, Egypt particularly is in a highly vulnerable region (IEA, 2023) due to its geography (Ganzour et al., 2024; Hamed et al., 2024), and reliance on natural resources (Egypt's Updated Nationally Determined Contributions, 2023). The World Bank's Climate Knowledge Portal (World Bank Climate Change Knowledge Portal, (n.d.) indicates that Egypt experiences a hot desert climate with significant variations in temperature and precipitation across different regions. Climate change projections for Egypt indicate rising temperatures, altered precipitation patterns, sea level rise, and increased sand and dust storms (Hamzawy, 2023). Figure 1(a) shows an estimate of the mean annual temperature for the Greater Cairo. The trend line clearly slopes upwards, showing a distinct warming trend over time due to climate change. Figure 1(b) shows the temperature anomaly for every month since 1979 up to now. The red bars indicate that the month is warmer than the 1980-2010 average, and the blue bars indicate that the month is cooler than the average. While the earlier years show a mix of warmer and cooler months, the recent period is marked by a strong prevalence of warmer-than-average temperatures. The blue bars become less frequent and less intense, with most months showing temperatures above the average. This strongly shows a significant, long-term warming trend and its acceleration in recent years and indicates more frequent and intense heat events. Figure 2(a) shows an estimate of mean total precipitation for each year. The trend line is relatively flat, with a very slight upward tilt, meaning nearly no significant increase or decrease in average yearly rainfall over time. However, Figure 2(b) shows how each month's precipitation deviates from the 30-year average (1980-2010). The green bars indicate that the month is wetter than average, and the brown bars indicate that the month is drier than average. The anomaly graph reveals that while the total amount might be stable, the distribution of rainfall within each year is quite variable. Some months experience significantly more rain than usual (green bars), while others are much drier (brown bars). Tall green bars are noticed frequently in the anomaly graph, particularly around 2020. These indicate months with exceptionally high rainfall, suggesting an increase in extreme precipitation events, even with a stable average.

According to Egypt's Climate Risk Profile (USAID-ATLAS Project), significant climatic shifts are projected by 2050. Average annual temperatures are expected to increase by 2 – 4 °C, with Upper Egypt experiencing the most significant warming. While overall rainfall is projected to decrease, the risk of extreme precipitation events and associated flash floods is expected to rise. Rising sea levels pose a threat to the Nile Delta and Mediterranean coastlines, increasing salinisation and coastal erosion (Climate Risk Profile: Egypt, 2018). Furthermore, a projected increase in the frequency and intensity of storms is expected (IEA, 2023). These projected changes directly threaten Egypt's archaeological and museum collections. Artefacts composed of organic materials, stone, and metal are particularly sensitive to the resulting fluctuations in temperature, humidity, and salinity, potentially leading to irreversible damage.



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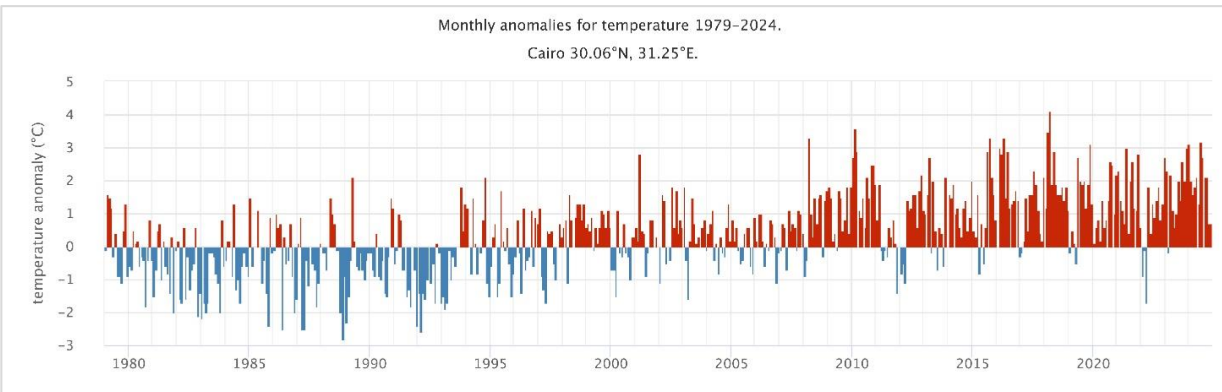
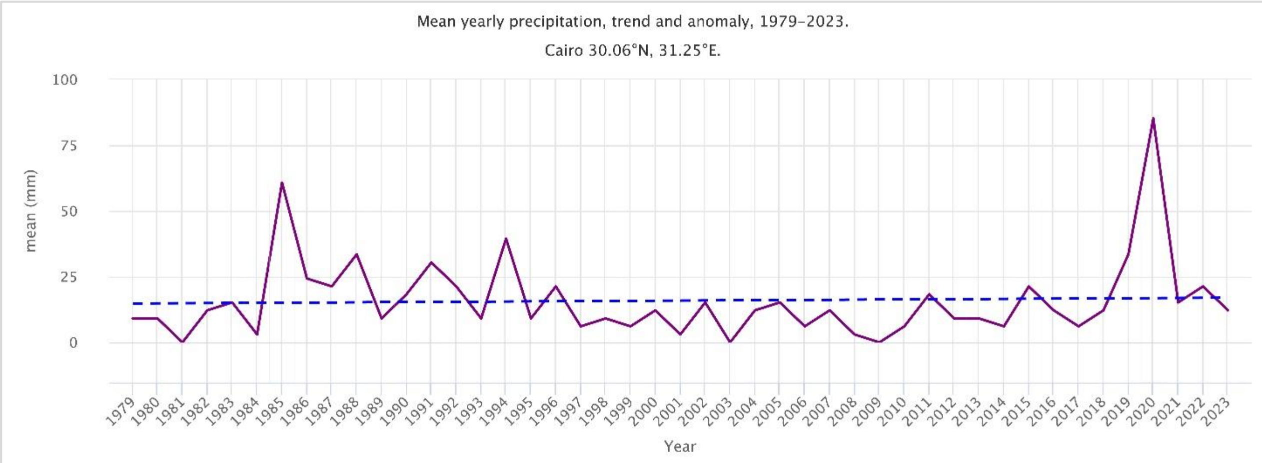


