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Review

The Interplay between Air Quality and Energy Efficiency in Museums, a Review

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Abstract: Energy efficiency in museums and buildings that house works of art or cultural heritage appears to be a difficult achievement if indoor air quality has to be kept at appropriate levels for artefacts' long-term sustainability. There is a gap in our scientific literature on the relationship between indoor air quality and energy efficiency, meaning that there are no numerical data that examine both of them simultaneously, although this is a theme that is broadly discussed by museum managers, curators, and scientists. It is certain that the two parameters, indoor air quality (IAQ) and energy efficiency (EEF) are conflicting and difficult to reconcile. Furthermore, IAQ is not only the determination of temperature, relative humidity, and CO_2, as is usually presented. Using green or renewable energy does not make a building "energy efficient". Hence, in the manuscript we review the literature on IAQ of museums and exhibition buildings, in conjunction with the consideration of their EEF. Hopefully, reviewing the literature for this problem may lead to carefully designed monitoring experiments. The selection, application, and testing of appropriate technological measures can lead to a new balance between the two conflicting parameters. Not only must solutions be found, but these solutions are necessary in the mitigation battle against climate change.

Keywords: indoor air quality; museum; historical buildings; works of art; energy efficiency; cultural heritage conservation

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1. Introduction

Climate change is a reality in today's world [1]. It is strongly dependent on the energy production by fossil fuels and the energy consumption by diverse human activities, both of which contribute to CO_2 and other greenhouse gases emissions. Climate change and occasionally erratic power supply conditions sped up the political decisions to reduce energy demand and to produce renewable energy, i.e., energy derived from natural sources that are replenished at a faster rate than they are consumed. Furthermore, energy efficiency (EEF) is strongly pursued in an effort to use less energy to achieve the same task or product.

The built environment is critical to achieving energy efficiency and other environmental objectives. Homes and buildings that are energy efficient use less energy to achieve comfortable living and working conditions. The Directive 2012/27/EU and the 2018 amending Directive on Energy Efficiency in the EU seek to save energy while also promoting good indoor air quality and comfort. However, they do not specify how to achieve both the goals of energy savings and satisfactory indoor environmental quality. The legislation governing indoor air quality (IAQ), in particular, is fragmented.

The amount of particulate matter (PM), airborne inorganic, organic, and biological particles, such as SARS-CoV-2, fungi, bacteria, and gaseous pollutants, present in the indoor air is defined as indoor air quality (IAQ). Indoor environmental quality (IEQ) includes not only air pollution within a building, but also lighting, thermal conditions, ergonomics, and other conditions that may be harmful to occupants. In other words, all the conditions within the building that allow it to be used for its intended purpose. Aside from human health and comfort, the IEQ has an impact on the materials used to create works of art. Since the 1970s, numerous studies have been conducted to investigate the deterioration of valuable objects housed in museums, churches, mosques, temples, and other historical buildings, as well as private collections [2–19].

Climate change influences outdoor air pollution and causes severe and frequent weather extremes [20]. This changes the indoor environment, affects IEQ and interferes with energy consumption [21,22], hence undermining climate change mitigation efforts [23].

The COVID-19 pandemic underscored the significance of maintaining proper IAQ control. Apart from the well-established fact that IAQ affects productivity and wellbeing, this control or lack of it has emerged as a key factor in the transmission of infectious diseases. Numerous studies support the notion that in order to achieve good IAQ, particularly in public buildings such as schools, hospitals, and museums, more energy expenditures are required for air filtration, ventilation, etc. EEF is thought to be inversely proportional to good IAQ [24,25]. In crowded buildings, balancing energy efficiency with good indoor air quality is even more difficult.

Museums preserve the cultural heritage of our planet and promote culture and knowledge. They are popular tourist destinations all over the world. According to UNESCO, the number of museums worldwide has increased from 22,000 in 1975 to 95,000 today [26]. These structures necessitate a large amount of energy for heating, cooling, and lighting, as well as good air quality. IEQ management is critical for the preservation of artworks as well as for the health of both staff and visitors. The world's cultural heritage is facing new challenges as a result of climate change and the need to conserve energy [27].

People in charge of the world's collections understand that displaying or storing them in appropriate environmental conditions prevents deterioration more effectively than restoring them. Air temperature and relative humidity have historically been the primary conservation concerns in buildings that house works of art, whether historical or modern. The range of these two parameters for artwork conservation frequently differs from the accepted range for visitor comfort; thus, much research is devoted to reconciling the two. This aspect will not be discussed further in this study because the emphasis is on the atmospheric pollutants that can endanger works of art in relation to the EEF.

Along with microclimatic conditions, the threat of air pollutants degrading the aesthetic value of works of art is an age-old concern [2,4]. Some examples of the deterioration of works of art associated with atmospheric pollution are, for objects made of marble, carbonization corrosion, soiling, blackening and biological colonization; for works of art made of metal, they include surface corrosion, the development of a stable patina, etc. [28–30]. This degradation of works of art has been well established through extensive experimentation. Furthermore, it is well known that buildings containing works of art have indoor air pollutant concentrations that exceed the threshold values for proper conservation [31–33].

