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Risk analysis for preventive conservation of heritage collections in Mediterranean museums: case study of the museum of fine arts in Alexandria (Egypt)

Abdelrazek Elnaggar[1,2*], Mahmoud Said[3], Ida Kraševec[2], Aly Said[4], Josep Grau-Bove[5] and Hosam Moubarak[6,7]

Abstract

The impacts of climate change on heritage collections in Mediterranean museums are serious and lead to accelerated material degradation, loss of value, increasing conservation costs and climatisation. Climate change scenarios and simulation models have been developed to predict the extreme and average future environmental conditions and to assess the future long-term risks caused by global warming for museum buildings and their collections in Mediterranean countries, with Egypt being particularly at risk. This paper presents the results of the risk analysis of the indoor and outdoor environments in Alexandria Museum of Fine Arts (AMFA) in Egypt to provide an overview of the current situation of conservation and museum management and to provide evidence-based data to support decision-making regarding preventive conservation given the museum's limited funding, capacity and resources. Unfortunately, the air quality in the museum cannot be considered satisfactory and specific measures need to be taken to improve the level of air quality and museum and building management. The results enabled an assessment of indoor air quality and provided information on potential risks to the museum building and collections, including variations in temperature (T) and relative humidity (RH), concentrations of NO_2, SO_2, O_3, CO_2, acetic and formic acid and lighting conditions, as well as the location and management of the museum. The results necessitate the development of a preventive conservation plan to address the challenges associated with high T/RH fluctuations and pollution pressure. This requires more regular use of the HVAC system within certain T/RH set points as well as minimising light exposure and the use of UV-filtering glazing. Care should be taken to ensure that housekeeping and emergency preparedness reduce the damping and salt florescence in the museum building. However, dealing with the impact of climate change on indoor and outdoor environments and museum collections in Mediterranean museums requires a holistic and adaptive approach that includes joint collaboration, research, training and strategic planning to ensure the long-term preservation of valuable cultural heritage collections in different climates with customised adaptations based on local environmental conditions, resources and needs. Resilience planning should be region-specific and take into account the potential impacts of extreme weather events, sea level rise and other climate-related challenges.

Keywords Museum management, Building, Location, Temperature, Relative humidity, Light, Pollution, IPERION HS

*Correspondence:
Abdelrazek Elnaggar
elnaggar@arch.asu.edu.eg
Full list of author information is available at the end of the article

Introduction

Museum collections should be safely preserved according to the highest possible standards of preventive conservation, learning from the international best practices to build more meaningful relationships between museum collections and people [1]. Heritage collections in Mediterranean museums could serve as a vehicle to promote dynamic and proactive cultural and touristic exchanges and intercultural dialogue between the northern and southern countries of the Mediterranean [2, 3]. However, the impact of climate change on Mediterranean heritage collections, human comfort and mass tourism is severe, leading to accelerated material degradation, loss of values, increasing conservation costs and climatisation along with other socio-economic risks [4]. Climate change scenarios were developed to predict the extreme and average future environmental conditions [5, 6]. In addition, simulation modelling was used to assess the future long-term risks induced by global warming for museum buildings and their collections in Mediterranean countries, with Egypt being particularly vulnerable [7]. Long term climate scenarios with forecasts for the indoor climate in historical buildings up to the year 2100 were created [8]. The results show that the predicted raise in outdoor temperatures in the Mediterranean region and extreme weather events will accelerate the degradation of building and heritage collections and increase the costs of air conditioning. Museums are facing raising energy costs while at the same time having to take the responsibility for reducing the carbon emissions in line with the EU Green Deal [9] is denuding. Although, several standards of cultural heritage institutions for the environmental management have been adapted [10, 11], the status of management in the museum sector is still a low [12]. The British Standards Guidance (PAS 198) can be assumed to be the closest to a performance-based standard [13] which is based on the concept of the 'expected collection lifetime' taking into account the resources available, significance of the objects, the planned use and display, and the expected rate of materials deterioration [14]. However, the EU standard EN 16893:20188 [15] has identified significant gaps in the understanding of the behaviour of heritage collections under adverse environmental conditions and risks. The development of environmental management models of heritage collections requires data collection, environmental monitoring, and stakeholder involvement [16]. There is no widespread or coordinated effort to align standards for the environmental management of heritage collections with public expectations and understanding of the environmental and climate impacts on human decisions and the conservation of heritage collections [17]. Existing international models of preventive conservation vary in scope, methodology and approach, as preventive conservation management is an area under constant review and development in the 21st Century. Due to the increase of specialised skills, materials, and equipment and the discrepancy between the highest and lowest standards of museum collection care [18, 19]. In addition, international museums often lack environmental monitoring and testing of artefacts due to a lack of funding, the necessary knowledge and human resources [20]. Research on preventive conservation management has shown that more in-depth research is needed in this area, taking into account experts' perceptions of current practises [21]. Recently a set of principles of green heritage science [22] has been formulated that promote the prevention of damage to heritage collections to ensure their preservation through risk assessment, public involvement, and effective management with maximisation of mass, energy, space, and time efficiency. This should be based on societal priorities with a level of complexity tailored to the specific local context and resources explored through participatory science [23] with diverse policy makers and stakeholders to analyse views on heritage conservation, management, and related practises and promote a collective understanding that can improve preventive conservation practises.

Monitoring of indoor and outdoor environments in museums usually occurs when acceptable conditions need to be ensured for the preventive conservation of objects and health and safety procedures for visitors and staff, when damage to objects is detected, and when new materials are introduced during building renovations [24, 25]. Digital tools, such as digital twins, the Internet of Things (IoT), and artificial intelligence (AI), have been used in the heritage science sector [26] for preventive conservation of heritage collections [27], modelling the built environment [28, 29] and predicting risks [30]. These digital tools have been used to monitor environmental conditions such as temperature, humidity, light exposure, and pollutants in real-time to gain insights into potential risks to heritage objects. New tools for processing and analysing air quality data in museums were reported providing key risk indicators for calculating risk levels for specific heritage materials such as canvas painting [31]. Computerised modelling of degradation phenomena in model canvas paintings observed in real case studies was developed as a function of T and RH fluctuations [32]. Supervised machine learning methods were also used to predict the environmental risks of heritage collections in historical buildings [33]. In addition, practical information on risk assessment of lighting conditions in exhibitions was provided to support decision making in preventive conservation [34]. However, the application of digital twins and related tools in preventive conservation modelling [35] posing challenges in terms of infrastructure, data analysis, standardisation, and funding [36] as well as the need to be address ethical considerations, to ensure that the technology aligns with conservation goals and respects the cultural significance of heritage objects.

