air

MDPI

Article

Air Quality and Energy Use in a Museum

Glykeria Loupa [1,2], Georgios Dabanlis [1], Evangelia Kostenidou [1] and Spyridon Rapsomanikis [2,*]

1 Laboratory of Atmospheric Pollution and Pollution Control Engineering of Atmospheric Pollutants, Department of Environmental Engineering, Faculty of Engineering, Democritus University of Thrace, 67100 Xanthi, Greece; gloupa@env.duth.gr (G.L.); gntampan@env.duth.gr (G.D.); ekosteni@env.duth.gr (E.K.)
2 Unit of Environmental and Networking Technologies and Applications ATHENA-RIC, University Campus, Kimmeria, 67100 Xanthi, Greece
* Correspondence: rapso@athenarc.gr

Abstract: Museums play a vital role in preserving cultural heritage and for this reason, they require strict indoor environmental controls. Balancing indoor environmental quality with reduced energy consumption poses significant challenges. Over the course of a year (2023), indoor microclimate conditions, atmospheric pollutant concentrations (O_3, TVOC, CO, CO_2, particulate matter), and energy use were monitored at the Archaeological Museum of Kavala. Maximum daily fluctuations in relative humidity were 15% in summertime, while air temperature variations reached 2.0 °C, highlighting unstable microclimatic conditions. Particulate matter was the primary threat to the preservation of artworks, followed by indoor O_3 and NO_2, whose concentrations exceeded recommended limits for cultural conservation. In 2023, the Energy Use Intensity (EUI) was 86.1 kWh m^{-2}, a value that is significantly correlated with the number of visitors and the outdoor air temperature. Every person visiting the museum was assigned an average of 7.7 kWh of energy. During the hottest days and when the museum was crowded, the maximum amount of energy was consumed. Over the past decade (2013–2023), the lowest EUI was recorded during the COVID-19 pandemic at 53 kWh m^{-2}. Energy consumption is linked to indoor environmental quality; thus, both must be continuously monitored.

Keywords: energy; indoor air; particulate matter; gaseous air pollutants; tourism

check for updates

Academic Editor: Alan W. Gertler

Received: 6 December 2024
Revised: 8 January 2025
Accepted: 13 January 2025
Published: 1 February 2025

Citation: Loupa, G.; Dabanlis, G.; Kostenidou, E.; Rapsomanikis, S. Air Quality and Energy Use in a Museum. *Air* **2025**, *3*, 5. https://doi.org/10.3390/air3010005

1. Introduction

Museums store valuable artefacts of our cultural heritage, which must be meticulously preserved to maintain their integrity over time. Consequently, maintaining adequate indoor environmental quality (IEQ)—including low atmospheric pollutant levels and microclimatic conditions suited to the artefacts—is essential. Furthermore, poor indoor air quality endangers both human well-being and productivity. Thus, museums' indoor environments have to offer a healthy atmosphere, along with visual and thermal comfort for both visitors and staff [1,2]. Following the COVID-19 pandemic, a surge in tourism led to overcrowding in many museums and cultural heritage sites, introducing new management challenges [3–8].

Indoor air pollution in museums originates from both outdoor and indoor sources. Most museums are in urban areas, making them vulnerable to outdoor pollutants like particulate matter (PM), nitrogen oxides (NOx), carbon monoxide (CO), ozone (O_3), and volatile organic compounds (VOCs). These pollutants enter museum spaces through ventilation systems and open doors or windows [9]. Additionally, numerous indoor atmospheric pollutant sources exist, such as cleaning agents, building materials and furnishings that can emit dust and several VOCs. The human activities of the staff and of the visitors can add to the indoor air several atmospheric pollutants, because they emit, for example, VOCs, CO_2 and skin flakes [7,10,11]. The movement of people in the exhibitions also provokes the resuspension of the settled particles. Some artefacts themselves can release pollutants, such as natural history specimens treated with preservatives [12]. Poorly designed display cases and ineffective storage facilities can exacerbate pollution by restricting air flow and thus allow atmospheric pollutant concentrations to build up [13].

Particulate matter (PM) is a less obvious but highly damaging component in the atmosphere of a museum, affecting the preservation of housed collections [14–17]. Airborne PM consists of solid and liquid particles of various sizes and chemical compositions, originating from both indoor and outdoor sources. Common types of PM include soot, pollen, and soil particles. Indoor PM sources within museums include human activity, fibres from clothing, resuspended particles from foot traffic, emissions from maintenance activities (such as cleaning and restoration), and emissions from building materials (like degraded plaster and paint). The composition of PM varies widely, encompassing inorganic compounds (e.g., salts), organic compounds (such as formic and acidic acid), and particles of biological origin (including bacteria, viruses, and fungi). PM can cause various types of damage to museum collections, including physical damage (surface degradation and soiling), chemical damage (corrosion and degradation of organic materials), and biodeterioration (such as mould growth). Small solid particles (under 75 μm in diameter) that settle on surfaces but may remain suspended temporarily are classified as 'dust', which poses a persistent challenge for museum curators [18–21]. For example, in 2010, the Conservation Department at the Victoria and Albert Museum in the UK evaluated strategies to manage dust deposition on exposed costumes from the Ballet Russes exhibition due to high visitor numbers [21].

PM is more than just an 'atmospheric pollutant'; understanding its full impact requires a range of analytical "off line" techniques. On the other hand, light-scattering devices offer a simple and accurate means to determine the number concentration and size distribution of PM [22,23].

In naturally ventilated museums—either modern or historical buildings—various air pollutants have been found to threaten stored collections, as discussed in Loupa et al. (2024) and referenced therein [7]. Atmospheric pollutant levels are not the only concern in museums. Microclimatic conditions, air exchange rate and lighting have to be appropriate for artefact conservation but also for the visitors' thermal and visual comfort [24,25].

Operating these buildings requires substantial energy, posing both environmental and economic challenges. Balancing appropriate indoor environmental quality (IEQ) with minimized energy use presents significant difficulties [26,27]. In Greece, data for primary energy use intensity (EUI) are taken from the energy performance certifications for non-residential buildings. On average, the annual EUI in Greek exhibition halls and museums is 312.5 kWh m^{-2} (ranging from a minimum of 65.8 kWh m^{-2} to a maximum of 632.5 kWh m^{-2}) [28]. Cooling demands the most energy, averaging 166.0 kWh m^{-2}, followed by lighting at 68.1 kWh m^{-2} and heating at 79.0 kWh m^{-2} [28]. Depending on local environmental factors, some museums rely more heavily on heating, others on cooling, and some buildings require energy primarily for dehumidification [29–31].

To improve energy efficiency in both historical and modern museum buildings, several technical interventions are recommended, including HVAC (Heating Ventilation and Air Conditioning) systems, ground-source heat pumps, and updated management programs [32,33]. Additionally, adopting renewable energy sources such as solar or wind power can further enhance sustainability in museum operations [34]. Renewable technologies in museums present both technical and financial challenges, but they can be overcome [35]. For example, in the modern museum of ancient Eleutherna, Crete, Greece, with a total annual energy consumption of 216,000 KWh, the installation of a geothermal heat pump at 123.2 KW has been proposed for its air-conditioning requirements, in addition to a solar-PV system with nominal capacity at 144 KW_{peak} that could generate all the electricity needed annually, which represents a cost-effective and reliable solution [36].

Strategies to enhance energy efficiency and sustainability in museums, as well as effective conservation processes for works of art, must be based on data acquired on-site [37,38]. Modern integrated environmental monitoring systems now continuously track environmental conditions, including gas and particle concentrations, temperature, and humidity, providing real-time data to guide and manage conservation strategies. Alongside IEQ data, collecting EUI metrics for each museum is essential. This study on the Archaeological Museum of Kavala, Greece, highlights the benefits of monitoring both IEQ and EUI.

2. Materials and Methods

2.1. Site Description

The Archaeological Museum of Kavala hosts representative artefacts from the Eastern Macedonia and Thrace in Greece, including mostly marbles and painted ceramic objects (https://archaeologicalmuseums.gr/el/museum/5df34af3deca5e2d79e8c1b8/archaeological-museum-of-kavala) (accessed on 6 December 2024).