The critical need to reduce our use of energy in all aspects of our lives and to meet our needs with renewables has emerged as a major issue in museum operations. The EEF will reduce operating costs and minimize the museum's environmental impact in a near-zero energy consumption museum or a "green" museum. These buildings, whether modern museums or other historical structures housing works of art, can set a good example of energy efficiency with acceptable IAQ and, in general, can reduce their environmental impact. Museums have the potential to play a larger role in reducing the human environmental footprint and combating climate change [34–36].

We have summarized the most recent understanding of the relationship between IAQ and EEF in this review. In addition, we discuss strategies for achieving appropriate IAQ in museums for cultural heritage conservation and human well-being without sacrificing energy savings or the quality of the visitors' experience.

Indoor air quality is a crucial parameter for preserving the high value and cultural significance of objects housed in museums or historical buildings, over the centuries. Gaseous pollutants, particulate matter, and microorganisms, if present in a museum, can create sometimes irreversible damage to works of art. For example, soiling, corrosion, color fading, cracks, and mold. In times of climate change, the world of museums encounters a new challenge: energy saving.

2. Materials and Methods

The publications that are included in the present work were written in English and were retrieved from several databases, such as Google, Scopus, Google Scholar and Web of Science. Examples of the key words used were: climate change; indoor air quality; electricity consumption; energy efficiency; greening; indoor environmental quality; retrofit; refurbish; thermal conditions; decarbonization; sustainability; controlling IAQ; energy saving. These key words were used in combination with the word "museum" or "cultural heritage" or "works of art" or "historical building".

This review is organized as follows: (a) a presentation of a basic IAQ model that describes the parameters that make up the IAQ and how the IAQ is related to the building's energy consumption; (b) a description of the threat to the conservation of the housed cultural heritage, a summary of proposed indoor air quality guidelines for some key atmospheric pollutants, and a summary of their measured atmospheric concentrations in museums; (c) a summary of the studies that reported indoor atmospheric pollutant monitoring with energy consumption/saving in museums; (d) interventions to improve IAQ in museums, in conjunction with EEF measures.

The current review highlights gaps in our understanding of the relationship between IAQ and EEF, i.e., what knowledge is well established and what requires further scientific investigation.

3. Results and Discussion

3.1. Indoor Air Quality and Energy Consumption Fundamentals

IAQ is affected by the concentrations of air pollutants, gases, or particles in the atmosphere. Indoor air pollutants can be transported from outside or emitted from inside. The indoor air pollutant concentrations and their diurnal variation will be shaped by building characteristics such as air exchange rate, material of the indoor surfaces, and occupant activity. Depending on the indoor activities, atmospheric pollutants emitted indoors may be the most serious threat to poor indoor air quality. To demonstrate this, a simple indoor model, shown in Figure 1, is discussed below.

In each room or in an entire building, where air can be assumed to be well mixed, the rate of change of an air pollutant concentration can be described by a mass balance equation, as follows [37,38]:

$$V\frac{dC_{in}}{dt} = PfC_{out} - fC_{in} + S - R \tag{1}$$

where C_{in} and C_{out} are the respective indoor and outdoor atmospheric pollutant concentrations (μg m^{-3}); f is the air flow rate (m^3 h^{-1}); the room air exchange rate (AER) is equal to f/V (h^{-1}); and S represents the emission rate of the air pollutant from the indoor sources (μg h^{-1}). The air pollutant loss rate R can be considered to be equal to $u_d AC_{in}$, where $k = u_d \frac{A}{V}$ (h^{-1}) is the average deposition rate of each pollutant on indoor surfaces. V is the volume of the room (m^3), A is the total interior surface area (m^2), and u_d is the average deposition velocity of each air pollutant (m h^{-1}). The parameter P only refers to PM and is defined as the particle penetration coefficient (dimensionless) [39]. In the case of gaseous pollutants, P = 1.