(b)

Figure 1. Climate Change Cairo, Egypt, 30.06°N 31.25°E: (a) the mean annual temperature and the linear climate change trend (dashed blue line), (b) the temperature anomaly for every month since 1979 up to now (Climate Change Cairo, n.d.).



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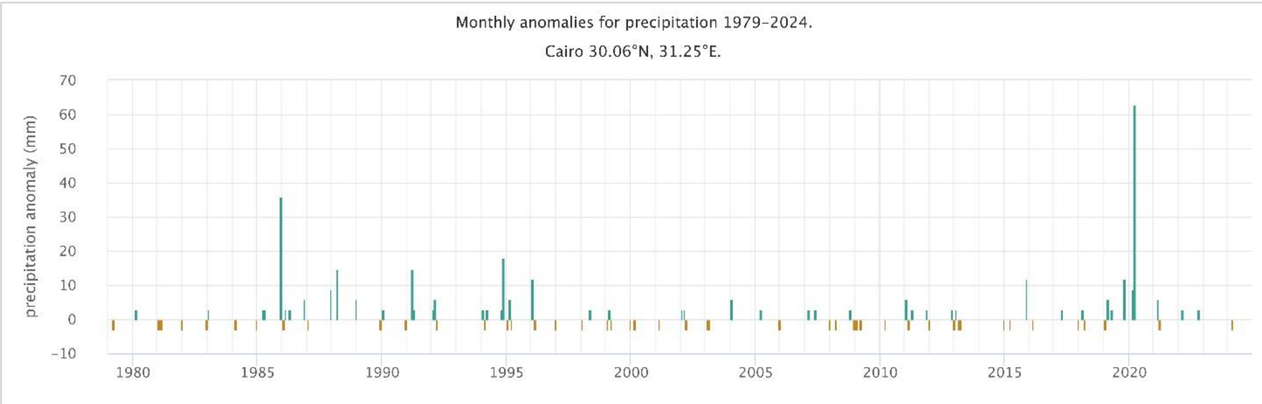


(b)

Figure 2. Climate Change Cairo, Egypt, 30.06°N 31.25°E: (a) the mean annual precipitation and the linear climate change trend (dashed blue line), (b) the precipitation anomaly for every month since 1979 up to now (Climate Change Cairo, n.d.).

2.1. Egypt's Overall Climate Commitments and Adaptation Strategies

Recognizing the urgency of addressing climate change, Egypt ratified the United Nations Framework Convention on Climate Change (UNFCCC) in 1994, marking its commitment to addressing climate change based on the principle of common but differentiated responsibilities (Egypt's Updated Nationally Determined Contributions, 2023). In alignment with the Paris Agreement, Egypt's Intended Nationally Determined Contribution (INDC) was submitted in November 2015 and subsequently updated, reflecting the country’s developmental objectives and climate policies through 2030 (National Strategy for Disaster Risk Reduction 2030: Summary for Dissemination, 2017). The country’s climate policies aim to balance developmental objectives with environmental sustainability, covering the period up to 2030 (Egypt's Updated Nationally Determined Contributions, 2023).