The museum was established in 1934 and reopened in 1964 at the current building. This building is a two-story building (with a basement) with a flat rooftop that has old insulation. The windows and the glazing of the indoor atriums are not insulated. The main material used in the construction was cement for the supporting structure, while bricks were used for the walls. The floors in the exhibition areas are paved with marble. Heating is provided by a central heating system with oil radiators, and cooling is achieved using a central air conditioning system. Ventilation is natural.

The museum is open from 8:30 h to 15:00 h and remains closed every Tuesday.

Figure 1 presents the floor plan of the museum's ground floor, showing the locations of the monitoring stations. In location GF2 (ground floor, location 2), a staircase leads to the basement (Bs), which serves as a refreshment area for visitors. A schematic illustration of the surrounding areas of the building is also included.

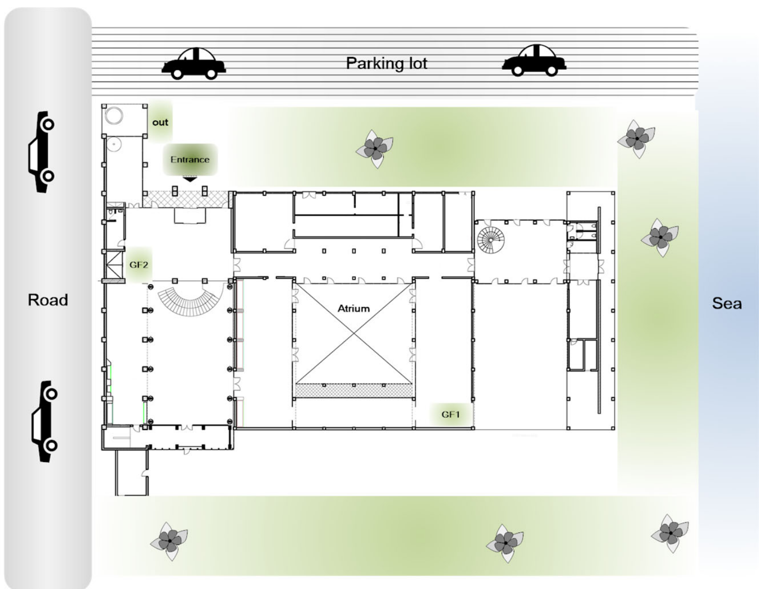


Figure 1. The floor plan of the ground floor of the museum and a schematic presentation its surrounding area. Below the GF2 (ground floor, location 2) is the basement (Bs).

The GF2 site covers an area of 97 m^2. The GF1 features an atrium in the centre. The two sides are approximately 45 m^2 apiece. The number of individual visitors is small, i.e., less than ten people. In the case of an organised group, each tour should not include more than thirty people.

2.2. Monitoring

The monitoring period spanned more than a year (from December 2022 to February 2024) to capture seasonal variations in indoor air quality parameters and corresponding outdoor conditions. Air pollutants (TVOCs, CO, CO_2, O_3, NO, NO_2) were monitored with a multi-gas sensor probe (model DirectSense II; GrayWolf Sensing Solutions; Annacotty, County Limerick, Ireland). Mass concentrations of particulate matter (PM) in six aerodynamic diameter ranges (PM_1, $PM_{2.5}$, PM_4, PM_7, PM_{10}, and TSP) were measured using an Aerocet 531s sensor (Met One Instruments Inc., Washington, DC, USA). All instruments were calibrated three times during the campaign. Both instruments also recorded air temperature (AT) and relative humidity (RH) and were connected to a laptop, where their instantaneous readings were recorded every five minutes (for 24 h per day).

On the ground floor (GF), measurements were conducted for twenty days in GF1 (ground floor, location 1), five days in the Bs and five days outdoors (location 'out', Figure 1) every month during the year 2023. Furthermore, for two months (January and February of 2024), the monitoring station was moved every week between GF1 (two days) and GF2 (five days) to trace their differences in the air pollutant concentrations. Location GF2 is near the building's entrance, where tickets are sold. A detailed record of activities was maintained at each monitoring location, and the daily visitor count was provided by staff.

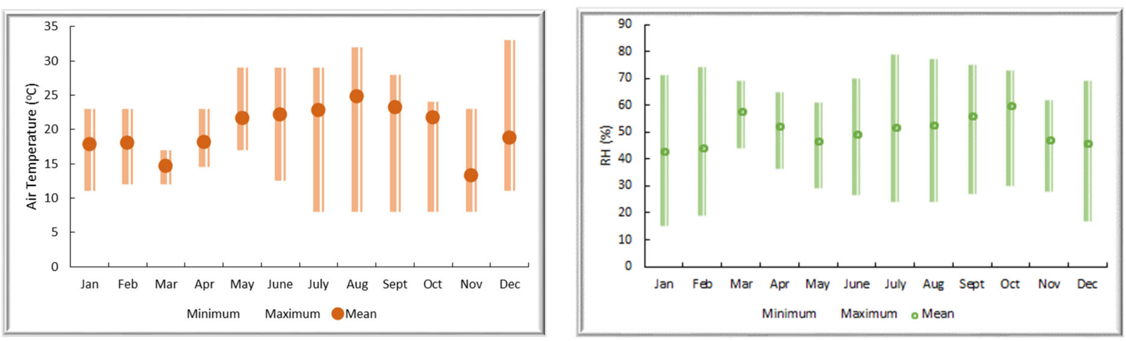
Outdoor wind speed and wind direction were measured with an Atmos-41 weather station (METER Group GmbH, 81379 München, DE, Germany) and logged on a ZL6 data logger (METER Group GmbH, 81379 München, DE, Germany) every 15 min. This station was on the roof of the building.

Data on the building's electric energy consumption were sourced from the Public Power Corporation S.A.-Hellas (DEH). Information on heating oil consumption, used during the two or three coldest months of the year, was provided by the technical staff, with an assumed energy yield of 10.6 kWh per litre of heating oil.

3. Results

3.1. Indoor Microclimate, Outdoor Meteorological Conditions and Energy Use Intensity

Figure 2 summarizes the monthly mean, maximum and minimum indoor air temperature and relative humidity in the ground floor exhibition (GF1) of the museum throughout 2023. Significant variations were recorded for both parameters.



(**a**) (**b**)

Figure 2. Indoor air temperature monthly variations (**a**); indoor relative humidity monthly variations (**b**) (GF1, 2023).

Kavala has a sunny, Mediterranean climate. Outdoor mean air temperatures around the museum ranged from 13.3 °C to 33.5 °C and the outdoor mean RH between 47% and 62%, reflecting the museum's coastal proximity. Indoor microclimatic conditions were influenced by these outdoor factors, as well as by the building's heating system in winter and cooling system in summer. The indoor environment was primarily adjusted for visitor thermal comfort rather than for artefact conservation [39,40]. Daily fluctuations in RH and AT and their rates are critical indicators for assessing potential damage to artworks. During August 2023, the highest daily AT variation was recorded at 2.0 °C, with an RH variation of 15%. In winter, daily AT variation peaked at 3.1 °C, with a corresponding RH variation of 8%.

Figure 3 illustrates the museum's EUI in relation to the mean outdoor air temperature.