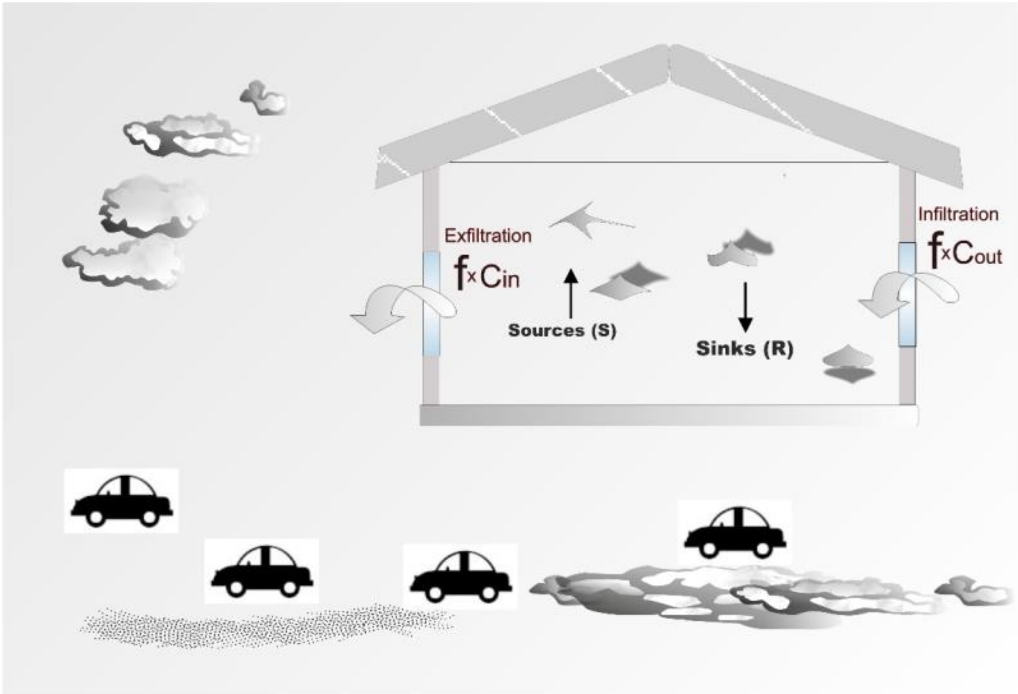

Figure 1. Schematic presentation of a simple IAQ box model. C_{in} and C_{out} are the indoor and outdoor air pollutant concentrations, f the air flow rate.

Certainly, the simple Equation (1) does not account for all of the variables that influence indoor air pollutant concentrations. Indoor chemical reactions, as well as coagulation or phase change processes in the case of PM, interfere with the terms S and R; deposition velocities are not stable and can be different for the diverse orientation of the surfaces; other phenomena also influence the indoor air pollutant concentrations [38,40–42].

Based on the simple model above, we can refute the widely held belief that changing the AER of a room would always improve its air quality. Indoor air pollution problems are not always solved by simply changing the AER. The solution is dependent on a combination of outdoor and indoor air pollutant concentrations, indoor air pollutant emission and loss rates, etc., and each combination is unique and may not be applicable for all pollutants under consideration [43,44].

Many studies use CO_2 concentrations as an indicator of IAQ. Indoor CO_2 concentrations are affected by the number of occupants, their metabolic rate, and in buildings without combustion sources, such as museums, they are only indicative of whether the AER is adequate for bio-effluent dilution [45]. Numerous other indoor air pollutants contribute to poor indoor air quality [46]. VOCs, for example, can come from both outdoor and indoor sources, such as human breath, personal care products, and cleaning products [47–50]. The materials that are used in the construction of the display cases can be also a source of dangerous VOCs, such as formic and acetic acid [51]. Particulate matter of various chemical compositions and sizes causes concern for human health, but it also endangers works of art [52,53].

As a result, there is no universal solution for every difficult indoor air pollution situation. An extensive IAQ monitoring program is required to propose IAQ control measures in each case.

Persily and Emmerich [54] explain that in a building with a heating, ventilation, and air conditioning (HVAC) system, the main link between IAQ and EEF is the parameter f in Equation (1), which is the air flow rate that infiltrates or exfiltrates (or exhausts) from the room per unit of time. The energy consumed to heat or cool the air, and to purify and circulate it within the building's duct system is analogous to the f; the higher the f, the greater the power requirement [54]. The air flow rate (f) in a naturally ventilated building is uncontrolled and varies over time. Buildings must consume energy in this case to achieve appropriate microclimatic conditions (heating or cooling), to purify the atmosphere, or to humidify or dehumidify the air [55]. Energy for lighting is also a significant consumer in museums [56]. To summarize, museums' primary energy (E) consumers are:

$$E = \text{heating (cooling)} + \text{lighting} + \text{air cleaning} + \text{air humidifying (or dehumidifying)} \quad (2)$$

The air flow rate (f) and indoor and outdoor air pollutant sources and sinks are the main factors that define the relationship between IAQ and EEF.