Risk management guidelines for cultural heritage have been facilitated by heritage institutions that promote the need to understand local contexts [37, 38] and define the optimal environmental levels for reducing the indoor environment risks in terms of air temperature, relative humidity, pollutant concentration and light levels [39]. These climatic risk assessment guidelines for informed decision making in preventive conservation, require higher costs, longer assessment times and specialised skills [40]. An economically efficient and easily applicable innovative approach to environmental risk assessment in contemporary museums has been introduced [41, 42] based on relevant guidelines, best practise, and the involvement of the museum staff to meet their daily needs and priorities, taking into account the available resources and aspects of conservation and human comfort. However, the development of local preventive conservation strategies is mainly based on international standards and neglects the local context, social values, and available resources [18, 43–45].

The heritage collections in Mediterranean museums are exposed to frequent and intense extreme weather events [46] and daily threats depending on the museum's outdoor and indoor environmental conditions [47], the location, the building, and the management of the museum. Initially, only the degradation caused by a single variable was considered, but later their cumulative effects were taken into account [48] to determine environmental specifications in heritage collections, e.g. canvas paintings [49, 50]. For example, major indoor risks in museum spaces in the Mediterranean region are the wide variations in temperature and relative humidity [48]. The environmental variables (temperature, relative humidity, pollution and light) have been identified as the main risks that can lead to other types of damage. In addition, gaseous pollutants and footprints are an unavoidable part of the indoor environment in museums. In recent years, the presence of pollutants such as acetic acid (AcOH), formic acid (HCOOH), formaldehyde (FDH), acetaldehyde (ADH), ammonia, NOx, SO_2, H_2S, O_3 and other volatile organic compounds (VOCs) in museum environments has come under the spotlight because they can contribute to the degradation of various materials from which the historical objects are made [51, 52]. Other factors such as inappropriate lighting, building materials, the ventilation system, heating, solar radiation, visitor numbers and the museum management system should also be considered [53, 54]. The dilution of indoor pollutants and the influx of outdoor pollutants into the museum building are influenced by changes in the ventilation regime of the building and by seasonal changes in T and RH [55]. Better indoor air quality with rational energy use and stakeholder engagement for better display of artistic heritage in Mediterranean museums can influence sustainability plans for cultural heritage collections and future retrofitting of museum buildings [56]. The preventive conservation management in the Egyptian museum buildings is still far from the required criteria due to many institutional, technical and economic barriers [57]. The international standards are sometimes adopted [19], while the local environment is still not considered in air quality in Egyptian museums due to lack of equipment, limited availability of professionals, and budget constraints. This, however, requires cooperation with international heritage science institutions to preserve Egyptian heritage collections that are of universal interest. In Mediterranean countries such as Egypt, the high temperatures, high humidity and heavy traffic with poor ventilation pose a significant risk to museum exhibits. Despite the great interest in air quality in museums around the world, there is no interest or data on air quality in museums and galleries in Alexandria. This research will present immediate suggestions for improving indoor air quality at the Alexandria Museum of Fine Arts (AMFA) that can be considered to protect the museum's collections from potential future degradation. This aim of this work is to understand the air quality and conduct risk analysis to optimize decision making regarding appropriate preventive conservation measures for the sustainability of the museum's collections. To our knowledge, this is the first comprehensive risk analysis performed in the Egyptian museums. It is remarkable that no research has been conducted in Egypt to standardise preventive conservation, although it would make economic sense to spend limited heritage funds on environmental strategies that simultaneously minimise material degradation, decontextualization of objects, and the cost of time-consuming remedial conservation.

The case study: Alexandria Museum of Fine Arts -AMFA (Egypt)

Alexandria is one of the cultural centres of the Mediterranean, renowned for its ancient and modern cosmopolitan heritage as well as its World Heritage Sites. The artistic heritage in Alexandria shows a multi-cultural value influenced by the diverse Mediterranean intellectual contexts, which is a distinctive feature of Alexandria. The city is characterised by an arid Mediterranean climate with hot dry summers and mild humid winters, while climate change scenarios expected that the city will get even hotter and drier with expecting flooding [58, 59].

The World Bank has listed Alexandria as one of the five Mediterranean coastal cities at very high risk of coastal flooding due to climate change [60]. However, in October 2015, the city experienced exceptional flooding caused by heavy rainfall in a short period of time, which severely affected the museum [61]. This study is being conducted at the AMFA, which is located in the Moharam Bek neighbourhood in the historic centre of the coastal city of Alexandria (see Fig. 1a, b) [62]. The museum can be considered typical of Mediterranean cities, which very often use old buildings for exhibition purposes. The museum is under the authority of the Egyptian Ministry of Culture and is considered to be the oldest museum building in Egypt built for this purpose. The impetus for founding the museum came from a sense of belonging to the city of Alexandria and its visual arts [63]. In 1904, the German art collector Edouard Friedheim donated his 210 collected paintings to the Municipality of Alexandria for the purpose of establishing a museum of fine arts, while the French merchant Baron Charles de Menasce, who had lived in the city, donated his own villa in 1936 to be used forever as a library and gallery for the exhibition of art collections. The villa was destroyed during the Second World War and the municipality had to store the artworks in the basement of the King Farouk Hospital of Ophthalmology in Alexandria. In 1954, the Director General of the Municipality of Alexandria (Mr. Hussein Sobhy) supported the reconstruction of the museum building where the collections are housed today. The museum houses an important collection of artworks (1381 objects) by local and international artists, which are displayed on two floors (see Fig. 1c). These include oil and gouache paintings, pencil on paper, prints, photographs and sculptures of European classical artworks from the Baroque, Romantic, Rococo and Orientalist periods (see Fig. 2). The collections originate from well-known European and local artists such as the German artist Mattias Grunewald 1801–1876 AD, the French artist Victor Adam (1470–1528 AD), the Italian artist Jacopo Robusti (Tintoretto 1518–1594 AD), the Flemish artists Bruegel (1525–1569 AD) and Jan Baptist Weenix (1663–1621 AD), and the Egyptian artists Abdel-Hadi