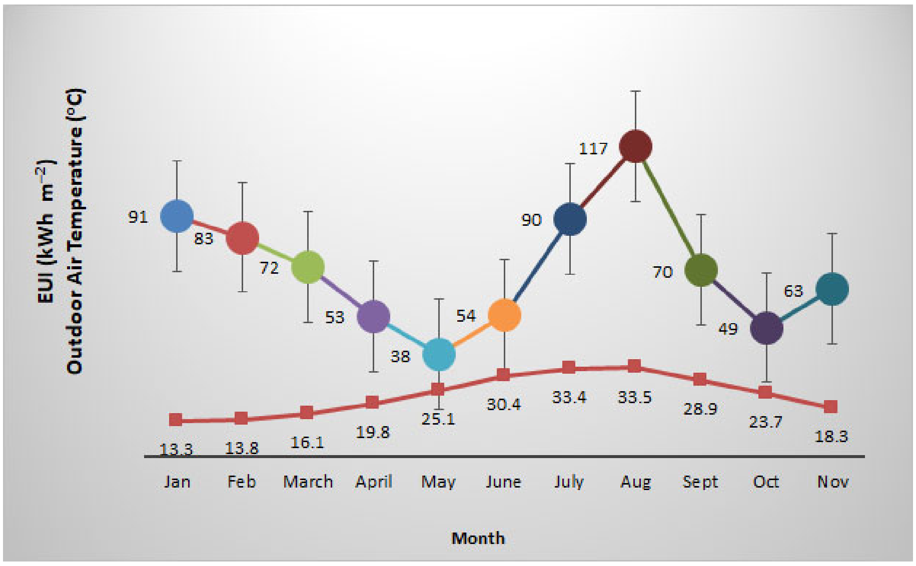


Figure 3. Mean monthly EUI in the museum along with mean monthly outdoor air temperature.

Approximately 88% of the total consumed energy was electrical. The energy use in this naturally ventilated museum is highly dependent on ambient weather conditions. The relationship of the mean monthly EUI (kWh m^{-2}) in the museum with the mean monthly outdoor air temperature (Temp.$_{out}$, °C) is of second order:

$$EUI = 0.51\ (Temp._{out})^2 - 23.5\ (Temp._{out}) + 316.1, \quad R^2 = 0.8189 \tag{1}$$

Linear regression resulted in a low coefficient of determination (R^2), and applying a higher-order polynomial fitting did not improve the R^2 value.

Another important parameter that affects the EUI is the number of people (visitors and employees) present in the museum. Its relationship with the number of people present in the museum (Pp, sum of people present per square meter, per month) is as follows:

$$EUI = 7.7\ (Pp) + 17.6, \quad R^2 = 0.6036 \tag{2}$$

By increasing the order of the polynomial fitting in the trend line, R^2 was increased. For example, for a second-order polynomial fitting, R^2 = 0.7018. We demonstrate in Equation (2) the simplest fitting, i.e., the linear relationship with a statistically significant R^2.

Figure 4 illustrates the synergistic impacts of two parameters: outdoor air temperature (Temp.$_{out}$) and the number of individuals per square meter on the EUI measured in kWh m^{-2} per month, represented in a 3D contour map utilizing the distance-weighted least squares smoothing technique. Figure 4 demonstrates that with elevated temperatures and heavy visitor attendance, the museum exhibited peak energy consumption.

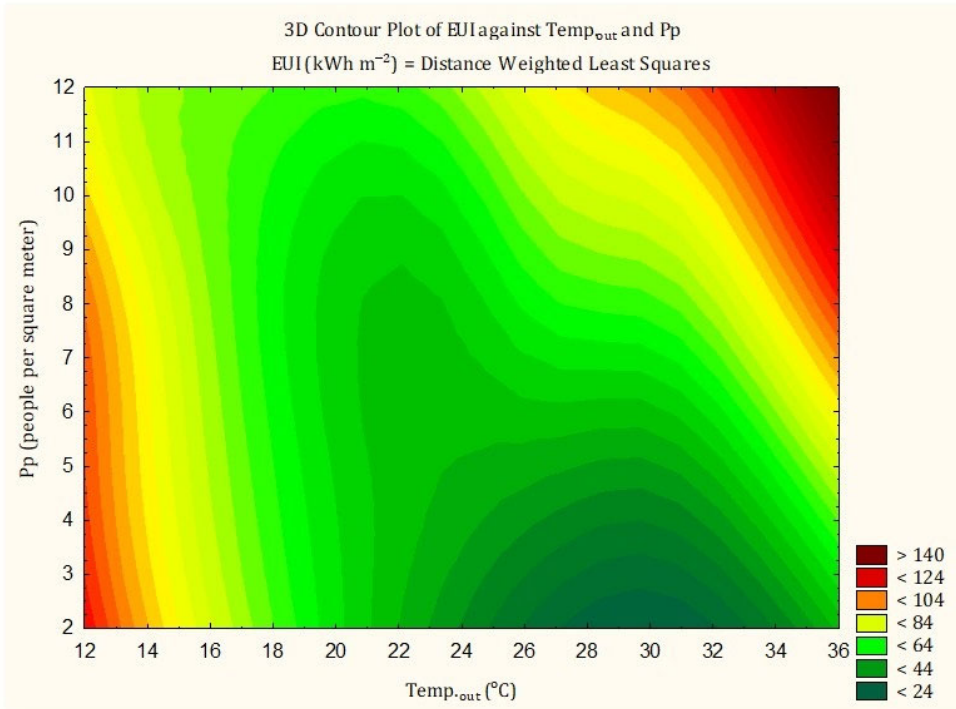


Figure 4. The relationship of EUI with the mean monthly outdoor air temperature and the number of the people present per square meter of the exhibition (GF1, 2023).

Figure 5 depicts the long-term EUI from 2013 to 2023. The linear relationship between EUI and time is also provided.

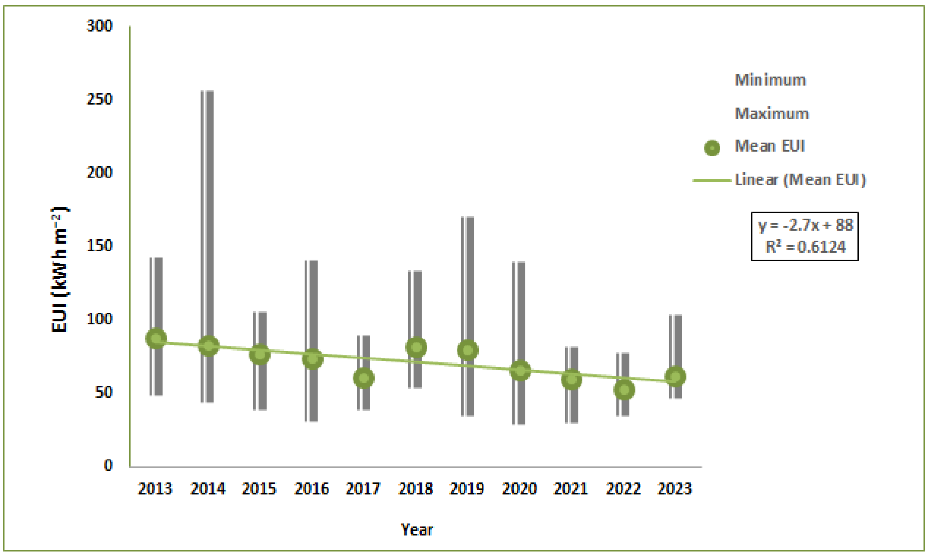


Figure 5. Yearly mean, max and mean EUI in the museum for a decade.

The yearly EUI ranged from 64 to 106 kWh m^{-2}, with peak values occurring during cultural events, such as lectures, music evenings, and special thematic exhibitions.

The museum staff's efforts to reduce energy consumption, along with the switch to more efficient lighting and possibly the impact of climate change—reflected in rising mean outdoor temperatures—are evident in the trend of the mean EUI, which decreased by

2.7 kWh m^{-2} over the examined decade [41]. This trend remained unchanged even when the pandemic years, 2021–2022, were excluded from the dataset.

3.2. Indoor Atmospheric Pollutants

Indoor air quality (IAQ) was influenced by outdoor air quality, as the building lacks a filtration system. Indoor pollutant sources, such as visitor presence and movement, also played a significant role. Table 1 summarizes the indoor and outdoor atmospheric pollutant concentrations at location GF1 for the year 2023, along with the respective indoor/outdoor (I/O) concentration ratios.

Table 1. Indoor and outdoor atmospheric pollutant concentrations at GF1 (2023).