3.2. IAQ in Museums

It is well established that air pollutants can harm works of art, and in some cases the damage is irreversible [33,57]. For example, O_3 and NO_2 concentrations must be close to zero in order to preserve works of art for an extended period of time [8,58]. Particulate matter in the air comes from both indoor and outdoor sources. The impact on works of art is determined by their size, concentration, and chemical composition [52,59]. The concentration and chemical composition of airborne particulate matter inside and outside of five museums in California (USA) were studied as part of an extensive monitoring program [60]. The Sepulveda House is an historical building with natural airflow and this museum had the highest indoor/outdoor (I/O) fine PM ratio = 0.94, i.e., the same levels as outdoors. On the contrary the Norton Simon Museum (with HVAC and PM filtering system) had the lowest I/O fine PM ratio, which was 0.18. The concentrations of black elemental carbon particles and fine soil-dust particles in all of the museums ranged from 20 to 100% of the outdoor levels, depending on the presence or absence of an HVAC and PM filtering system. At the sites with a HVAC and a PM filtering system, the indoor airborne particles were mostly fine, consisted largely of organic matter and at two sites, indoor concentrations of organic matter exceeded the respective outdoor concentrations. According to the authors, PM deposition can affect the surfaces of works of art by soiling them or by attacking them chemically, depending on PM chemical composition [60].

Table 1 compares guidelines developed by the World Health Organization (WHO) for the most common air pollutant concentrations for human health protection, with guidelines proposed for the preservation of housed works of art for the same pollutant. The preservation target is the amount of time (in years) that the objects can be exposed to the indicated level of pollutants without deterioration.

Table 1. Proposed guideline values for air pollutant concentrations.

		Human Health WHO (2021) [61]	**Museums Tétreault (2003) [9]**	**Museums Grzywacz, C.M. (2006) [57]**	
Main sources	Air pollutant	Indoors or outdoors	Maximum concentrations for one year preservation	Sensitive materials	Other materials
Outdoor	O_3 (ppb)	50 (24-h)	5	<0.05	0.5–5
Outdoor	NO_2 (ppb)	5 (annual)	5	<0.05–2.6	2–10
Indoor Outdoor	$PM_{2.5}$ (μg m^{-3})	5 (annual)	10		

Table 2 summarizes the findings of some monitoring campaigns that measured indoor and outdoor pollutant concentrations (and the respective I/O ratio) in museums or historical buildings. Only the results for the pollutants presented in Table 1 are included in Table 2. It should be noted that the average time for the reported atmospheric pollutant concentrations and the applied monitoring method varies by museum.

Table 2. Air pollutant concentrations as measured in museums/historical buildings.

Museum/Historical Building	O_3 (In) (Ppb)	O_3 (Out) (Ppb)	O_3 (I/O)	NO_2 (In) (Ppb)	NO_2 (Out)(Ppb)	NO_2 (I/O)	Fine PM (in) ($\mu g\ m^{-3}$)	Fine PM (Out) ($\mu g\ m^{-3}$)	PM (I/O)	References
Sainsbury Centre for Visual Arts, Norwich, UK (no air conditioning system)				10	12	0.80				[62]
Correr Museum, Venice, Italy winter				10.4	24.3	0.43				[63]
summer				10.6	14.2	0.75				
Victoria and Albert Museum, London, UK				20.7	20.8	1.00				
Residenz, Würzburg, Germany				9.1	14.3	0.64				
Bethnal Green Museum (natural ventilation)				22.6	26.8		8	6	1.33	[32]
Museum of London, UK (HVAC and air filtration)				5.8	3.6		2	13	0.15	
Gene Autry Museum (USA) (HVAC and air filtration)										[64]
Buffer zone (roll-up door was closed)	7	28	0.27 ±0.15	13	39	0.32 ±0.15				
Buffer zone (roll-up door was opened)	22	25	0.88 ±0.15	56	65	0.85 ±0.15				
Trail View Window	3	8	0.33 ±0.15							
São Paulo History Museum, Brazil (MP), Exhibition (natural ventilation)	10–14		0.72–0.99	14.5		0.57	5.8	6.8	0.85	[65,66]
São Paulo State Art Museum, Brazil (PE), Exhibition (HVAC)	3		0.22	12		0.46	5.1	8.4	0.61	
Museu de Arqueologia e Etnologia, São Paulo, Brazil (HVAC and air filtration)							3.5	6.2	0.56	[66]
Galleria degli Uffizi in Florence, Italy (natural ventilation)	19–30	40–70								[67]

Table 2. *Cont.*

Museum/Historical Building	O_3 (In) (Ppb)	O_3 (Out) (Ppb)	O_3 (I/O)	NO_2 (In) (Ppb)	NO_2 (Out)(Ppb)	NO_2 (I/O)	Fine PM (in) ($\mu g\ m^{-3}$)	Fine PM (Out) ($\mu g\ m^{-3}$)	PM (I/O)	References
Jinsha Site Museum, Chengdu, China							33.3 ± 6.6	39.4 ±11.4	0.85	[68]
five museums (2 with natural ventilation) Yangtze River, China winter	2–9		0.46–1.5	1–9		0.16–0.75	33.9–79.6		0.89–1.09	[69]
summer	1–19		0.14–0.95	1–11		0.03–0.92	52.8–113.0		0.61–0.94	
Archaeological museum of Thessaloniki, Greece, (natural ventilation)							40.5 ± 19.1	24.1 ±8.85	1.8	[59]
Plantin-Moretus Museum, Antwerp, Belgium (natural ventilation)	Very low			NO (in) ≈ NO (out)			12–15	21–31	0.39–0.66	[70]
Museum (criminology findings), Athens, Greece	25.4 ± 7.9			20.0 ± 12.6	19.7		20.3 ± 2.7	24.0		[71]

Several studies, both old and new, have reported particle number concentrations and size distribution, PM chemical composition, VOCs, organic and inorganic acids, SO_2, H_2S, CO_2, and microorganisms [16,17,28,32,72–80]. Table 2 shows a small sample of such studies to demonstrate that the issue of elevated indoor air pollutants is always current.