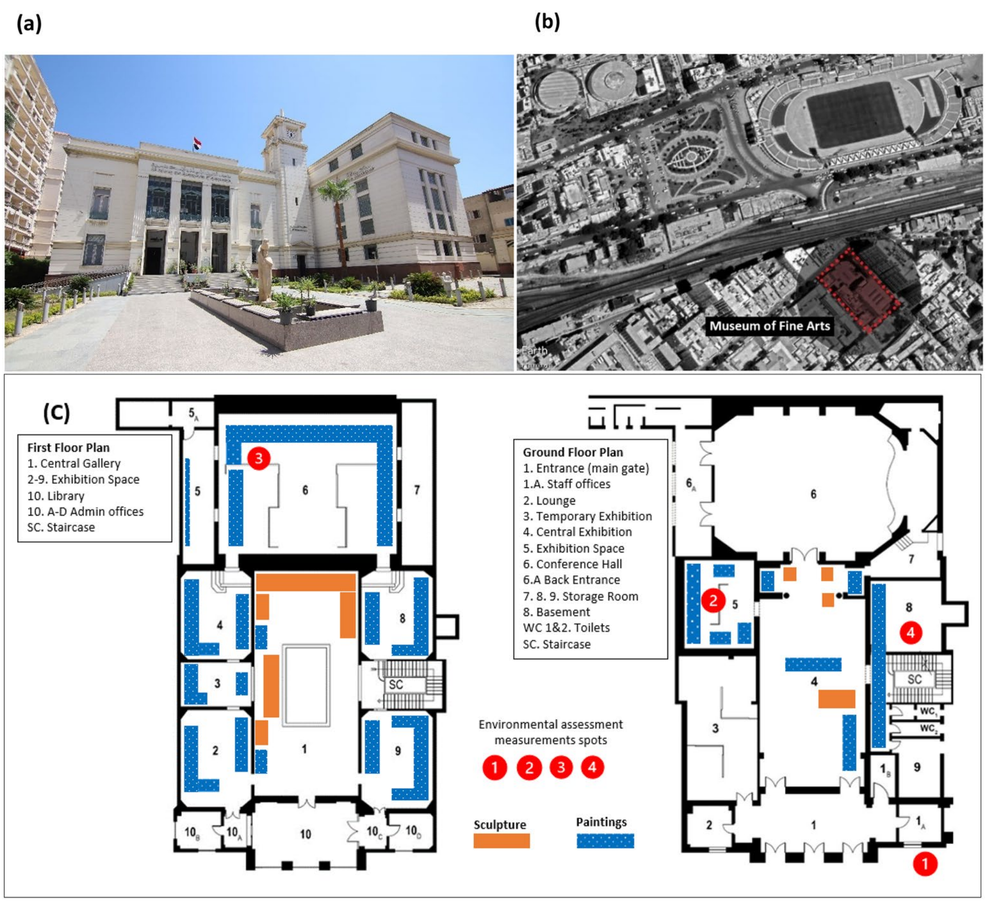

Fig. 1 **a** the exterior of the museum building; **b** a satellite image (by google map) of the museum location next to the football stadium and train station, **c** museum plan and floors including the typology of collections

Fig. 2 Shows 360° photos of the paintings' collections on the ground floor and the main gate of the museum

Al-Gazzar (1925–1966 AD); Mohamed Mahmoud Khalil (1877–1941 AD) and other art collectors who lived in Alexandria (e.g. Edouard Friedheim, Charles de Menasce and Prince Omar Tosson). The paintings include drawings, lithographs, prints and photographs in various media and materials. Paintings in oil or mixed media on canvas or panel are usually framed without glazing. Works of art on paper, on the other hand, are framed and glazed. The museum also houses a collection of sculptural artworks of various sizes and materials such as clay, ceramics, bronze, painted plaster, marble, artificial and natural stone. This diverse and varied collection shows the evolution of art over five centuries from classical art schools to the modern art movements making it an excellent collection for art history and art education. It also tells the story of Alexandria, which was once a cosmopolitan city where many wealthy European families and property owners lived and were part of the Alexandrian community.

Location

The museum is not far from the immediate coastal inundation (approx 1 km), and is located near lakes in a busy and vibrant urban area next to intensively used urban outbuildings (see Fig. 1b). In addition, the museum is located at a crossroads in the city centre with heavy car traffic and no parking space for taxis or buses or public transport, considering that it is a multifunctional building as a museum, theatre, and library. The museum is located next to the railway station tunnel, where rainwater often collects in winter and obstructs traffic while the trains noise and vibrations may affect the human comfort and collections safety in the museum. The location of the museum due to poor accessibility, high air pollution from traffic, vibrations and noise from the railway station. However, the location allows for active collaboration with the local community, which has created a network to support the museum, with extensive educational and community programmes organised weekly by museum staff.

Building

Before 2013, the museum had been closed for thirty years due to rain damage. During this time, the collection was packed away and stored. Through a major investment by the Egyptian Ministry of Culture, the museum was renovated and reopened in 2013 after an intensive renovation, that included the addition of a studio, a rear garden and a hall for temporary art exhibitions. When the exhibition was redesigned, additional partitions and structures were installed that unify the interior spaces into a single design scheme without interfering with the building's structure and are fully reversible. On the ground floor, several colours were used to differentiate the various themes of the exhibits, while the entire first floor is painted white. Several interventions were made in the museum's concrete building to improve the architectural elements, safety, environment and visual identity. These include installing a concrete ceiling on the second floor instead of a glass roof, closing all windows (except those in the entrance façade), installing artificial lighting and an HVAC system, reorganising the collections, renovating the exhibition spaces, and installing lifts for visitors with disabilities.

The museum is located in a concrete building where the structures and natural ventilation often do not meet the requirements for the conservation and preservation of museum collections and human comfort [64]. The museum building is spread over two floors with a total exhibition area of approximately 1900 m^2, with a large opening between floors and wall openings between rooms to allow cross ventilation. The building has thick solid brick walls without windows, which reduces solar heat gain increases security, but compromises natural ventilation, which is only provided through the museum's main door. This can lead to a poor state of conservation caused by problems due to dust accumulation and humidity [65]. In fact, dampness is one of the main problems in the museum building, caused by rain, wet mopped floors as part of improper housekeeping and water leaks in the internal water system and pipework (see Fig. 3). Among the drastic accidents that affected the museum building was the heavy rain in Alexandria in 2019, where the museum was closed for five days to recover from the flooding disaster caused by rainwater. The contaminated rains and underground water entering the museum through the sewage system and the ceiling caused cracks in the walls, vegetation, and salt weathering indicating high risk to the paintings [66, 67] (see Fig. 3). Site visits and observations also revealed moisture-related problems in the collections, such as the mechanical decomposition of organic, hygroscopic materials, especially painted wooden panels. Furthermore, the conversion of historic buildings into exhibition spaces and the renovation of existing exhibits can pose additional environmental risks, including the emission of volatile organic compounds[106] which has not yet been investigated for this museum.