PM ($\mu g\ m^{-2}$)	GF1		Out		
	Mean	**Std.Dev.**	**Mean**	**Std.Dev.**	**I/O**
PM_1	13.33	8.01	5.60	2.78	2.38
$PM_{2.5}$	17.61	11.35	9.85	4.79	1.79
PM_4	26.99	25.17	24.84	11.44	1.09
PM_7	33.47	34.54	45.18	19.37	0.74
PM_{10}	35.19	37.31	53.76	22.77	0.65
TSP	36.70	39.65	63.07	26.00	0.58
Gases	**Mean**	**Std.Dev.**	**Mean**	**Std.Dev.**	**I/O**
TVOC (ppb)	321.65	124.87	190.66	31.49	1.69
CO (ppb)	189.38	185.60	315.33	204.16	0.60
CO_2 (ppm)	468.92	62.91	471.78	24.57	0.99
O_3 (ppb)	6.46	12.78	13.77	18.20	0.47
NO (ppb)	124.91	24.63	184.80	15.45	0.68
NO_2 (ppb)	46.64	32.12	85.05	21.21	0.55

The I/O concentration ratios for PM_1, $PM_{2.5}$, PM_4 and TVOC were greater than one, indicating the presence of indoor sources.

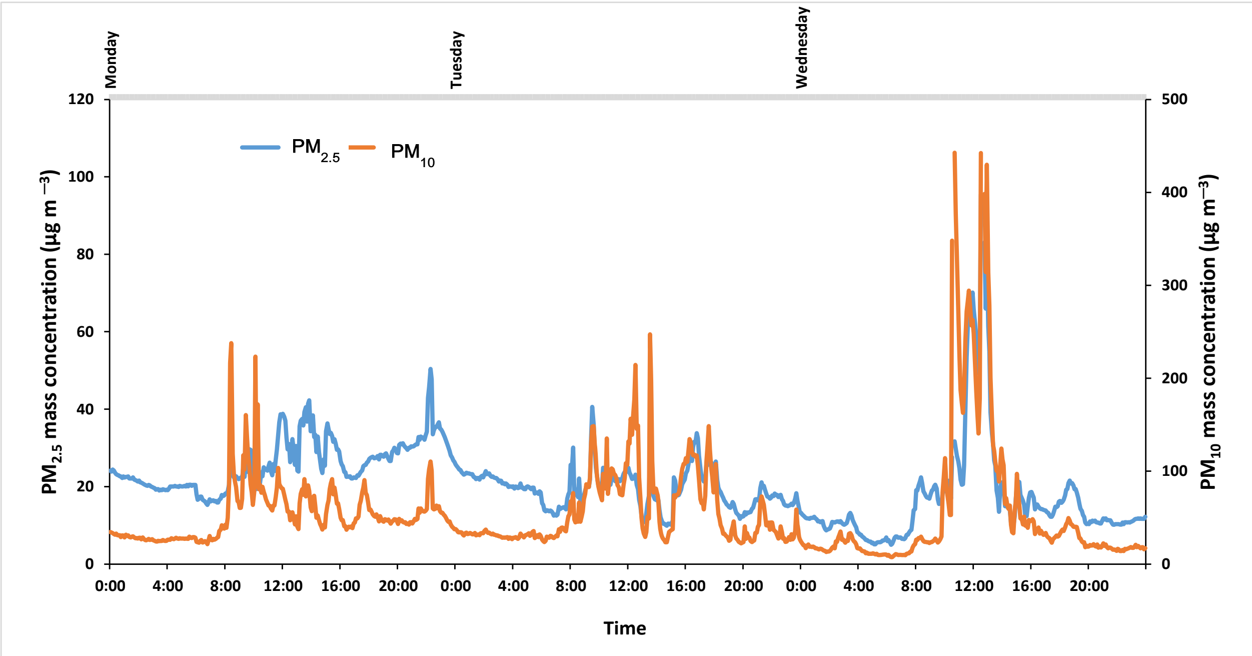
Figure 6a,b show a snapshot of the time series data for certain indoor PM and gaseous pollutant concentrations on the ground floor (GF1) of the museum. Every Tuesday, the museum was closed to the public, with only personnel present for cleaning, dusting, and occasional repairs. On all other days, the museum closed at 15:00. On the Monday depicted in these figures, 10 tourists visited the museum, while on Wednesday, a group of 120 tourists visited, resulting in increased concentrations of indoor atmospheric pollutants.

3.2.1. Air Change Rate (ACH)

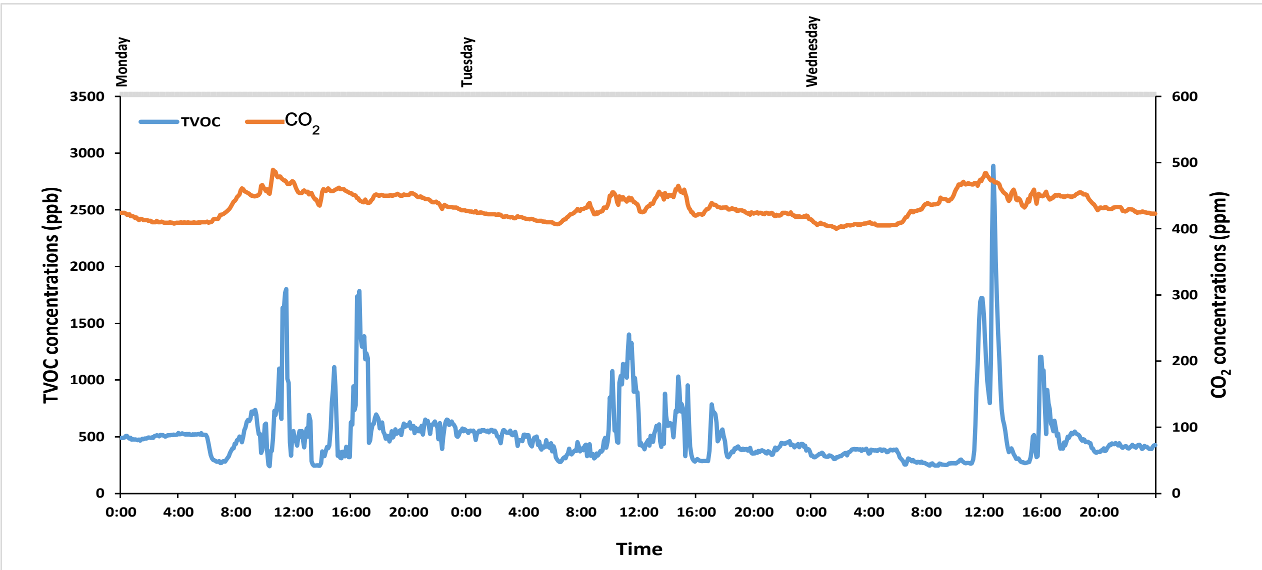
The decay of indoor CO_2 concentrations after a group left GF1 or after the museum closed at 15:00 allowed for the estimation of the ACH [7]. When the museum was open, the ACH ranged from 0.32 to 0.54 h^{-1}, while after 15:00, it dropped to between 0.08 and 0.12 h^{-1}.

3.2.2. IAQ Comparison Between Two Locations

Certain areas of the museum experienced higher visitor concentrations than others. At the entrance, where tickets are sold, all visitors in groups, wait for at least ten minutes, while in other areas, visitors are more dispersed. Figure 7 compares atmospheric pollutant concentrations across multiple places, namely GF1, GF2, and Bs (January and February 2024).