Key initiatives under Egypt’s climate strategy include embarking on a significant energy transition, investing in renewable energy sources and improving energy efficiency (Aboulnaga and Elsharkawy 2024; AlSiyabi et al., 2024; Gibson at al., 2024; Raihan et al., 2024). Egypt has already initiated various adaptation projects focusing on mitigating climate risks in agriculture, water resources, and coastal zone (Elemam and Eldeeb 2023). Moreover, Egypt has actively engaged with the international community to secure financial and technical support for climate action (Salah et al., 2022; Abdelaty et al., 2023; Egypt's Updated Nationally Determined Contributions, 2023).

Despite Egypt's commendable progress in addressing climate change, these efforts largely focus on sectors like agriculture, water resources, and coastal protection. Cultural heritage remains underrepresented in Egypt’s national climate agenda. This gap underscores the need for targeted strategies to protect heritage institutions and collections.

2.2. Climate Change Risks to Cultural Heritage

Climate change poses significant risks to Egypt's museum collections. The impacts of temperature fluctuations, humidity changes, increased precipitation, rising sea levels, air pollution, and strong winds cause impacts ranging from artefact degradation to structural vulnerabilities in museum buildings (Esteban-Cantillo et al., 2024). Rising temperatures and fluctuating humidity accelerate chemical reactions and internal stresses in artefacts, leading to cracking, warping, and mould growth, particularly in organic materials (Grottesi at al., 2023). Historic buildings are susceptible to thermal expansion, flooding, and seismic activity (Bocan et al., 2024), increasing maintenance costs and requiring advanced climate control systems. Environmental hazards like air pollution, sea-level rise, and intense precipitation further compound these risks, jeopardizing the preservation of both artefacts and museum infrastructure.

3. CONCEPTUAL FRAMEWORK: INTEGRATING PREVENTIVE CONSERVATION PRACTICES AND CLIMATE CHANGE ADAPTATION STRATEGIES

Preventive conservation aims at creating optimal conditions to preserve cultural heritage for future generations. Despite its extreme importance, preventive conservation practices often cause significant energy consumption, particularly through the use of active climate control systems, which has sparked debates revolved around whether objects should be allowed to adapt to their environment, as natural adaptation could reduce the dependency on energy-intensive systems. However, this approach risks exposing artefacts to unpredictable environmental fluctuations, which, in the current era of climate change, could lead to accelerated deterioration. Instead, museums must adopt climate-resilient strategies to ensure artefact preservation, particularly those made of organic material that are highly sensitive to such changes.

As an example, Figure 3 shows King Tutankhamun feather fan, the only feather fan found in the King's tomb, which has long been housed at EM and has undergone significant degradation under unfavourable environmental conditions of direct sunlight and fluctuating temperature and humidity. There is a plan to transport the fan to the GEM – probably by the end of 2024 – to be displayed in an oxygen-free showcase (Kamal et al., 2018). To compare the condition of the fan in both location, ImageJ software was used to approximately quantify the damage by calculating the percentage of feather loss over time. As shown in Figure 4, feather loss progressed rapidly under EM's condition, showing a total loss after approximately 200 years. In contrast, after transporting the fan to GEM, the anoxic conditions will dramatically slow the degradation.

Figure 3. King Tutankhamun feather fan photos over years.

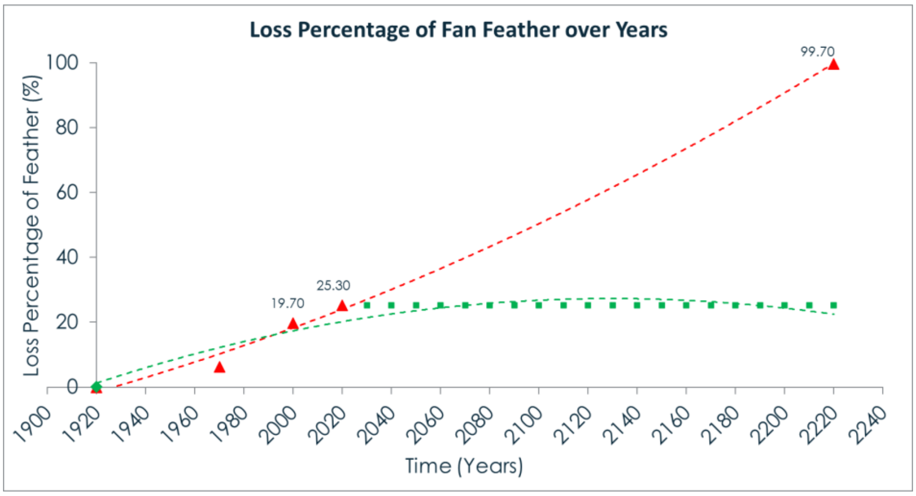


Figure 4. A line graph comparing feather loss in King Tutankhamun fan over time at EM and GEM, showing the projected time until total feather loss.