Methods

In order to avoid complex simulations and considering that the AMFA requires less expertise, cost, and assessment time, the risk analysis was carried out based on the simplified methodology [41] which is based on the assessment of the indoor enviroment, recognation of risks to museum building/mangment tin order to optimise decsion making for preventive conservation and define apporporaite conservation and management procedures at minimised cost. While the elements of preventive conservation are broad, the AMFA's risk analysis in this paper will provide a deep understanding of the most important aspect of air quality factors through an access application to the infrastructure project, H2020 IPERION HS (Integrated Platform for the European Research Infrastructure on Heritage Science) [68]. The analysis was carried out in collaboration between the AMFA, the Heritage Lab at the University of Ljubljana (Slovenia) and the Preventive Conservation Lab at University College London (UK). The methods include onsite environmental monitoring data (T, RH, pollutants, and light) as well as participatory research such as literature review, screening of museum records and archives, and interviews with museum staff about the museum's history, policies, and risk analysis, as well as assessment of building performance, and collection conditions. In addition, a multiple stakeholders' panel discussion was held with the participation of museum staff, contemporary art authorities in Egypt, the community, academic experts, and heritage researchers.

Fig. 3 **a** shows the museum entrance near the train station, tunnel, stadium, adjunct high buildings; **b** shows the salt weathering and dampness in the wall behind the painting

Environmental monitoring

Temperature (T) and Relative Humidity (RH) monitoring

Monitoring of natural seasonal variations (for one year) in indoor and outdoor temperature (T) and relative humidity (RH) was conducted using HOBO U12 data loggers from Onset (Onset, USA; T and RH ranges and accuracy: −20° to 70 °C ± 0.35 °C, RH: 5% to 95% RH ± 2.5%; time accuracy ± 1 min per month at 25 °C). The data loggers were placed in the ground floor gallery and outside the main door of the museum, out of direct contact with the sun and walls and away from windows and other heat sources. The source data with a time step of 30 min was extracted from the data loggers using HOBO software, cleaned, and organised using MS Excel and analysed and visualised using the Tableau application.

Analysis of pollution gases

Gaseous pollutants were sampled in triplicate at four locations: in front of the main gate of the museum, in a gallery on the ground floor, in a gallery on the first floor and in a basement storage area. In this work, passive samplers were used for all pollutants. Such samplers are typically exposed for an extended period of time (several days to weeks) but are small and do not require external supply of power. As a result, sensitive but time-averaged data are collected that are representative of long-term conditions of the object environment and are less affected by short term variations or spikes in concentrations [70]. Nitrogen dioxide (NO_2) and sulphur dioxide (SO_2) as well as acetic acid (AcOH) and formic acid (HCOOH) were sampled using UMEx 200 passive samplers (SKC USA; Sampling rates: SO_2: 15.2 ml/min with a relative standard deviation of 16.5%, NO_2: 17.3 ml/min with a relative standard deviation of 11.5%; Validated Concentration Ranges: SO_2: 0.4–8 ppm, 15 min to 24 h NO_2: 0.051 to 8.5 ppm, 15 min to 24 h) with triethanolamine, each containing a sampling strip and a blank strip, and exposed for 7 days, then sealed and transported to the laboratory and analysed according to the procedure in [69]. The strips were sonicated in 2 ml ultrapure water (MQ; Millipore, USA) for 20 min. The extracts were filtered through 0.45 µm philtres (Chrom4, Germany) before being injected into an ion chromatograph, Dionex ICS-5000 (Thermo, USA), which consists of an eluent generator, an electrochemical suppressor and a conductivity detector. Sulphur dioxide (SO_2) and ozone (O_3) were sampled using SP10 and SP20 samplers (Passam AG, Switzerland, sampling rate: 11.2 ml/min at 20 °C; detection limit: 2 µg/m^3 for a 2-week exposure), exposed for 28 days, then sealed and transported to the laboratory and analysed using ion chromatography. For formaldehyde sampling, UMEx 100 passive samplers with DNPH (SKC, UK; Sampling rate: 28.6 ml/min with a RSD (Relative Standard Deviation) of 7.6% at wind velocity of 5 to 100 cm/sec for 15 min to 24 h; Lower Detection Limits: 7 days-0.0002 mg/m^3) were exposed for 7 days, then sealed and transported to the laboratory and analysed by high pressure liquid chromatography (HPLC) with UV–VIS detection at 365 nm (Agilent 1100 series, Agilent, USA). The YMC Triart C18 column (150 × 4.6 mm × 5 µm) was used with the HPLC method of [70]. In addition, short-term air quality measurements of carbon dioxide (CO_2) emissions were recorded in the exhibition spaces during public events (respectively, monitoring time 45 min and 60 min; number of attendees: 100 and 200 people; dates: 3rd April 2023) to understand the impact of visitors on the indoor environment and to estimate the rate of air change. The HOBO carbon dioxide/T/RH data logger MX1102 sensor (Onset, USA; Measurement range: 0 to 5,000 ppm; accuracy: ± 50 ppm ± 5%) was exposed during some exhibitions (in the temporary exhibition room) and public events (in the theatre) with a large amount of people. The recording interval was 10 min, data was extracted using HOBOconnect software and plotted using MS Excel. The air exchange levels (AER levels) between the outdoor and indoor environments of the museum were predicted based on the museum rooms' dimensions and measured Indoor/outdoor pollutants and CO_2 emissions ratios using the IMPACT [2] model [71]. In addition, a 360° virtual tour was created using the RICOH THETA V 360° camera (RICOH, Japan) in HDR mode and Theta software to support the air exchange calculation.

Illuminance measurements

The illuminance of the artificial visible light (Ev) was measured in real time during the museum's working hours (9.00 am–3.00 pm) using a KENNON FERVI L014 lux meter (Ranges: 0–50000 lx; accuracy: ± 5%) at various points in front of the paintings and exhibits and an average value was determined. The illuminance of the artificial visible light (Ev) was measured in real time during the museum's working hours (9.00 am–3.00 pm) using a KENNON FERVI L014 lux metre at various points in front of the paintings and exhibits and an average value was determined.

Information-gathering, on-site observation, interviews, and group discussions

In order to refine the daily needs and technical skills of museum staff and to identify the potential risks, causes of damage, proper preventive conservation procedures and human comfort requirements, a six-hour fieldwork was conducted by eighteen heritage science scholars and teachers with the support of the museum director and staff (see Fig. 4). Later, in collaboration with the Egyptian Ministry of Culture, a workshop [72] was organised with the participation of various stakeholders in Egypt (e.g. fine arts authorities, museum directors, curators, conservators, artists, academics, heritage conservationists and the local community, etc.) to discuss optimising decision making for preventive conservation, prioritising interventions and reducing internal costs. In addition, photo campaigns were carried out to document the collections and analyse risks using a NIKON D7500 DSL camera.

Fig. 4 Shows the fieldwork by heritage science scholars and instructors, with the museum director and staff, conducted at the museum gallery

Results and discussion

Environmental assessment

The investigation of the environmental conditions reveals several challenges. The large fluctuations in relative humidity and temperature, uncontrolled ventilation, and inappropriate pollution levels and lighting are considered the main risks in the museum, especially for the delicate and fragile art collections such as watercolours, gouaches, pencils and charcoal drawings on paper, which are hung in the corridor near the museum entrance [73].