Works of art have been and continue to be threatened as a result of a variety of indoor and outdoor pollutant sources [81]. Museums are typically located in congested, central areas with significant outdoor air pollution, which can be transported indoors via windows, ventilation systems, or by visitors (for example road dust from their shoes) [82]. Indoor sources, on the other hand, are unambiguous in museums. Visitors are an obvious and significant source of indoor air pollution. People emit particulate matter, including bioaerosols, through their skin and clothing, and by speaking and breathing, and they also cause PM resuspension [83–85]. Other chemical compounds, such as VOCs, are also emitted by people through their breath and personal care products, as well as from building and construction materials [50,86,87]. Vacuuming and cleaning the rooms can release a variety of gaseous and particulate pollutants into the atmosphere [49,88].

A sophisticated HVAC system with appropriate air filtration is the most commonly recommended intervention to reduce indoor air pollutants [89]. Without air filters, the HVAC system cannot adequately protect the artworks housed [90]. Hu et al. [69] measured indoor air pollutants above the recommended levels in five museums (three of which had HVAC systems but no filtration) (Table 2). Hisham and Grosjean [64,91] monitored the IAQ in museums in California, USA; these authors measured indoor and outdoor concentrations of O_3, NO_2, SO_2, H_2S, total reduced sulfur (TRS), peroxyacetyl nitrate (PAN), methyl chloroform, and tetrachloroethylene in three of the 12 examined museums. In the remaining nine museums, they monitored NO_2, PAN, nitrate, methylchloroform, tetrachloroethylene, and nitric acid. They concluded that the chlorinated hydrocarbon I/O concentration ratios were greater than unity in all locations, indicating indoor sources. Many consumer and industrial products, such as cleaning products, contain chlorinated hydrocarbons [64,92]. Hisham and Grosjean [64,91] observed that the influx of outdoor air diluted the chlorinated hydrocarbons and reduced their I/O ratio. On the contrary, because pollutants like PAN originate outside, the influx of outdoor air increased their I/O ratio. Except for two museums, the authors reported that PAN indoor concentrations were close to outdoor levels in all of them. They observed that, in museums without an HVAC system, indoor air pollutant concentrations were very close to outdoor levels. They found a modest removal of NO_2, PAN, and chlorinated hydrocarbons in museums with HVAC systems. Only one of the three museums equipped with HVAC and chemical filtration achieved low I/O air pollutant concentration ratios [64].

Nazaroff et al. [60] monitored airborne particles indoors and outdoors of museums in California, USA: a historical museum, an archaeological museum, and three art museums. In the historical museum, the Sepulveda House, the indoor fine-particle concentrations were nearly identical to those outdoors. However, the coarse particle concentrations were much lower than outdoors. The indoor particle concentrations at the three museums with sophisticated HVAC systems and particle filtration were significantly lower than those measured outdoors. In particular, the lowest indoor particle concentrations were found at the Norton Simon Museum. In this museum, with a high air recirculation rate, the infiltrated air from outdoors and the recirculated air passed through a series of air filters. Thus, among all the museums studied, its indoor PM levels were the lowest [60]. Godoi et al. [90] found that the Oscar Niemeyer Museum (MON) in Curitiba, Brazil has satisfactory air quality, which may be favoring the conservation of its art collection. The quantity of bulk particles in the MON was lower than outdoors. However, air filters with a higher efficiency were suggested for use in the HVAC system of the MON, particularly to capture fine particles.

HVAC systems with an appropriate air filtration system (and heat recovery) make it possible to prevent outdoor atmospheric pollutants from entering the museum. Thus, the inflow of fresh outdoor air can be increased (f in Equation (1)) to supply clean outdoor air indoors to dilute the indoor-generated atmospheric pollutants. However, applying such a system to historical buildings, such as churches, is difficult, and it is unclear whether they will function properly to provide stable conditions for the conservation of works of art [93]. In any case, it is an expensive addition to any museum, old or new. To keep these systems running properly, not only for the safety of visitors but also to maintain stable conditions for the housed works of art, they must be constantly monitored, resulting in an increased cost for their operation and maintenance. Failure of these systems can have serious consequences for the conservation of works of art [94–96]. Humidifiers or desiccant systems are also used in museums to control humidity. These systems must be carefully installed and maintained in order to function properly [18,97].