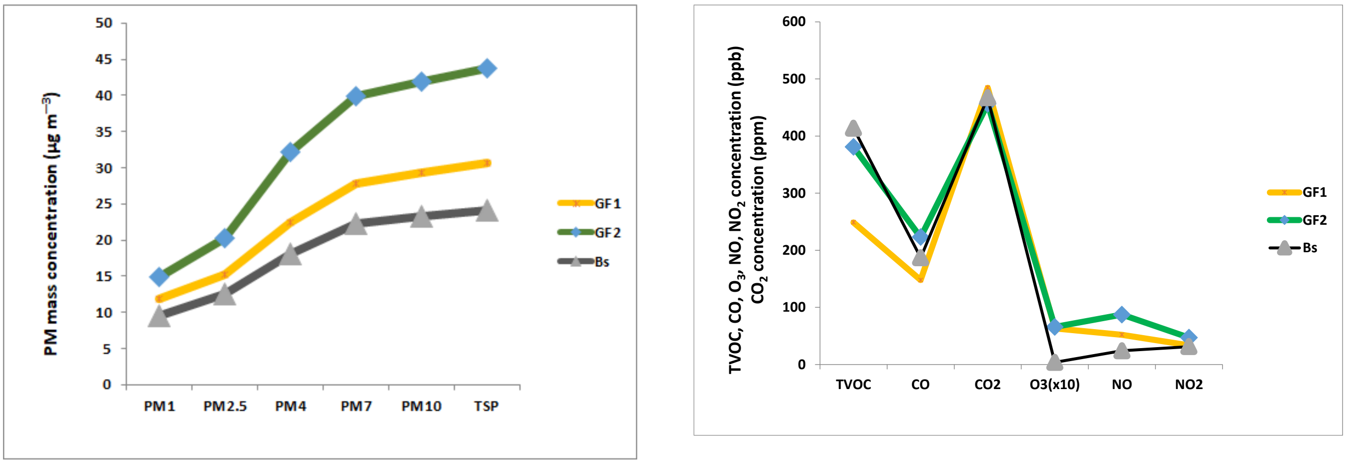
(**a**)



(**b**)

Figure 6. Time series of indoor atmospheric pollutant concentrations (9, 10 and 11 January 2023). (**a**) $PM_{2.5}$ and PM_{10} mass concentrations; (**b**) TVOC and CO_2 concentrations.

The GF2 had the highest PM concentrations. In the present study, pollutants from outside sources, like CO, O_3, and NO_x, were more increased in the GF2 than in the other sites, owing to the opening of the museum's main door.



(**a**) (**b**)

Figure 7. Comparison of mean indoor air pollutant concentrations measured in different locations (2024).). (**a**) PM mass concentrations; (**b**) Gaseous air pollutant concentrations.

4. Discussion

The Archaeological Museum of Kavala is a relatively new, naturally ventilated building situated between the Gulf of Kavala on one side and a busy road on the other. The prevailing wind direction from the South, coming from the sea, assists in limiting the infiltration of elevated air pollutant concentrations from nearby traffic and the parking lot. Indoor atmospheric pollutant concentrations in naturally ventilated museums (with variable air exchange rate) are affected not only by indoor sources, but also depend on the outdoor atmospheric pollution, and thus on the building location and the relevant outdoor activities. Hence, I/O concentration ratios are highly variable. The most studied pollutants in museums are O_3, NO_2 and PM. O_3 and NO_2 pose an established risk to painting materials, textiles, and biological colorants in museums. PM can endanger any material, ranging from simple soiling to chemical attack. For example, in the São Paulo History Museum (Brazil; naturally ventilated), indoor O_3 concentrations ranged between 10 and 14 ppb (I/O was 0.72 to 0.99), while indoor NO_2 was 14.5 ppb with an I/O ratio of 0.57. The indoor fine PM concentration was 5.8 μgm^{-3}, whereas the outdoor concentration was 6.8 μgm^{-3} (I/O = 0.85). In the mechanically ventilated São Paulo State Art Museum (Brazil), indoor O_3 concentrations were 3 ppb (I/O = 0.22) and indoor NO_2 concentrations were 12 ppb (I/O =0.46), resulting in much reduced atmospheric pollutant concentrations. The indoor fine PM concentration was 5.1 μgm^{-3}, while the outdoor concentration was 8.4 μgm^{-3} (I/O = 0.61) [42,43]. In another recent study, in five site museums (two naturally ventilated) of Yangtze River civilization, in Yangtze River area, China, in wintertime, indoor O_3 concentrations were between 2 and 9 ppb (I/O ranged between 0.26 and 1.5), NO_2 concentrations were between 1 and 9 ppb (I/O ranged between 0.16 and 0.75), and fine PM mass concentrations were between 33.9 and 79.6 μgm^{-3} (I/O ranged between 0.89 and 1.9). In the summertime, indoor concentrations ranged between 1 and 19 ppb (I/O ranged between 0.14 and 0.95); NO_2 concentrations 1–11 ppb (I/O ranged between 0.03 and 0.92); fine PM mass concentrations were between 52.8 and 113.0 μgm^{-3} (I/O ranged between 0.61 and 0.94) [44]. Indoor PM emissions, dynamics, and chemistry have a substantial impact on indoor PM mass concentrations, size distributions, and chemical composition. The penetration factor, deposition velocity, resuspension rate, gas-to-particle conversion, condensation, evaporation, and coagulation all have a different effect on PM concentrations in each size bin [45–50]. Indoors, PM_1 and $PM_{2.5}$ concentrations were approximately twice as high as outdoor levels. Visitors' emissions probably contribute to the museum's highest PM_1 I/O ratio and elevated $PM_{2.5}$ I/O ratio. People release PM in these size bins through their clothing, skin, breathing, and speaking, including bioaerosol [45,51–54]. PM_1 corresponds mainly to the accumulation mode (aerodynamic diameter between 0.1 μm to 2.5 μm), meaning that these particles tend to persist in the atmosphere. Airborne particles in this size range are too large to undergo rapid Brownian motion, yet too small to settle out quickly. Additionally, they do not readily agglomerate to form larger particles. In a review of fine PM in indoor cultural heritage buildings, Grau-Bové and Strlič (2013) discovered that the I/O ratio was higher for particles ranging from 0.1 to 1 μm [15]. Simultaneous indoor and outdoor PM concentration measurements were performed in two medieval churches in Cyprus. During guided tours at St. John Cathedral in Nicosia with tourists (20–30 each tour), the greatest I/O mass concentration ratio of 2.51 was found in the 0.5–1.0 μm size bin, without any services or candle burning. The respective I/O ratio for St. Paraskevi in Yeroskipou, Paphos, was 1.88. It is important to note that these measurements were obtained with a different instrumentation, but the most significant advantage was the simultaneous indoor and outdoor measurements [45].

To preserve artefacts effectively, the annual average $PM_{2.5}$ concentration should be kept below 10 μg m^{-3} [55]. However, $PM_{2.5}$ levels exceeded this recommendation, which is similar to the findings from the Archaeological Museum of Abdera, Greece, as well as with other museums [7]. Particulate matter consists of various organic, inorganic, and biological compounds, some of which can chemically damage artefact surfaces or, at a minimum, detract from the aesthetic value of the displayed items. The issue of PM deposition on artworks is a longstanding global challenge [26,56]. Removing these particles from surfaces is both difficult and costly [57].

Airborne PM is the worst enemy of aged marble and clay antiquities. The smaller the particles, the more difficult they are to remove. To combat particle soiling, air cleaning technologies, such as electrostatic precipitators or high efficiency filters in the HVAC system, could be installed. Filters with a MERV (minimum efficiency reporting value) greater than 8 are regarded sufficient for capturing tiny particles [46,58–60].

In the museum under study, indoor concentrations of ozone (O_3) and nitrogen dioxide (NO_2) also exceeded recommended guidelines, i.e., the O_3 annual average value was above 5 ppb and NO_2 above 10 ppb [6,55,61,62].

When the museum was closed, the low air change rate (ACH) limited the dilution of atmospheric pollutants, allowing slow-rate chemical reactions to take place [63]. As a result, total volatile organic compound (TVOC) concentrations from indoor and outdoor sources were higher during closed hours, likely due to the low ACH, emissions from building materials, and ongoing chemical reactions. For example, certain VOCs from cleaning sprays can decompose, producing CO among other by-products [64]. This may explain instances where indoor CO levels increased independently of outdoor concentrations, a trend observed in both the Kavala and Abdera archaeological museums.