Indoor Temperature (T) and Relative Humidity (RH)

The fluctuations in indoor temperature and relative humidity were measured in a range of 16,41–28,76 °C (˜difference 12 °C) and 45,9–83,78% (difference ˜38%) over the year, respectively, while the fluctuations in outdoor temperature are in a range of 16,41–28,39 °C (difference ˜12 °C) and 41,96–77,78% (difference ˜55%) over the year, respectively [74] (see Table 1, Fig. 5). It can be seen that the indoor temperatures are almost the same as the outdoor temperatures most of the time, except in May and June. In contrast, the indoor climate has higher fluctuations in relative humidity throughout the year, and the seasonal cycle is almost higher than that of the outdoor climate, except in May and July when the HVAC system is partially operating to improve human comfort. The relative humidity fluctuates ˜20% in summer (especially in May and September). The high internal gains could be due to the flow of visitors and a presumably low ventilation rate due to the low ratio between the opening area and the building volume. Considering the climate during summer and its consequences in terms of preventive conservation requirements needs is a characteristically Mediterranean problem [75]. The high relative humidity limits drying possibilities and increases the risk of mould growth and insect infestation. The uncontrollable fluctuations in temperature and relative humidity appear to be strongly influenced by outdoor conditions, apart from the heat and humidity gains that are probably due to the high number of visitors in summer [76]. In the months of August, September and October, when the air conditioning is partially in operation during the museum's working days and hours, the temperature and relative humidity values have stabilized [77, 78], with less fluctuation compared to the other seasons, but values are still above international conservation standards [79]. Uncontrolled hydrothermal fluctuations with reduced ventilation can cause serious physicochemical and biological damage to the composite materials in the collections and discomfort to visitors [24]. Indeed, signs of deterioration such as craquelure have been observed on several paintings.

Air pollution

Pollutant monitoring was performed in February–March. Formaldehyde and HCOOH concentrations were around 10 μg/m^3 at all sites, with the exception of the basement (35 μg/m^3 and 4 μg/m^3 respectively), which is probably due to the existence of paper archives and wooden shelves in the basement. AcOH concentrations were almost the same at all sites (around 30 μg/m^3). While internally generated volatile organic compounds and acetic and formic acid have been cited as a cause of decay in museums [20], the organic components formaldehyde, acetic and formic acid are present in low concentrations at all sites and may

Table 1 the maximum (max), minimum (min) and average (av) values of indoor and outdoor air temperature and relative humidity during the monitored period (1 year)

Month	Indoor						Outdoor					
	Temperature (T°C)			Relative humidity (RH%)			Temperature (T°C)			Relative humidity (RH%)		
	min	max	av	min	max	av	min	max	av	min	max	av
January	19,36	26,03	21,12	57,23	83,78	70,88	19,46	25,81	21,12	54,01	75,35	66,19
February	18,51	25,14	20,02	61,9	80,11	69,8	18,03	25	20,08	49,33	74,01	65,05
March	16,41	24,29	18,24	50,44	76,26	68,83	16,41	25,06	18,5	42,95	74,23	63,58
April	19,12	21,62	19,67	60,97	76,92	68,99	19,38	22,44	20,01	54,21	70,62	62,64
May	20,24	25,21	22,41	54,26	80,6	70,33	20,72	25,91	22,45	49,54	74,81	64,65
June	23,3	25,89	24,98	59,97	77,22	70,9	23,28	26,2	24,86	49,95	72,7	65,68
July	25,84	28,76	27,29	59	81,2	74,68	25,59	28,34	27,04	54,91	76,86	70,23
August	26,54	28,29	27,7	60,3	80,94	72,97	26,84	28,39	27,37	56,06	77,78	69,76
September	25,52	28,44	27,67	51,25	81,19	70,1	24,82	28,32	27,13	45,32	77,63	67,69
October	26,35	27,82	27,16	51,34	76,96	64,97	25,96	27,45	26,66	47,61	72,79	61,78
November	21,84	26,81	24,39	52,13	68,94	61,29	21,84	26,13	23,99	48,06	65,64	57,08
December	20,77	22,56	21,39	45,9	67,87	61,11	20,03	22,08	21,29	41,96	65,79	55,71