This study proposes an integrated framework that combines preventive conservation with climate change adaptation strategies, offering a balanced solution that prioritises sustainability and resilience. The key components of the proposed strategy include:

Risk Assessment and Environmental Monitoring which is foundational. By employing continuous monitoring through reliable sensors, museums can collect actionable data. This information enables timely interventions to mitigate environmental threats to artefacts.

Infrastructure Resilience is essential for ensuring that museums remain functional, and their collections are safeguarded against both gradual climate changes and sudden environmental shocks. This includes retrofitting museum buildings with climate-resilient designs and materials, such as energy-efficient HVAC systems, flood-resistant foundations, and structural reinforcements for seismic activity.

Energy Efficiency is critical for reducing the environmental impact of conservation efforts. Renewable energy sources, such as solar panels, and energy-efficient technologies can minimise the carbon footprint of museum operations.

Localised Climate Control offers targeted solutions for protecting sensitive objects, particularly in museums with aging infrastructure. Developing microclimates ensures stable conditions for specific artefacts, reducing the need for energy-intensive, museum-wide climate systems while enhancing preservation.

Policy Alignment plays a crucial role in securing long-term support and funding for conservation efforts. By embedding heritage preservation into national and international climate adaptation strategies, museums can ensure sustained financial backing while aligning their operations with broader sustainability goals. This includes advocating for protective regulations to safeguard museum perimeters from urban development, natural hazards, and pollution, as well as promoting sustainable retrofitting practices and the adoption of renewable energy solutions.

Decision-Making processes are enhanced through data-driven, collaborative approaches. Conservation insights, real-time environmental data, and stakeholder input form the basis for informed and proactive strategies. By integrating these elements, museums can prioritise actions effectively, ensuring that immediate and long-term conservation goals are met.

Emergency Preparedness is essential in addressing climate-induced risks, including flooding, dust storms, and extreme temperature events. Developing robust disaster response frameworks and conducting regular training drills ensures that museum staff are equipped to protect collections during emergencies, minimizing potential damage.

Community Engagement fosters shared responsibility for heritage preservation. Involving local communities, policymakers, and the public through outreach initiatives not only raises awareness of climate impacts on cultural heritage but also encourages active participation in conservation efforts.

4. OVERVIEW OF SELECTED MUSEUMS

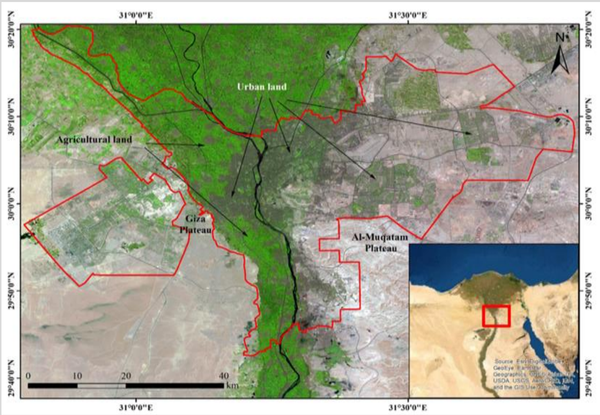
Egypt has approximately 84 museums of various types, including 75 archaeological, historical and regional museums, and 9 natural and applied science museums, as announced by the Central Agency for Public Mobilization and Statistics (CAPMAS) (Annual Bulletin of Cultural Statistics, 2022). To provide a comprehensive understanding of the various preservation challenges and strategies employed in Egyptian museums, the selection of the two museums considered in this study (GEM, and EM) was guided by specific criteria as follows.

1) Geographical representation: both museums are located in the Greater Cairo area – an area that includes the Cairo and Giza governorates as well as nearby peri-urban areas and newly developed towns in the desert regions (Figure 5:left) – which houses the largest concentration of museums in Egypt (Annual Bulletin of Cultural Statistics, 2022) (Figure 5:right), and at the same time captures the greatest geographical variations in climate, environmental conditions, and preservation approaches.

2) Type of museum facility: the museums represent the two distinct categories of museum infrastructure in Egypt - a modern institution with cutting-edge facilities designed to incorporate advanced conservation technologies (GEM); and a historical museum that dates back over a century, currently undergoing retrofitting efforts to improve its conservation capacity and respond to climate change risks (EM).