The microclimatic conditions were not stable as recommended and showed significant daily and seasonal variations. In summer, air conditioning was active only during opening hours, and relative humidity (RH) was higher when the museum was closed, with daily variations reaching up to 15%. Meanwhile, air temperature (AT) increased by 2 °C during closed hours. A similar pattern was observed in the Archaeological Museum of Abdera during hot, sunny days. In winter, AT rose by 2 °C when the museum opened due to the activation of the central heating system. RH varied by up to 8% daily, and on some days, RH was higher during opening hours due to the intrusion of humid air from the nearby sea. Uncontrolled AT and RH, especially rapid variations in these factors, as well as unmanaged lighting, are capable of damaging works of art. Several standards are created to form the advantageous environment for both visitors and works of art [65,66]. Note that there does not exist a range of microclimatic conditions suited for all types of exhibited materials. It has become difficult for technical staff to meet stringent environmental standards that attempt to address a variety of competing criteria, plus to achieve energy saving [40,67–70].

A two-month comparison in 2024 between three locations in the museum supported that the GF2, near the entrance of the museum, was the most polluted location, affected by the infiltration of untreated outdoor air as well as from the use of disinfection liquids and by the emissions of accumulated people.

The EUI during the decade from 2013 to 2023 fluctuated between 64 kWh m^{-2} and 106 kWh m^{-2} which is near the lower end of the levels documented in Greek museums (minimum 65.8 kWh m^{-2} and maximum 632.5 kWh m^{-2} [28]) and below the levels reported for other museums [29,30]. In 2023, total energy consumption was 86,123 kWh, primarily from electricity, with the largest portion used for cooling, followed by heating and lighting. The energy consumption was correlated with the outdoor air temperature and the number of people present indoors. The highest EUI was recorded during the hottest days with the largest number of visitors, due to air conditioning operation. Each person visiting the museum consumed on average 7.7 kWh of energy. In an extensive study of energy consumption in 28 museums in the province of Barcelona (Catalonia, Spain), it was found that the average EUI per person (per visit) in history museums, like the museum under study, was 15.8 kWh [71]. An earlier study at museums, which aligned with the research of Farreny et al. [71], reported values ranging from 0.35 to 28.89 kWh per visit [72].

Between 2013 and 2023, a slight decrease in energy of consumption of 2.7 kWh per year, was observed. Light bulbs were gradually replaced with LED bulbs, climate change increased the outdoor temperature, thus less heating was needed, and the pandemic possibly decreased the number visitors for more than two years. All these factors could contribute to this decrease over the last decade. However, it is uncertain as to whether this trend will continue. Recent increases in local tourists, coupled with rising outdoor temperatures, have led to heightened cooling demands [32]. Unfortunately, there are no data on indoor air quality during this decade so that one can examine its fluctuations.

A study is now being developed to enhance the museum's energy efficiency through improved insulation and the integration of photovoltaic panels. Nonetheless, the assessment of the effects of these modifications on indoor air quality remains uncertain [38].

5. Conclusions

This study investigated concerns about the management the Archaeological Museum of Kavala, Greece, regarding energy consumption and indoor environmental quality. Operating naturally ventilated museums requires substantial energy, which poses challenges both environmentally and economically. It is essential to implement measures that preserve stable microclimatic conditions conducive to the housed artworks and mitigate atmospheric pollutants concentrations, particularly suspended particulates. Simultaneously, these measures should neither necessitate excessive energy use nor impose intolerable financial burdens.

The management of a museum and the preventive conservation require data and tools to make the best decisions on dealing with factors that threat works of art. These factors are the microclimatic conditions, light, atmospheric pollutants, including dust and biological aerosol, vibration, visitors and several organized events. The continuous monitoring and the appropriate analysis of the recorded environmental conditions is fundamental to achieve the best conditions for the works of art, the comfort of the visitors and energy savings. The one year of monitoring in the museum has revealed that as the building was operating, it was unprotected from external and internal threats. The implementation of an HVAC system with sufficient filtration will improve indoor environmental quality. This installation is costly. Also, the proper maintenance and operation of the facility will result in increased energy usage. The utilization of renewable energy sources will reduce operational costs. To maintain a balance, it is essential to monitor energy use and interior environmental factors continuously by installing and operating the appropriate instrumentation and sensors [38]. Considerations regarding the accessibility and opening times of the museum can hence be adjusted for the benefit of the protection of the exhibited artefacts.

Author Contributions: Conceptualization, G.L.; Data curation, G.L. and G.D.; Investigation, G.D.; Methodology, G.L. and E.K.; Supervision, S.R.; Writing—original draft, G.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are unavailable due to confidentiality conflicts.

Acknowledgments: We would like to thank the academic editor of the journal and the two anonymous reviewers for their valuable comments and corrections.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. González-Martín, J.; Kraakman, N.J.R.; Pérez, C.; Lebrero, R.; Muñoz, R. A state–of–the-art review on indoor air pollution and strategies for indoor air pollution control. *Chemosphere* **2021**, *262*, 128376. [CrossRef] [PubMed]
2. Kumar, P.; Singh, A.B.; Arora, T.; Singh, S.; Singh, R. Critical review on emerging health effects associated with the indoor air quality and its sustainable management. *Sci. Total Environ.* **2023**, *872*, 162163. [CrossRef] [PubMed]
3. Centorrino, P.; Corbetta, A.; Cristiani, E.; Onofri, E. Managing crowded museums: Visitors flow measurement, analysis, modeling, and optimization. *J. Comput. Sci.* **2021**, *53*, 101357. [CrossRef]
4. Goulding, C. The museum environment and the visitor experience. *Eur. J. Mark.* **2000**, *34*, 261–278. [CrossRef]
5. Canosa, E.; Norrehed, S. *Strategies for Pollutant Monitoring in Museum Environments*; Riksantikvarieämbetet: Stockholm, Sweden, 2019.
6. Baer, N.S.; Banks, P.N. Indoor air pollution: Effects on cultural and historic materials. *Mus. Manag. Curatorship* **1985**, *4*, 9–20. [CrossRef]
7. Loupa, G.; Dabanlis, G.; Resta, G.; Kostenidou, E.; Rapsomanikis, S. Indoor Microclimatic Conditions and Air Pollutant Concentrations in the Archaeological Museum of Abdera, Greece. *Aerobiology* **2024**, *2*, 29–43. [CrossRef]
8. Kraševec, I.; Markelj, J.; Elnaggar, A.; Cigić, I.K. Indoor air pollutants and their seasonal monitoring in European museums. *Herit. Sci.* **2024**, *12*, 50. [CrossRef]
9. Vergelli, L.; Frasca, F.; Bertolin, C.; Favero, G.; Siani, A.M. A review on inorganic gaseous pollutants in conservation spaces: Monitoring instrumentation and indoor concentrations. *Environ. Monit. Assess.* **2023**, *196*, 85. [CrossRef]
10. Adams, S.J.; Ford, D. Monitoring of deposited particles in cultural properties: The influence of visitors. *Atmos. Environ.* **2001**, *35*, 4073–4080. [CrossRef]
11. Pagonis, D.; Price, D.J.; Algrim, L.B.; Day, D.A.; Handschy, A.V.; Stark, H.; Miller, S.L.; de Gouw, J.; Jimenez, J.L.; Ziemann, P.J. Time-Resolved Measurements of Indoor Chemical Emissions, Deposition, and Reactions in a University Art Museum. *Environ. Sci. Technol.* **2019**, *53*, 4794–4802. [CrossRef]
12. Schieweck, A.; Lohrengel, B.; Siwinski, N.; Genning, C.; Salthammer, T. Organic and inorganic pollutants in storage rooms of the Lower Saxony State Museum Hanover, Germany. *Atmos. Environ.* **2005**, *39*, 6098–6108. [CrossRef]
13. Alvarez-Martin, A.; McHugh, K.; Martin, C.; Kavich, G.; Kaczkowski, R. Understanding air-tight case environments at the National Museum of the American Indian (Smithsonian Institution) by SPME-GC-MS analysis. *J. Cult. Herit.* **2020**, *44*, 38–46. [CrossRef]
14. Saridaki, A.; Glytsos, T.; Raisi, L.; Katsivela, E.; Tsiamis, G.; Kalogerakis, N.; Lazaridis, M. Airborne particles, bacterial and fungal communities insights of two museum exhibition halls with diverse air quality characteristics. *Aerobiologia* **2023**, *39*, 69–86. [CrossRef]
15. Grau-Bové, J.; Strlič, M. Fine particulate matter in indoor cultural heritage: A literature review. *Herit. Sci.* **2013**, *1*, 8. [CrossRef]