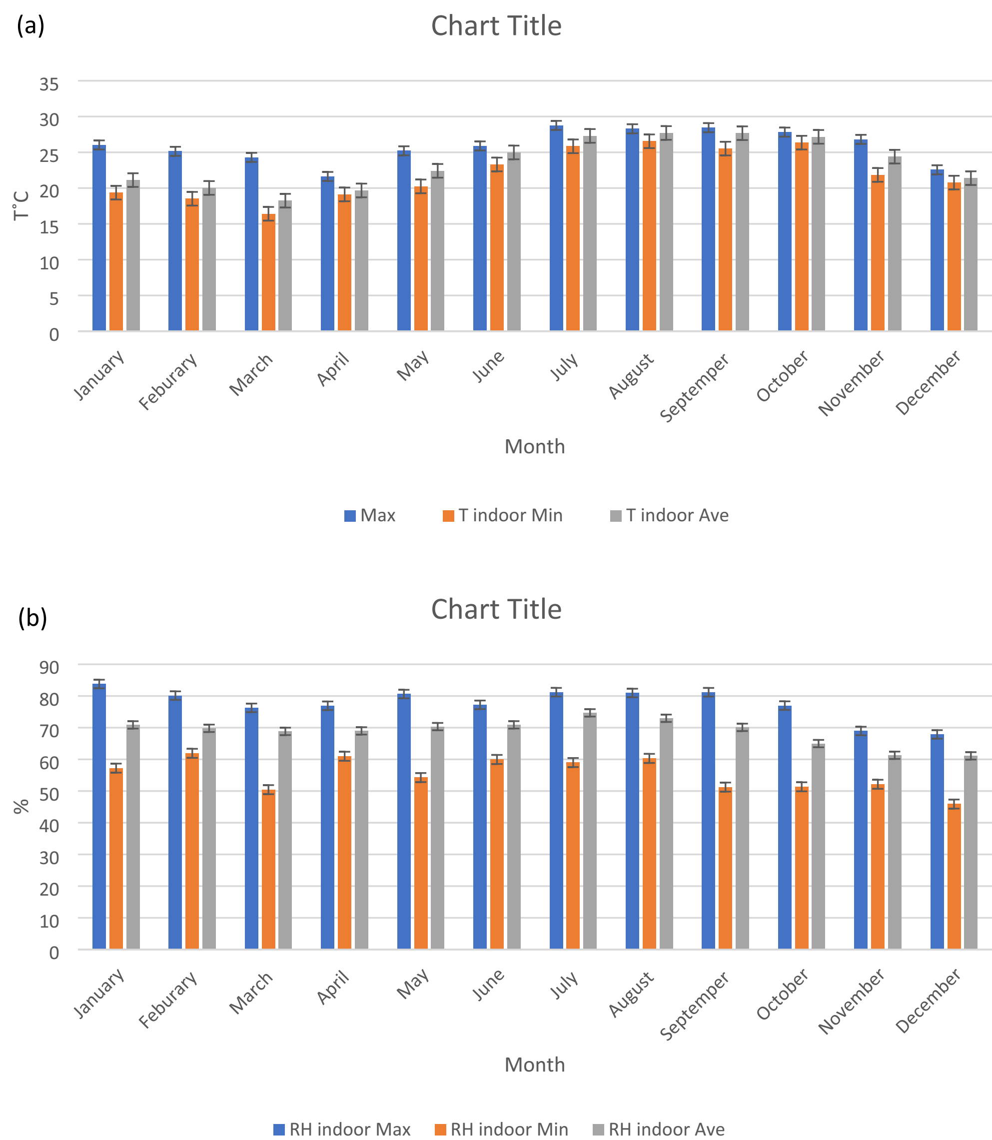

Fig. 5 Shows **a** the average temperatures and **b** the average relative humidity fluctuations through the year in the indoor environments of the museum exceeding the international standard

not be a cause of concern for the objects [80], but could have a high degree of risk for human health.

Annual air temperature and humidity fluctuations could be the main cause of organic acid concentrations variations, as more organic compounds are released from paper, paints, and wooden materials at higher temperatures [96]. In contrast, NO_2 concentrations in the outdoor area and in the two galleries are more than three times the recommended concentrations (the recommendation for long-term storage is (20 μg/m^3) [81]. NO_2 concentrations outdoors and indoors (ground floor, 1st floor) are almost the same (70–80 μg/m^3), except in the basement (35 μg/m^3) [82]. Similar concentrations have been reported [83, 84] and are generally attributed to traffic and industrial activities in the city. The estimated high air exchange rate is consistent with the finding that indoor NO_2 concentrations are similar to outdoor concentrations. High NO_2 concentrations can pose a risk to items made of cellulose materials, carbonaceous materials, leather, certain metals and acid-sensitive pigments and dyes [24]. The results indicate that the objects can be damaged within a few years and that the damage requires conservation intervention. SO_2 was measured in acceptable concentrations of less than (3 μg/m^3) [81]. There is little significant difference between outdoor and indoor ratios ($p = 0.047$), but indoor concentrations appear to be higher. Since there are no indoor SO_2 sources, the I/O ratio is most likely 1. In the case of O_3, there is no statistically significant difference between the external O_3 concentration measured at the main door and the internal concentration measured on the first floor. The measured ozone concentrations were below 10 μg/m^3 at all locations (the recommendation is 20 μg/m^3 but could reach dangerous concentrations in summer due to the formation of ozone from NO_x in photochemical reactions [85]. The comparable concentrations of all pollutants between the outdoor area and the gallery indicate high air exchange rates of unfiltered air from outside into the building and between the floors of the building, which is consistent with the T and RH measurements. The basement has a different climate with lower NO_2 and higher formaldehyde concentrations, indicating both lower ventilation rates and a greater number of formaldehyde-emitting materials, such as museum artefacts or furniture or cleaning materials.

The measured CO_2 concentration during two events allowed an estimation of the air exchange rate (AER) of two gallery spaces on the first floor of the building. The estimated AER is $(9.8 \pm 3.6)/h^{-1}$ in one gallery and $(6.0 \pm 1.7)/h^{-1}$ in the other. These values are not atypical for naturally ventilated public spaces [86]. They indicate a high level of air exchange with the outside, which means that the fluctuations in humidity and pollutant levels inside are strongly influenced by the outside conditions. Many unframed paintings, particularly those on display in the entrance corridor, are therefore possibly at risk from wind and gas contamination from outside, e.g. from the heavy traffic around the museum. The museum's HVAC system only operates during a few weeks of the summer season and only during the museum's opening hours (from 9.00 am to 3.00 pm) to lower the operating costs. Natural ventilation through the main gate is utilised all year round when the HVAC is not in operation. The museum's environmental monitoring shows that the temperature, relative humidity, light and wind speed do not meet international optimal conservation standards [87], even for a museum with almost uniform collections [88–90] (lighting = 50 lx; T = 20 °C; RH = 40–60% with an allowable variation of ± 5%). The results also show that CO_2 concentrations are higher during public events than during the week. The data shows the correlation between the CO_2 concentration and the number of visitors, which indicates poor ventilation [91]. At a public event where 100 people were present in 500 m^3, the CO_2 concentration tripled (from 932 to 2669 ppm and the relative humidity increased from 47 to 56%). At another event, where 200 people were present in 2250 m^3, the CO_2 concentration rose from 1285 to 2179 ppm and the humidity from 51 to 62%). However, air pollution inside the museum building, as well as an inadequate indoor microclimate, can negatively affect the health of visitors and employees. At a low degree of air pollution over longer periods, more severe effects such as surface alteration, color change or even weakening of the material may occur [92].

Light levels

During the environmental investigation in the museum, it became clear that there is no natural lighting in the galleries and exhibition rooms. To improve the visibility of the artworks, higher illuminance levels than the conservative standards were used in the museum (see Fig. 6). The museum has used high levels of artificial lighting in some areas of the exhibitions, especially on the 1st floor, to enhance the aesthetic qualities of the objects and displays. Most of the lamps are hung away from the objects to avoid heat build-up, but the light intensities recorded are higher or lower than the relevant international

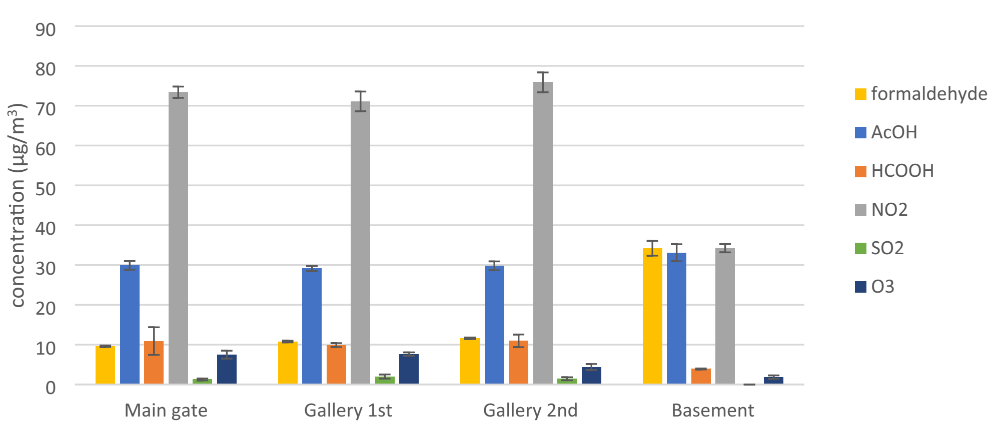

Fig. 6 Shows the pollutants concentrations in the outdoor (main gate), ground floor (gallery 1st), 1st Floor (gallery 2nd), and the basement