3.3. IAQ and EEF in Museums

Saving energy and producing energy from renewable sources has become a global necessity, and it is a critical component of the "green building" concept. The IEQ is a fundamental credit category in many green building rating systems (GBRSs), including LEED, Green Globes, WELL, and BREEAM [98]. However, in a study published by Licina and Langer (2021), measurements did not demonstrate that these GBRSs reduced indoor atmospheric pollutants [99]. In the case of museums, particularly historical buildings, it appears to be a difficult endeavor to reduce indoor air pollution while also saving energy [100].

Several studies have emerged that propose solutions for retrofitting museums to save energy. For example, Katsaprakakis et al. [101] present the findings of a proposed project aimed at improving the energy efficiency of the Natural History Museum of Crete, Greece, from class D to class A+ using a combination of passive and active measures. The IAQ was not assessed. The new Audain Art Museum (Whistler, BC, Canada), a Class AA building, was opened in 2020. In this museum, overall heating energy savings account for 70% of total energy savings. As long as the sophisticated air filters work properly, a combination of them ensures good IAQ. However, measurements were not used to assess the IAQ in this study [94].

The balance between acceptable microclimatic conditions (for works of art and visitor thermal comfort) and the EEF was examined in museums by monitoring indoor air temperature and relative humidity, and the EEF was typically evaluated using simulation tools [97,102,103]. CO_2 concentrations were also monitored and reported as an IAQ indicator in some studies. The latter is far from scientific reality. Table 3 compiles a list of relevant publications.

Table 3. IEQ and EEF in museums and historical buildings.

Museum/ Historical Building	Microclimatic Conditions	CO_2	Other Atmospheric Pollutants	Energy Consumption /Saving	References
"La Specola" Museum of Florence (Italy)	Yes			simulation	[15]
Viking Age Museum (Norway)	Yes			simulation	[102]
Museum in Pisa (Italy)	Yes			simulation	[104]
Technical Museum Nikola Tesla (Zagreb Fair, Croatia)	Yes	Yes		measurements before and after refurbishment	[105]
Athens University Museum (Greece)	Yes	Yes	TVOC	Suggestions for building retrofitting	[106]
The Hermitage Amsterdam (the Netherlands)	Yes			simulation and measurements	[103,107]

Table 3 shows that proper IAQ monitoring (aerosol, VOCs, etc.) simultaneous with EEF modeling/monitoring is largely absent in museums. Despite this, there are few studies for buildings other than museums. Asere and Blumberga [24] investigated the effect of reducing energy consumption on IAQ in several public buildings in Latvia using a simulation tool. They conclude that energy efficiency measures in public buildings reduce national energy consumption while worsening IAQ. It was dubbed the "energy efficiency/indoor air quality dilemma". Chatzidiakou et al. [108] compared two schools, an old Victorian building and a new, low-carbon designed building. Their findings revealed that school building maintenance and operation, as well as occupant behavior, had a significant impact on IAQ and energy consumption.

Hence, it is more than obvious that a nearly acceptable IAQ requires an appreciable amount of supplied energy (energy consumption), proving the contrasting effects of the two parameters. High IAQ leads to low EEF and vice versa. It is important here to emphasize that dedicated, specific, and systematic studies of these two interplaying parameters are very few or absent from the literature.

4. Promoting IAQ and EEF in Museums

To ensure the longevity of the aesthetic value of the exhibits, specific and consistent environmental conditions must be maintained in all buildings housing works of art, whether modern or historical. These conditions must be maintained at all times, whether there are visitors or not. Furthermore, the building must provide visual and thermal comfort, as well as good IAQ for visitors and staff. These objectives necessitate a significant amount of energy, primarily for lighting, heating or cooling, and systems that humidify or dehumidify the atmosphere in the exhibition halls, as well as in the storage rooms and offices. Nonetheless, energy conservation efforts in museums are inevitable [109,110].

Ventilation is one of the most important aspects of a museum's IAQ and EEF. The majority of published studies agree that a sophisticated HVAC system with appropriate air filtration can control indoor atmospheric pollutants in the museum, at least to some extent [60,90]. Other control strategies are also available, as is guidance for museum authorities and curators to prevent the deterioration of works of art due to air pollutants. Every museum can set its own air pollutant concentration targets based on the materials that make up its collections (marble, ceramic, silver, copper, and so on). The relevant literature discusses showcases, standalone air purifiers, and non-invasive treatments for exhibits. However, measures that can be taken to achieve adequate IAQ must take other factors into account, such as resource availability and priority setting.

Concerning EEF, several studies proposed museum-specific interventions [105,111,112]. These include using renewable energy sources, natural daylight lighting and replacing old lighting with non-energy-consuming lamps, mixed mode ventilation, phase change materials, display cases, and other building modifications where possible, such as adding an intelligent facade system with external shading, natural ventilation, and night cooling systems [34,56,104,113–116].