3) Significance of the museum's collection: the focus was on museums with internationally significant cultural heritage collections, as the preservation of these valuable artefacts is of utmost importance.

4) Accessibility and availability of data: both museums were able to provide the necessary data and information required for the study.



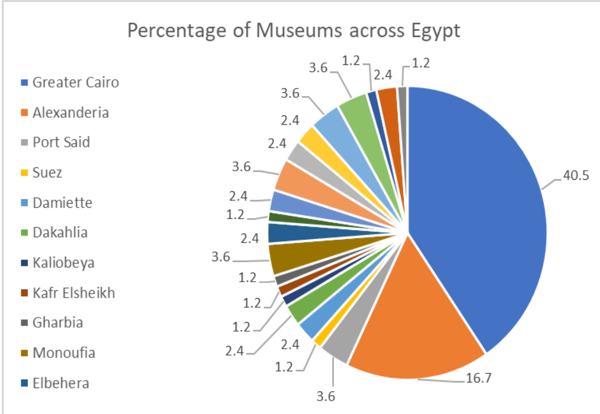


Figure 5. Greater Cairo: Left: A Google Earth map of Egypt showing the boundary of Greater Cairo (red line) (Hereher et al., 2022); Right: Percentage of no. of museums in each governorate in Egypt showing the highest percentage in Greater Cairo.

4.1. The Grand Egyptian Museum (GEM)

Located just 2 kilometres from the pyramids of Giza, GEM represents one of the most ambitious cultural heritage projects in modern history. The museum is a state-of-the-art facility showcasing Egypt's rich archaeological treasures in a world-class preservation and exhibition environment thanks to the efforts exerted inside its conservation centre (GEM-CC), which was built before the construction of the museum itself and is equipped with cutting-edge technologies. Among GEM's most notable exhibits is the most complete collection of artefacts from the tomb of King Tutankhamun, displayed together for the first time in one location.

4.2. The Egyptian Museum (EM)

EM is one of the most iconic cultural institutions in the world. It is located near the heart of Cairo, Tahrir Square, and it has been a symbol of Egypt's archaeological wealth since its opening in 1902, attracting millions of visitors over the years and continuing to be a focal point for scholars and tourists alike. The museum is the first purpose-built museum, featuring a neoclassical façade and spacious galleries that reflect early 20th-century architectural trends in museum design. It houses an unparalleled collection of artefacts spanning from the Predynastic Period to the Greco-Roman era, with over 120,000 artefacts on display, including monumental statues, delicate jewellery, and the famed golden mask of King Tutankhamun. In 2019, the Egyptian Ministry of Antiquities announced the launch of the European Union-funded project, "Transforming the Egyptian Museum of Cairo (Ministry of Tourism and Antiquities 2019)," aiming at modernising the museum and enhancing its exhibition spaces. The initiative was part of a collaboration with five prestigious European museums and was designed to bring the museum up to the highest international standards to ensure its recognition as a UNESCO World Heritage Site as applied for subsequently in 2021 (UNESCO, 2022).

5. PREVENTIVE CONSERVATION PRACTICES IN SELECTED MUSEUMS

GEM employs advanced preventive conservation strategies to ensure optimal preservation conditions for its extensive collection. Central to these efforts are its state-of-the-art environmental monitoring systems, which provide real-time data on temperature, humidity, and air quality throughout the museum, which helps the conservation team to maintain stable indoor conditions essential for delicate artefacts such as wood, textiles and papyrus. Preventive conservation guidelines and protocols (Kamal et al., 2018) were developed by GEM-CC to guide creating the exhibitions and ensure best practice in artefact preservation. Conservation decisions at the GEM are supported by its in-house laboratories, where experts conduct scientific analyses to evaluate artefact conditions and recommend interventions. For example, decisions regarding microclimate enclosures are informed by preventive conservation needs, balancing conservation needs with exhibition goals. The installation of artefacts in exhibition galleries was led by GEM-CC. The strategic planning of the installation process based on the concept of minimizing risks to the collection and ensuring the creation of preservation-quality exhibit galleries, integrating the in-house preventive conservation team throughout the process (Kamal, 2022). In galleries, a Building Management System (BMS) instantly manages the environmental data acquired by HVAC system and RH-active control systems. The BMS is a fully operational control system that measures the data, processes it with other information, and ultimately triggers the control action (Ali et al., 2024; Fahmy, 2024).