conservation standards in museums. While several measurements of light intensity on different objects on the ground floor gave an average value of 130 lx, the maximum illumination values measured on different types of paintings on the first floor were in the range of 450–650 lx, and the average minimum value was around 30 lx, both of which are far from the standard requirements for conservation (150 lx) and human comfort (> 300 lx) [87]. There are no UV blockers or limitation of light exposure, which could lead to fading of the painting collections, while the intense lighting system could be a source of ignition in the museum. However, the prolonged exposure of objects to direct or indirect artificial light causes serious damage and chemical changes over time, leading to harmful photochemical deterioration of the painting and other sensitive materials such as fading, yellowing, or darkening [89].

Museum and collection management

The workshop discussion, the interviews and the site visits have shown that preventive conservation in Egyptian museums in general and in the AMFA in particular poses a number of challenges. Staff at the AMFA Museum have to deal with several challenges from an operational perspective, including the lack of a museum mission, resources and guidelines for collection management, display, loans, storage, conservation and emergency preparedness. The AMFA has free admission and no annual budget for museum operations. Although, the modest operating costs of the museum are covered by the Central Authority for Contemporary Museums of the Ministry of Culture. The museum is open to visitors from Saturday to Friday (except Mondays) from 9.00 am to 4.00 pm. However, the number of visitors to the museum varies depending on the season, social activities and temporary exhibitions. Since the renovation in 2013, the number of visitors has increased by 100–150% each year, while the number of visitors before the COVID-19 pandemic was around 25,000 visitors per year (an average of 68 visitors per day), including educational and community activities. With 25,000 visitors in 2019, the museum remained a very modest figure compared to the high visitor capacity of, for example, the Bibliotheca Alexandrina, which has more than 1.5 million visitors and is almost within walking distance of the museum [93]. This suggests that the museum is not under pressure from visitors or tourism [94]. Another critical threat to the museum is the lack of a clear management system or plan. The building underwent reconstruction in the 1950s and extensively renovated in 2013 after a long closure. The number of security guards and cleaning staff is sufficient, but more curators and conservators need to be hired to do the necessary collection management and conservation work. In addition, the basic equipment for museum operations, documentation and conservation science must be secured. There is also a lack of adequate regular maintenance of the buildings, electrical and technical installations. Compared to the rich community engagement and educational activities in the museum, there is little scientific research on the collections that would allow for a better interpretation of the significance of the collection or a better understanding of its art history. There is also a lack of sufficient staff to meet the museum's conservation, curatorial, technical and IT needs. There is a need for basic documentation systems and operating equipment such as computers, printing presses and theatre facilities. The museum does not yet have a written emergency plan and relies on quick and clear communication with local authorities. The security of the collection is ensured by the museum director, the curators, and the security service. The museum has a permanent police/security service that provides round-the-clock security for the museum and visitor access, as well as physical protection such as locked windows and secured doors. Only authorised personnel have access to some of the interior rooms/areas. There are electronic surveillance cameras and alarm systems managed by the museum's security service, allowing real-time visual monitoring by security staff, but there are still blind spots. There are fire extinguishers in all areas of the museum, but no smoke detectors or fire extinguishers. Fire extinguishers are distributed throughout the museum halls and are regularly checked by the local fire safety authorities (Fig. 7).

The predominant type of collections is mainly organic, such as oil paintings, paper, photographs and wooden sculptures. The collections are categorised and exhibited in homogeneous object types according to their sensitivity to the uncontrolled environmental conditions. However, the more sensitive objects such as watercolours, gouaches, pencils, pastels and charcoal on paper are displayed near the main gate and are exposed to greater fluctuations in temperature, humidity and outdoor pollutants (see Fig. 2). In addition, the collections are displayed openly and without closed display cases, while some paintings have been glazed. While 80% of the collections are on permanent display in the galleries and corridors, the rest of the collections are in storage, often used for temporary exhibitions prepared from time to time by the museum staff. The stored collections are located in a small room (with secured and alarmed doors) next to the museum's public toilets (see Fig. 1) in a poor state of conservation and in an uncontrolled environment with dusty and damp floors, shelves and rooms without suitable furniture [38, 95]. The collections are in direct contact with acidic materials (wood, paper) and are exposed to biological attacks. Various types of insects were found

Fig. 7 360° photo showing the intensive use of artificial lighting (1st floor)

in the storage room. However, it was clear from the interviews and workshop discussions that the preventive conservation in Egyptian museums remains unplanned and requires in-depth research to improve the conservation process and increase public involvement [96]. Egyptian museums face several challenges in conservation management that lead to arbitrary decisions [97]. Egyptian art museums suffer from poor conservation management, absence of conservation guidelines [98]. The irresponsible development of resources and the low priority given to conservation management have led to arbitrary decisions that have neglected the qualifications of collection values. In Egypt, there has been an increase in the number of museums filled with a number of valuable but poorly documented collections for which there is no value assessment for decision-making in collection management [43, 99]. Most collections in Egyptian museums are displayed or stored without systematic standards for environmental control which poses a high risk of damage [100]. Despite the complexity of the challenges in conservation practise in Egypt, there is a need to develop a systematic institutional framework for preventive conservation management that takes into account various factors affecting decision-making and monitoring the impact of conservation interventions [19]. Museums need to adopt environmental sustainability concepts, e.g. by reducing T/RH variations, pollutants, greenhouse gas emissions, energy efficiency and the use of sustainable materials in the renovation of museum buildings [101]. In addition, regular maintenance of museum buildings and spaces is an important process to minimise or prevent damage to museum collections, reduce internal costs and improve human comfort [18]. Therefore, conducting risk analyses and developing conservation and museum management strategies [53] must be prioritised in order to extend the lifespan of the artistic museum heritage and the museum building and promote priority conservation needs, attractive display and satisfactory human comfort [102]. Short and long-term integrated management plans with evidence-based decision-making need to be established to provide the very modest budget required to operate and preserve museum collections with sufficient, well-maintained, and secured exhibition and public spaces [96]. However, in terms of climate change adaptation and mitigation, the capacity of Egyptian museums to manage these risks and prepare communities for potential future disasters and climate change impacts is limited [103] as the organizational set-up of the emergency response system in the city is highly centralised with limited horizontal and vertical coordination between local authorities down to the communities' level. However, efforts have already been made to reduce the risks of coastal flooding in Alexandria due to the projected sea level rise and more frequent and intense extreme storm events [104].