In addition, new indices [117], such as life cycle analysis, used to calculate energy consumption and greenhouse gas emissions [118], and "choosing by advantages", are being developed to aid decisions for innervations [119].

Controlling energy consumption as well as IAQ in museums and historical buildings that preserve our world's history remains a challenge. Extensive IAQ and EEF monitoring campaigns must be carried out in each museum, tailored to each special housed collection. Every proposed strategy for improved IAQ, comfort, and climate resilience, as well as the goal of energy savings, should be based on the "world" of hard numerical data.

Finally, in the context of climate change, the Coalition of Museums for Climate Justice has encouraged the museum world to consider "*their tremendous potential to influence climate action through their programs, research, and advocacy*" [120,121]. Museums can contribute to climate change actions, and, because they attract a large number of visitors, these structures can serve as a model for balancing IAQ and EEF [34–36].

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References

1. IPCC. *Climate Change 2021: The Physical Science Basis*; Cambridge University Press: Cambridge, UK, 2021; p. 3949.
2. Thomson, G. *The Museum Environment*; Butterworths: London, UK, 1978.
3. Toishi, K.; Kenjo, T. Some aspects of the conservation of works of art in buildings of new concrete. *Stud. Conserv.* **1975**, *20*, 118–122.
4. Baer, N.S.; Banks, P.N. Indoor air pollution: Effects on cultural and historic materials. *Mus. Manag. Curatorship* **1985**, *4*, 9–20. [CrossRef]
5. Hedley, G. Relative humidity and the stress/strain response of canvas paintings: Uniaxial measurements of naturally aged samples. *Stud. Conserv.* **1988**, *33*, 133–148. [CrossRef]
6. Brimblecombe, P. The composition of museum atmospheres. *Atmos. Environ. Part B Urban Atmos.* **1990**, *24*, 1–8. [CrossRef]
7. Drakou, R.; Zerefos, C.S.; Ziomas, I.C.; Ganitis, V. Numerical simulation of indoor air pollution levels in a church and in a museum in Greece. *Stud. Conserv.* **2000**, *45*, 85–93.
8. Pavlogeorgatos, G. Environmental parameters in museums. *Build. Environ.* **2003**, *38*, 1457–1462. [CrossRef]
9. Tétreault, J. *Airborne Pollutants in Museums, Galleries and Archives: Risk Assessment, Control Strategies and Preservation Management*; Canadian Conservation Institute: Ottawa, ON, Canada, 2003.
10. Oikawa, T.; Matsui, T.; Matsuda, Y.; Takayama, T.; Niinuma, H.; Nishida, Y.; Hoshi, K.; Yatagai, M. Volatile organic compounds from wood and their influences on museum artifact materials I. Differences in wood species and analyses of causal substances of deterioration. *J. Wood Sci.* **2005**, *51*, 363–369. [CrossRef]
11. Loupa, G.; Charpantidou, E.; Kioutsioukis, I.; Rapsomanikis, S. Indoor microclimate, ozone and nitrogen oxides in two medieval churches in Cyprus. *Atmos. Environ.* **2006**, *40*, 7457–7466. [CrossRef]
12. Ryhl-Svendsen, M. Indoor air pollution in museums: Prediction models and control strategies. *Stud. Conserv.* **2006**, *51*, 27–41. [CrossRef]
13. Godoi, R.H.M.; Potgieter-Vermaak, S.; Godoi, A.F.L.; Stranger, M.; Van Grieken, R. Assessment of aerosol particles within the Rubens' House Museum in Antwerp, Belgium. *X-ray Spectrom. Int. J.* **2008**, *37*, 298–303. [CrossRef]
14. Mašková, L.; Smolík, J.; Ondráček, J.; Ondráčková, L.; Travnickova, T.; Havlica, J. Air quality in archives housed in historic buildings: Assessment of concentration of indoor particles of outdoor origin. *Build. Environ.* **2020**, *180*, 107024. [CrossRef]
15. Sciurpi, F.; Ghelli, A.; Pierangioli, L. "La Specola" Museum in Florence: Environmental Monitoring and Building Energy Simulation. *Procedia Struct. Integr.* **2020**, *29*, 16–24. [CrossRef]
16. Uring, P.; Chabas, A.; Alfaro, S.; Derbez, M. Assessment of indoor air quality for a better preventive conservation of some French museums and monuments. *Environ. Sci. Pollut. Res.* **2020**, *27*, 42850–42867. [CrossRef]
17. Ilieș, D.C.; Marcu, F.; Caciora, T.; Indrie, L.; Ilieș, A.; Albu, A.; Costea, M.; Burtă, L.; Baias, Ș.; Ilieș, M.; et al. Investigations of Museum Indoor Microclimate and Air Quality. Case Study from Romania. *Atmosphere* **2021**, *12*, 286. [CrossRef]
18. Camuffo, D. *Microclimate for Cultural Heritage: Measurement, Risk Assessment, Conservation, Restoration, and Maintenance of Indoor and Outdoor Monuments*; Elsevier: Amsterdam, The Netherlands, 2019.
19. Yüksel, A.; Arıcı, M.; Krajčík, M.; Civan, M.; Karabay, H. Energy consumption, thermal comfort, and indoor air quality in mosques: Impact of Covid-19 measures. *J. Clean. Prod.* **2022**, *354*, 131726. [CrossRef]
20. Kinney, P.L. Interactions of climate change, air pollution, and human health. *Curr. Environ. Health Rep.* **2018**, *5*, 179–186. [CrossRef]
21. Nazaroff, W.W. Exploring the consequences of climate change for indoor air quality. *Environ. Res. Lett.* **2013**, *8*, 015022. [CrossRef]
22. Salthammer, T.; Zhao, J.; Schieweck, A.; Uhde, E.; Hussein, T.; Antretter, F.; Künzel, H.; Pazold, M.; Radon, J.; Birmili, W. A holistic modeling framework for estimating the influence of climate change on indoor air quality. *Indoor Air* **2022**, *32*, e13039. [CrossRef]
23. Isaac, M.; Van Vuuren, D.P. Modeling global residential sector energy demand for heating and air conditioning in the context of climate change. *Energy Policy* **2009**, *37*, 507–521. [CrossRef]
24. Asere, L.; Blumberga, A. Energy efficiency—Indoor air quality dilemma in public buildings. *Energy Procedia* **2018**, *147*, 445–451. [CrossRef]
25. Kakoulli, C.; Kyriacou, A.; Michaelides, M.P. A Review of Field Measurement Studies on Thermal Comfort, Indoor Air Quality and Virus Risk. *Atmosphere* **2022**, *13*, 191. [CrossRef]