EM employs basic preventive conservation measures to protect its collections. Ventilation is predominantly natural, with exceptions in specific areas like the King Tutankhamen's gallery, where a HVAC system has been installed to ensure precise control of indoor microclimatic conditions during the summer months (Zaki et al., 2015). These areas also benefit from environmental monitoring for temperature and relative humidity. The museum enforces strict, regular cleaning schedules; however, pest management practices are applied only occasionally. Conservation staff carry out routine inspections to identify early signs of deterioration. Recently, the museum has initiated collaboration with international partners, such as the European Union (EU), which secured some resources for retrofitting efforts, introduced limited basic environmental monitoring systems and upgraded limited exhibition areas to meet modern conservation standards.

6. CHALLENGES AND OPPORTUNITIES FOR INTEGRATING PREVENTIVE CONSERVATION AND CLIMATE ADAPTATION STRATEGIES

6.1 The Grand Egyptian Museum

The primary challenge at GEM is its location in a desert area exposing it to severe climate challenges, including rising temperatures, and increased dust and sandstorms. These factors require continuous adaptation of preventive measures, such as enhanced air filtration systems with extensive maintenance efforts, which normally comes at a high cost. The museum's expansive garden can help purify air and act as an external protective shield against sandstorms. However, it is still crucial to significantly invest in expanding the surrounding green area to mitigate these risks.

The design of the GEM incorporates high gallery ceilings of up to 15 meters and these spaces are controlled by the HVAC system. Although the air supply is designed to flush air from the floors (Figure 6), significant energy is still required to condition such extreme heights, which is exacerbated by the noticeable reliance on active control systems in several of the showcases. GEM has made a remarkable stride toward energy consumption by signing a cooperation agreement with the Industrial Modernisation Centre and the Electricity and Renewable Energy Authority at the Electricity Ministry to establish a solar power plant for the museum’s building (Independent, 2022). The agreement has already resulted in the installation of its solar energy station. However, the current use of the solar plant remains on a small scale, generating only a fraction of the museum's total energy needs. Despite the tremendous roofing space available at GEM, which could be utilised for additional solar panels to significantly increase energy production, this potential has yet to be fully realised. To achieve substantial reliance on clean energy, GEM requires a comprehensive and integrated strategic plan to optimise the use of its available infrastructure and systematically transition to solar power as a primary energy source.

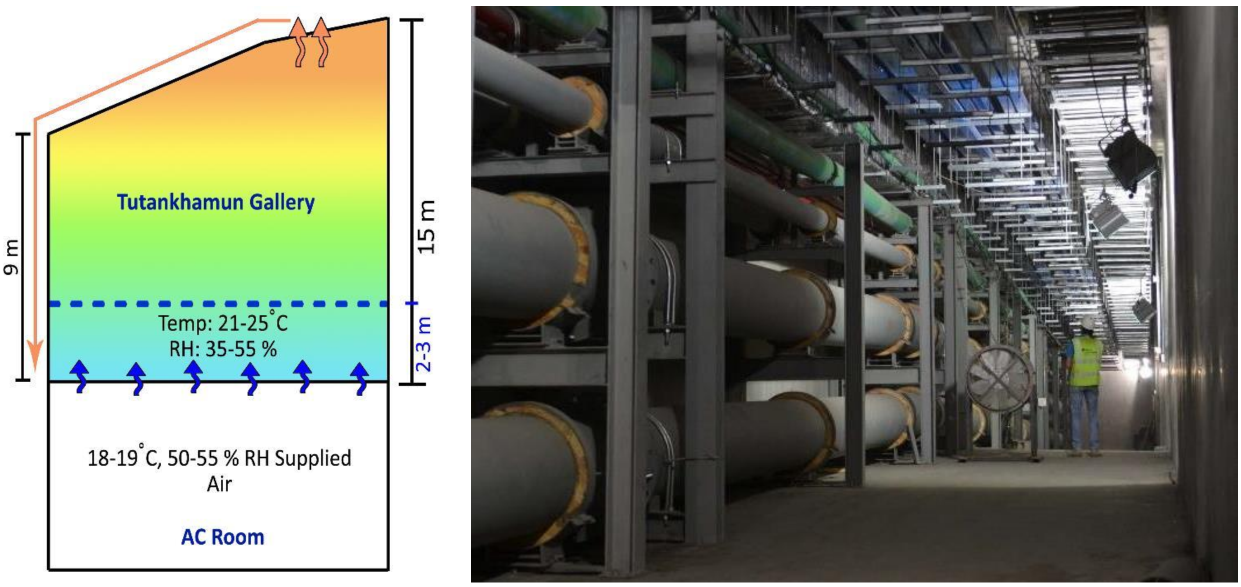


Figure 6. HVAC system at GEM. Left: plan of exhibit halls and HVAC operation. Right: The huge underground plant.