16. Hu, T.; Lee, S.; Cao, J.; Chow, J.C.; Watson, J.G.; Ho, K.; Ho, W.; Rong, B.; An, Z. Characterization of winter airborne particles at Emperor Qin's Terra-cotta Museum, China. *Sci. Total Environ.* **2009**, *407*, 5319–5327. [CrossRef]
17. Mouratidou, T.; Samara, C. PM2.5 and associated ionic component concentrations inside the archaeological museum of Thessaloniki, N. Greece. *Atmos. Environ.* **2004**, *38*, 4593–4598. [CrossRef]
18. Lloyd, H.; Lithgow, K.; Brimblecombe, P.; Yoon, Y.H.; Frame, K.; Knight, B. The effects of visitor activity on dust in historic collections. *Conserv.* **2002**, *26*, 72–84. [CrossRef]
19. Proietti, A.; Panella, M.; Leccese, F.; Svezia, E. Dust detection and analysis in museum environment based on pattern recognition. *Measurement* **2015**, *66*, 62–72. [CrossRef]
20. Schmidt, A.L.; Bronée, P.; Kemp, K.; Fenger, J. Airborne dust in a museum environment. In *IAP Copenhagen 2001, Copenhagen, Denmark, 8–9 November 2001*; The National Museum of Denmark: Copenhagen, Denmark, 2001; Volume 71, Available online: http://www.iaq.dk/iap/iap2001/iap2001.pdf#page=73 (accessed on 6 December 2024).
21. Shah, B.; Hunter, S.; Adams, S. Dust to Dust. Access to Access. Available online: http://www.vam.ac.uk/content/journals/conservation-journal/spring-2011-issue-59/dust-to-dust.-access-to-access./?srsltid=AfmBOooDN6Adto_u4dUQ1xeIZot13dw0ZFqd1WTc5-TbKId0QPZ60ZeY (accessed on 6 December 2024).
22. Brizzi, S.; Łydżba-Kopczyńska, B.; Riminesi, C.; Salvadori, B.; Sawoszczuk, T.; Strojecki, M.; Syta, O.; Thickett, D.; Torres-Elguera, J.; Towarek, A.; et al. Surveying analytical techniques for a comprehensive analysis of airborne particulate samples in museum environments. *TrAC Trends Anal. Chem.* **2024**, *176*, 117766. [CrossRef]
23. Saraiva, N.B.; Pereira, L.D.; Gaspar, A.R.; Costa, J.J. Measurement of particulate matter in a heritage building using optical counters: Long-term and spatial analyses. *Sci. Total Environ.* **2023**, *862*, 160747. [CrossRef]
24. Ilieș, A.; Caciora, T.; Marcu, F.; Berdenov, Z.; Ilieș, G.; Safarov, B.; Hodor, N.; Grama, V.; Shomali, M.A.A.; Ilies, D.C.; et al. Analysis of the Interior Microclimate in Art Nouveau Heritage Buildings for the Protection of Exhibits and Human Health. *Int. J. Environ. Res. Public Health* **2022**, *19*, 16599. [CrossRef] [PubMed]
25. Camuffo, D. *Microclimate for Cultural Heritage: Measurement, Risk Assessment, Conservation, Restoration, and Maintenance of Indoor and Outdoor Monuments*; Elsevier: Amsterdam, The Netherlands, 2019.
26. Dabanlis, G.; Loupa, G.; Tsalidis, G.A.; Kostenidou, E.; Rapsomanikis, S. The Interplay between Air Quality and Energy Efficiency in Museums, a Review. *Appl. Sci.* **2023**, *13*, 5535. [CrossRef]
27. Fouseki, K.; Cassar, M. Energy Efficiency in Heritage Buildings—Future Challenges and Research Needs. *Hist. Environ. Policy Pract.* **2014**, *5*, 95–100. [CrossRef]
28. Droutsa, K.G.; Balaras, C.A.; Lykoudis, S.; Kontoyiannidis, S.; Dascalaki, E.G.; Argiriou, A.A. Baselines for Energy Use and Carbon Emission Intensities in Hellenic Nonresidential Buildings. *Energies* **2020**, *13*, 2100. [CrossRef]
29. Huang, Z.; Gou, Z. Electricity consumption variation of public buildings in response to COVID-19 restriction and easing policies: A case study in Scotland, UK. *Energy Build.* **2022**, *267*, 112149. [CrossRef]
30. Kramer, R.P.; Maas, M.P.E.; Martens, M.H.J.; van Schijndel, A.W.M.; Schellen, H.L. Energy conservation in museums using different setpoint strategies: A case study for a state-of-the-art museum using building simulations. *Appl. Energy* **2015**, *158*, 446–458. [CrossRef]
31. Mueller, H.F.O. Energy efficient museum buildings. *Renew. Energy* **2013**, *49*, 232–236. [CrossRef]
32. Cadelano, G.; Cicolin, F.; Emmi, G.; Mezzasalma, G.; Poletto, D.; Galgaro, A.; Bernardi, A. Improving the Energy Efficiency, Limiting Costs and Reducing CO_2 Emissions of a Museum Using Geothermal Energy and Energy Management Policies. *Energies* **2019**, *12*, 3192. [CrossRef]
33. Brophy, S.S.; Wylie, E. *The Green Museum: A Primer on Environmental Practice*; Altamira Press: Lanham, MD, USA, 2013.
34. Calderón-Vargas, F.; Asmat-Campos, D.; Chávez-Arroyo, P. Sustainable tourism policies in Peru and their link with renewable energy: Analysis in the main museums of the Moche route. *Heliyon* **2021**, *7*, e08188. [CrossRef]
35. Eti, S.; Yüksel, S.; Dinçer, H.; Kalkavan, H.; Hacioglu, U.; Mikhaylov, A.; Danish, M.S.S.; Pinter, G. Assessment of technical and financial challenges for renewable energy project alternatives. *Clean. Eng. Technol.* **2024**, *18*, 100719. [CrossRef]
36. Vourdoubas, J. Possibilities of Creating Net Zero Carbon Emissions Cultural Buildings: A Case Study of the Museum at Eleutherna, Crete, Greece. *Am. Sci. Res. J. Eng. Technol. Sci. (ASRJETS)* **2019**, *56*, 207–217.
37. Annelies, C.; Vincent, L.B.; Geert, B.; Melissa, K.; Rebecca, N.; Bhavesh, S.; Wickens, A.J. *Tools for the Analysis of Collection Environments*; Getty Museum: Los Angeles, CA, USA, 2022.
38. Richardson, E.; McCauley Krish, K.; Cummings, M.; Schooping, M.; Hopke, P.; Tétreault, J. Interrogating Pollutants in Collecting Institutions During the Implementation of HVAC Energy-Saving Strategies: Lessons Learned and Practical Implications for Optimizing Sustainable Environmental Control. *Stud. Conserv.* **2024**, *69*, 305–313. [CrossRef]
39. Sciurpi, F.; Carletti, C.; Cellai, G.; Piselli, C. Indoor Air Quality in the Uffizi Gallery of Florence: Sampling, Assessment and Improvement Strategies. *Appl. Sci.* **2022**, *12*, 8642. [CrossRef]
40. Elkadi, H.; Al-Maiyah, S.; Fielder, K.; Kenawy, I.; Martinson, D.B. The regulations and reality of indoor environmental standards for objects and visitors in museums. *Renew. Sustain. Energy Rev.* **2021**, *152*, 111653. [CrossRef]