Conclusion

The results enabled an assessment of indoor air quality and provided information about potential risks to museum collections. Unfortunately, the air quality in the museum cannot be considered satisfactory. Given the large variations in T and RH values and the high concentration of some of the gaseous pollutants measured, due to traffic and visitors as well as poor ventilation, specific measures need to be taken to improve the level of air quality. Although some paintings are kept in protective glazing, adequate environmental control should be put in place, taking into account the museum's resources. Due to the uniform collections in the museum, the selection of appropriate temperature and relative humidity set points based on the most sensitive objects (e.g. colour paintings) is recommended. To avoid serious damage to the collections, T-values should be kept as far as possible within a recommended set point, where daily fluctuations must not exceed 4 °C. The ideal humidity level is an average of 50% (± 10%), but values between 45 and 60% are also acceptable. The fact that the museum's exhibits are exposed to high T/RH fluctuations and pollution pressure is a fact that requires further attention, whereby more regular use of the HVAC system should be considered. However, an energy audit is recommended to assess the most appropriate measures to control T and RH before the HVAC system is fully utilised. Pollutant concentration measurements show seasonal differences related to ventilation and/or air exchange rates between the AMFA building and the outdoor environment. The I/O concentration ratios indicate a higher penetration of outdoor-generated pollutants and a greater dilution of indoor air in winter than in summer. Based on the relationship between indoor and outdoor pollutant concentrations, we can distinguish between the main sources. On the one hand, NO2, O3 and SO2 show a clear outdoor origin and are related to emissions from traffic on the street next to the museum building. On the other hand, organic acids such as acetic acid and formic acid clearly originate indoors, most likely from housekeeping and cleaning fluids as well as building materials such as renovation materials and wooden shelves and frames. Therefore, it is important that you consider new materials or paints in future renovations to consider preventative protection and the value of the existing building. The amount of CO2 could have negative effects on people that need to be better controlled to manage them. Ventilation methods in museum buildings can fulfil several functions, including improving indoor air quality and thermal comfort, particularly in the summer months, through the use of air conditioning and light mechanical equipment such as fans. Healthy indoor air movement provides sufficient air velocity to maintain an acceptable level of thermal comfort when the local temperature and humidity require it. Illuminance is one of the greatest threats to the integrity of AMFA collections. To minimise potential photochemical changes, it is necessary to gradually switch light sources to LEDs, as these generate less heat, consume less energy and are generally easier to regulate. In addition, reducing the annual energy exposure could be reduced by rotating the artefacts or installing an IR control system that only switches the light on when people are present is also a good suggestion. UV-filtering glazing should be used first for the masterpieces and the most sensitive artefacts in the museum to limit exposure to artificial light. Staff should also consider rotating the objects on display to minimise exposure to light. Visitors play an important role in converting risks to the museum. To protect museum objects from long-term damage, it may therefore be an option to place them behind glass or in display cases. In addition, all exhibitions and storage rooms need to be cleaned regularly, with cleaning chemicals carefully selected and water consumption reduced to improve the air quality in the rooms and reduce the risk of biological damage. The maintenance of the museum should be considered and specific guidelines should be followed. The museum building is structurally in good condition and does not pose a serious risk to visitors. Dampness in the building, e.g. from heavy rainfall and flooding, has a major impact on the museum and causes salt efflorescence on the walls behind the paintings. It is necessary to find a solution for the building's drainage system to eliminate the moisture problem and develop emergency action plans in case of flooding or excessive rainfall. Whilst a new roof screen was introduced into the building, the rainwater drainage systems needed to be routed outside the building and floors, with the drainage systems leading away from the walls. Given the size of the exhibition spaces and the air distribution required in such large museum exhibition spaces, cooling through natural ventilation by opening the windows is not an option, while mechanical ventilation with air diffusers should be introduced in the short term to achieve good air mixing. Consideration was given to moving the sensitive collections of inked and multicoloured paper from near the gate to the halls with less fluctuating climatic conditions. However, in the event of extreme weather warnings, consideration should be given to moving the sensitive objects to safer storage areas. The storage rooms should be located away from the public toilets and equipped with suitable furniture. Given the challenges associated with the museum's location, the accessibility of the museum for emergency services must be planned as a top priority. In addition, the museum should seek interdisciplinary expert advice for future renovations of museum buildings or the design of exhibitions.

However, dealing with the effects of climate change on indoor and outdoor environments and museum collections in the Mediterranean requires a holistic and adaptive approach that includes collaboration, research and strategic planning to ensure the long-term preservation of valuable heritage collections. Collaboration and training between Mediterranean and Egyptian museums, heritage institutions, researchers and conservation professionals should be encouraged to document and share information on climate impacts, risk analyses, successful mitigation measures and adaptation strategies. Museums should develop a microclimate appropriate to the specific typology and sensitivity of each collection to ensure conservation of collections, energy conservation and human comfort. While certain environmental management principles are applicable in different climates, the effectiveness and sustainability of specific approaches may vary depending on regional characteristics such as relative humidity/temperature range and pollution levels. Therefore, different climate zones may require customised adaptations based on local environmental conditions, resources and needs. Resilience planning should be region-specific and consider the potential impacts of extreme weather events, sea level rise and other climate-related challenges.

The main issues facing the Museum of Fine Arts in Alexandria depend on advances in heritage science, particularly in terms of environmental management procedures, planning regulations and financial resources. The main challenge facing Egypt's cultural heritage sector is the implementation of preventive conservation assessment plans as a first step in the process of conserving various modern objects housed in different geographical areas in Egypt. This should be done within the framework of a collections management strategy that prioritises the number of qualified staff, the minimum available budget/resources and the social values of the collections through clear written guidelines and in respect to the nine principles of green heritage science.

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Availability of data and materials
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Declarations

Competing interests
The authors declare no competing interests.

Author details
[1]Department of Archaeological Science and Excavations, Faculty of Archaeology, Ain Shams University, 11566, Cairo, Egypt. [2]Heritage Science Lab Ljubljana (HSLL), Faculty of Chemistry and Chemistry Technologies, University of Ljubljana, Ljubljana, 1000, Slovenia. [3]Centre d'Études Alexandrines (CEAlex), Alexandria, 5371052, Egypt. [4]Ministry of Culture, Alexandria Museum of Fine Arts, Alexandria, 5413416, Egypt. [5]Institute of Sustainable Heritage, University College London, London, WC1E 6BT, UK. [6]Faculty of Business, Alexandria University, Alexandria, 5424010, Egypt. [7]Faculty of International Business and Humanities (FIBH), Egypt-Japan University of Science and Technology, Alexandria, 5221241, Egypt.

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