6.2 The Egyptian Museum

The primary concern at EM is that its ventilation is natural, depending on the opening of windows of the museum, which allows gaseous and particulate pollutants to easily enter the building and disfigure the collection, particularly the ones on open display. Insects and other pests find their way to the collection in both exhibition and storage spaces, attacking vulnerable collections, such as textile, wood, and papyrus. In respect to the building's nature and humble infrastructure, windows can be retrofitted with adjustable panels incorporating high-efficiency particulate air (HEPA) filters to block gaseous and particulate pollutants. This measure will protect collections from outdoor pollution while allowing for controlled air exchange. As for pests, a comprehensive Integrated Pest Management (IPM) strategy (Elkhial and Kamal, 2018) could be implemented including sealing entry points for insects, using traps, and training staff to identify and address pest infestations. Regular monitoring and non-invasive methods, such as anoxic treatment, can address pest-related damage. Additionally, illumination at EM is generally dependent on daylight from the museum's open windows, complimented by artificial lighting which is not UV filtered. As an approach to address the risk posed by illumination, existing artificial lighting can be fitted with UV filters, and as a long-term strategy, they could be replaced by LED lamps to reduce short wavelength light damage to sensitive artefacts, such as textiles and papyrus. Daylight can be managed by installing UV-blocking window films or curtains to manage exposure. These solutions will reduce the harmful effects of radiation on artefacts while improving overall illumination consistency.

No monitoring system is generally used for environmental control and the factors behind that are the lack of financial resources, the building's historical nature, and staffing. The collaboration project at EM prioritises maintaining stable conditions for high-value artefacts, such as King Tutankhamun's mask and other significant items from the King's collection, through the use of localised air conditioning and specialised display cases. However, much of the remaining collection, including artefacts made of sensitive materials like textiles and wood, remains exposed to fluctuating temperatures and humidity, further complicating conservation efforts (

Figure 7). As a solution, EM can adopt a holistic strategy for upgrading the exhibition and storages through the collaboration projects and can begin with cost-effective, portable monitoring systems for temperature, humidity, and pollutant levels, which can provide immediate data on environmental conditions without requiring large-scale infrastructure changes, and will help prioritise areas requiring immediate attention, such as high-traffic exhibition spaces or vulnerable storage areas.

The decision-making process at EM often reflects the resource constraints and the reactive nature of its conservation practices. Until now, the museum has addressed immediate threats but have not had the capacity to anticipate or prevent long-term risks. Furthermore, the decision-making framework lacks full integration with broader climate adaptation strategies, leaving the museum more vulnerable to external environmental pressures, such as urban pollution and climate-induced events like rainfall or extreme heatwaves. The decision makers could alternatively develop a long-term conservation master plan including key components: planning for urban pollution control, rainfall risk management, and temperature regulation around the museum which could be intensified by collaborating with external conservation scientists, engineers, and local stakeholders and involving them in decision-making processes. Additionally, work with policy makers can also help develop a land-use planning policies to protect the museum perimeter from urban pollution and natural hazards.

Figure 7. The effect of rising temperature on multilayered artefacts at EM resulted in buckling, separation of gilded layeres, and melting of wax. Images taken at EM in 2018.

7. COMPARATIVE INSIGHTS AND OPPORTUNITIES FOR INTEGRATION

It can be drawn from the findings in the previous section that GEM's advanced systems and proactive management position it as a model for integrating preventive conservation and climate adaptation. EM, despite its limitations, demonstrates resilience through retrofitting and international collaborations. Both museums face challenges in sustainability, resource constraints, and limited policy integration. However, collaboration between the two biggest, most important, leading museums in Egypt, GEM and EM, could offer significant potential for implementing the proposed framework as summarised in Table *1*.

Table 1: Comparative Insights on Preventive Conservation and Climate Adaptation in Selected Museums

Criterion	GEM: Strengths	EM: Strengths	Shared Limitations	Opportunities for Integration
Environmental Monitoring	Advanced monitoring systems for real-time data	Basic monitoring through retrofitting	Limited integration of predictive analytics	Introduce uniform environmental data sharing and analysis tools across both institutions.
Climate Control	Comprehensive, energy-intensive HVAC systems	HVAC and artefact-specific cases	Aging infrastructure in EM hinders upgrades	Pilot localised microclimate control systems to bridge EM's constraints.
Decision-Making	Centralised, proactive, data-informed	Reactive and constrained by manual records	EM lacks a comprehensive data-driven decision-making framework	Establish a shared decision-making platform incorporating GEM's expertise to enhance EM's reactive practices.
Energy Efficiency	Emerging focus on energy efficiency	Minimal focus on energy efficiency	Both museums face challenges integrating renewable energy solutions	Develop joint renewable energy projects (e.g., solar panels) supported by international funding.
Policy Alignment	Embedded in national and international projects	Gains from EU-funded initiatives	Both museums require stronger policy ties to Egypt's climate adaptation frameworks	Advocate for heritage preservation within Egypt's national climate action strategies.
Emergency Preparedness	Advanced systems, seismic and fire resistance	Basic disaster response frameworks	Resource constraints in EM limit advanced disaster preparedness	Conduct joint training drills and emergency response workshops leveraging GEM's resources and expertise.
Community Engagement	Educational programs and outreach	Strong visitor engagement due to central location	Both lack programs to directly involve communities in conservation	Design collaborative community programs that educate and engage local stakeholders in preventive conservation efforts.