41. Gratton, G.; Padhra, A.; Rapsomanikis, S.; Williams, P.D. The impacts of climate change on Greek airports. *Clim. Change* **2020**, *160*, 219–231. [CrossRef]
42. Cavicchioli, A.; Souza, R.O.C.d.; Reis, G.R.; Fornaro, A. Indoor Ozone and Nitrogen Dioxide Concentration in Two Museums of the São Paulo Megacity—Brazil. *E-Preserv. Sci.* **2013**, *10*, 114–122.
43. Cavicchioli, A.; Morrone, E.P.; Fornaro, A. Particulate matter in the indoor environment of museums in the megacity of São Paulo. *Química Nova* **2014**, *37*, 1427–1435. [CrossRef]
44. Hu, T.; Jia, W.; Cao, J.; Huang, R.; Li, H.; Liu, S.; Ma, T.; Zhu, Y. Indoor air quality at five site museums of Yangtze River civilization. *Atmos. Environ.* **2015**, *123*, 449–454. [CrossRef]
45. Loupa, G.; Karageorgos, E.; Rapsomanikis, S. Potential effects of particulate matter from combustion during services on human health and on works of art in medieval churches in Cyprus. *Environ. Pollut.* **2010**, *158*, 2946–2953. [CrossRef]
46. Li, J.; Fan, G.; Ou, Y.; Deng, Q. Characteristics and control strategies of indoor particles: An updated review. *Energy Build.* **2023**, *294*, 113232. [CrossRef]
47. Stratigou, E.; Dusanter, S.; Brito, J.; Riffault, V. Investigation of PM10, PM2.5, PM1 in an unoccupied airflow-controlled room: How reliable to neglect resuspension and assume unreactive particles? *Build. Environ.* **2020**, *186*, 107357. [CrossRef]
48. Chatoutsidou, S.E.; Lazaridis, M. Assessment of the impact of particulate dry deposition on soiling of indoor cultural heritage objects found in churches and museums/libraries. *J. Cult. Herit.* **2019**, *39*, 221–228. [CrossRef]
49. Lv, L.; Zhao, B. Shape-dependent aerosol dynamics in indoor environments: Penetration, deposition, and dispersion. *J. Hazard. Mater.* **2024**, *480*, 136305. [CrossRef]
50. Lv, Y.; Wang, H.; Wei, S.; Wu, T.; Liu, T.; Chen, B. The experimental study on indoor and outdoor penetration coefficient of atmospheric fine particles. *Build. Environ.* **2018**, *132*, 70–82. [CrossRef]
51. Asadi, S.; Wexler, A.S.; Cappa, C.D.; Barreda, S.; Bouvier, N.M.; Ristenpart, W.D. Aerosol emission and superemission during human speech increase with voice loudness. *Sci. Rep.* **2019**, *9*, 2348. [CrossRef]
52. You, S.; Wan, M.P. Experimental investigation and modelling of human-walking-induced particle resuspension. *Indoor Built Environ.* **2014**, *24*, 564–576. [CrossRef]
53. Fu, N.; Kim, M.K.; Huang, L.; Liu, J.; Chen, B.; Sharples, S. Experimental and numerical analysis of indoor air quality affected by outdoor air particulate levels (PM1.0, PM2.5 and PM10), room infiltration rate, and occupants' behaviour. *Sci. Total Environ.* **2022**, *851*, 158026. [CrossRef]
54. Han, Q.; Huang, H.; Li, C.; Tang, H. An experimental study on the characteristics of human respiratory aerosol emission in different activity intensity states. *Build. Environ.* **2025**, *267*, 112314. [CrossRef]
55. Tétreault, J. *Airborne Pollutants in Museums, Galleries and Archives: Risk Assessment, Control Strategies and Preservation Management*; Canadian Conservation Institute: Ottawa, ON, USA, 2003.
56. Loupa, G.; Rapsomanikis, S. Air pollutant emission rates and concentrations in medieval churches. *J. Atmos. Chem.* **2008**, *60*, 169–187. [CrossRef]
57. Lloyd, H.; Brimblecombe, P.; Lithgow, K. Economics of Dust. *Stud. Conserv.* **2007**, *52*, 135–146. [CrossRef]
58. Tétreault, J. *Control of Pollutants in Museums and Archives–Technical Bulletin 37*; Government of Canada, Canadian Conservation Institute: Ottawa, ON, Canada, 2021.
59. Lazaridis, M.; Katsivela, E.; Kopanakis, I.; Raisi, L.; Mihalopoulos, N.; Panagiaris, G. Characterization of airborne particulate matter and microbes inside cultural heritage collections. *J. Cult. Herit.* **2018**, *30*, 136–146. [CrossRef]
60. Afshari, A.; Ekberg, L.; Forejt, L.; Mo, J.; Rahimi, S.; Siegel, J.; Chen, W.; Wargocki, P.; Zurami, S.; Zhang, J. Electrostatic Precipitators as an Indoor Air Cleaner—A Literature Review. *Sustainability* **2020**, *12*, 8774. [CrossRef]
61. Grzywacz, C.M. *Monitoring for Gaseous Pollutants in Museum Environments*; Getty Publications: Los Angeles, CA, USA, 2006.
62. Fermo, P.; Comite, V. Indoor Air Quality in Heritage and Museum Buildings. In *Handbook of Cultural Heritage Analysis*; D'Amico, S., Venuti, V., Eds.; Springer International Publishing: Cham, Switzerland, 2022; pp. 1003–1031.
63. Papadakis, N.; Katsaprakakis, D.A. A Review of Energy Efficiency Interventions in Public Buildings. *Energies* **2023**, *16*, 6329. [CrossRef]
64. Jamiu, A.; Ayodele, A. Carbon monoxide formation from total volatile organic compounds from the use of household spray products. *J. Air Pollut. Health* **2023**, *8*, 361–380. [CrossRef]
65. Ashrae. *Thermal Environmental Conditions for Human Occupancy*; American Society of Heating, Refrigerating and Air Conditioning Engineers; Ashrae: Atlanta, GA, USA, 2020.
66. *16893:2018, C.B.E.*; Conservation of Cultural Heritage—Specifications for Location, Construction and Modification of Buildings or Rooms Intended for the Storage or Use of Heritage Collections. BSI Standards Limited: London, UK, 2018.
67. Gallego-Maya, I.; Rubio-Bellido, C. Use of International Adaptive Thermal Comfort Models as a Strategy for Adjusting the Museum Environments of the Mudejar Pavilion, Seville. *Energies* **2024**, *17*, 5480. [CrossRef]

68. Frasca, F.; Verticchio, E.; Bosco, E.; Kuka, E.; Lee, D.S.-H.; Andersen, C.K.; Bertolin, C.; Siani, A.M. Assessing microclimate thresholds for heritage preventive conservation to achieve sustainable and energy efficiency goals in a changing climate. *Sci. Rep.* **2024**, *14*, 18707. [CrossRef]
69. Schito, E.; Conti, P.; Testi, D. Multi-objective optimization of microclimate in museums for concurrent reduction of energy needs, visitors' discomfort and artwork preservation risks. *Appl. Energy* **2018**, *224*, 147–159. [CrossRef]
70. Mostafa Refat Ismail, M.; Aly Nessim, A.; Fathy, F. Factors affecting museum buildings and heritage spaces in terms of energy optimization and comfort. *Ain Shams Eng. J.* **2024**, *15*, 103069. [CrossRef]
71. Farreny, R.; Oliver-Solà, J.; Escuder-Bonilla, S.; Roca-Martí, M.; Sevigné, E.; Gabarrell, X.; Rieradevall, J. The metabolism of cultural services. Energy and water flows in museums. *Energy Build.* **2012**, *47*, 98–106. [CrossRef]
72. Oliver-Solà, J.; Núñez, M.; Gabarrell, X.; Boada, M.; Rieradevall, J. Service sector metabolism: Accounting for energy impacts of the Montjuïc urban park in Barcelona. *J. Ind. Ecol.* **2007**, *11*, 83–98. [CrossRef]