A significant portion of the integration opportunities lies in leveraging GEM's advanced systems and expertise to address EM's resource constraints. **Environmental monitoring**, **climate control**, and **decision-making** can be strengthened through collaboration between the two museums. GEM could conduct training sessions and workshops that train staff on identifying vulnerable artefacts, collecting and analysing environmental data, and making data-informed conservation decisions. For example, GEM's expertise in microclimate systems could be used to assist EM in identifying high-priority zones for localised climate control systems. These systems could be tested and refined in collaboration with GEM to ensure effectiveness. Similarly, GEM and EM could co-develop joint disaster response plans and conduct regular drills focusing on climate-induced risks, such as flooding and extreme heatwaves, enhancing preparedness for both institutions.

Both museums could work together on **community engagement** by launching public awareness campaigns, media programs, interactive exhibits, and school workshops to highlight the impact of climate change on cultural heritage. These initiatives could engage local communities, policymakers, and even international audiences, fostering a collective sense of responsibility for heritage preservation in the face of climate change. This can serve as a powerful tool to advocate for heritage-specific **policy alignment** into Egypt's broader climate adaptation frameworks, including safeguarding museum perimeters from urban encroachment and embedding sustainable building practices, retrofitting projects, disaster preparedness strategies, and renewable energy initiatives. The advocacy efforts led by GEM and EM, in collaboration with communities, can push for legislative actions that prioritise preventive conservation within climate policy agendas.

Energy efficiency initiatives offer another avenue for integration. Joint renewable energy projects between GEM and EM, such as the expansion of GEM's rooftop solar panel system into a large-scale solar plant and the potential use of surrounding areas at EM, could attract international attention and funding. By positioning these projects as part of a national heritage conservation initiative, the museums could demonstrate the importance of aligning conservation with sustainability. Moreover, **policy alignment** could facilitate the implementation of such energy-efficient projects as they will be supported by national and regional policies.

These collaborative actions demonstrate the potential for GEM and EM to set a precedent for integrating preventive conservation with climate change adaptation. The proposed initiatives are not only relevant to Egyptian museums but also applicable to institutions worldwide, offering a model for global heritage preservation efforts.

8. CONCLUSION

Climate change presents a critical and urgent threat to cultural heritage worldwide, and Egypt, with its rich history and vast collections, is no exception. This study has explored the integration of preventive conservation and climate adaptation strategies as a means to safeguard Egypt's cultural treasures in the face of the growing climate crisis. A comparative analysis of the preventive conservation practices of the Grand Egyptian Museum (GEM) and the Cairo-Egyptian Museum (EM) was conducted and has provided valuable insights into how museums can adapt to and mitigate climate risks while ensuring the long-term preservation of their collections.

The study demonstrates that the integration of preventive conservation with climate adaptation strategies is not only essential but also achievable, offering practical insights for application in diverse museum contexts. The study reveals that GEM has made significant strides in advanced environmental monitoring, climate control, and data-driven decision-making, setting a high standard for modern museum practices. However, even GEM faces challenges related to energy consumption and sustainability. In contrast, EM—with its historical building and ongoing retrofitting efforts—illustrates the need for adaptive solutions tailored to older infrastructures. While EM has made progress in benefiting from the international collaboration in establishing localised preventive conservation practices, there remain significant gaps in proactive conservation and data-driven decision-making, which undermine the museum's ability to manage risks effectively.

The study identifies several key opportunities for both museums that can also be generalised in other museums to integrate climate adaptation and preventive conservation more effectively, including the development of joint renewable energy projects, the introduction of localised climate control solutions, and the creation of shared decision-making platforms. This research also calls for integrating heritage preservation into national and international climate action plans for securing the necessary funding, resources, and political will to protect cultural heritage.

By sharing the findings, lessons learned, and best practices of studied museums with the international conservation community, this study not only informs Egypt's conservation strategies, but also contributes to the global discourse on preserving cultural heritage in the face of climate change. The insights provided aim to empower museums worldwide to address climate risks while ensuring the sustainability and resilience of their collections.

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