26. UNESCO. *Museums around the World*, 26th ed.; De Gruyter Saur: Munich, Germany, 2020.
27. Leissner, J.; Kilian, R.; Kotova, L.; Jacob, D.; Mikolajewicz, U.; Broström, T.; Ashley-Smith, J.; Schellen, H.L.; Martens, M.; van Schijndel, J.; et al. Climate for Culture: Assessing the impact of climate change on the future indoor climate in historic buildings using simulations. *Herit. Sci.* **2015**, *3*, 38. [CrossRef]
28. Anaf, W.; Bencs, L.; Van Grieken, R.; Janssens, K.; De Wael, K. Indoor particulate matter in four Belgian heritage sites: Case studies on the deposition of dark-colored and hygroscopic particles. *Sci. Total Environ.* **2015**, *506–507*, 361–368. [CrossRef]
29. Blades, N.; Cassar, M.; Oreszczyn, T.; Croxford, B. Preventive conservation strategies for sustainable urban pollution control in museums. *Stud. Conserv.* **2000**, *45*, 24–28. [CrossRef]
30. Katsanos, N.; De Santis, F.; Cordoba, A.; Roubani-Kalantzopoulou, F.; Pasella, D. Corrosive effects from the deposition of gaseous pollutants on surfaces of cultural and artistic value inside museums. *J. Hazard. Mater.* **1999**, *64*, 21–36. [CrossRef]
31. Tétreault, J. *Control of Pollutants in Museums and Archives–Technical Bulletin 37*; Government of Canada, Canadian Conservation Institute: Ottawa, ON, Canada, 2021.
32. Cassar, M.; Blades, N.; Oreszczyn, T. Air pollutant levels in air-conditioned and naturally ventilated museums: A pilot study. In Proceedings of the International Council of Museum (ICOM) 12th Triennial Meeting, Lyon, France, 29 August–3 September 1999; Available online: https://discovery.ucl.ac.uk/id/eprint/2274/ (accessed on 25 March 2023).
33. Blades, N.; Oreszczyn, T.; Bordass, B.; Cassar, M. *Guidelines on Pollution Control in Heritage Buildings*; Technical Report; UCL: London, UK, 2000.
34. Brophy, S.S.; Wylie, E. *The Green Museum: A Primer on Environmental Practice*; Altamira Press: Walnut Creek, CA, USA, 2013.
35. Cole, L.B.; Lindsay, G.; Akturk, A. Green building education in the green museum: Design strategies in eight case study museums. *Int. J. Sci. Educ. Part B* **2020**, *10*, 149–165. [CrossRef]
36. McGhie, H. Evolving climate change policy and museums. *Mus. Manag. Curatorship* **2020**, *35*, 653–662. [CrossRef]
37. Shair, F.H.; Heitner, K.L. Theoretical model for relating indoor pollutant concentrations to those outside. *Environ. Sci. Technol.* **1974**, *8*, 444–451. [CrossRef]
38. Nazaroff, W.W.; Cass, G.R. Mathematical modeling of chemically reactive pollutants in indoor air. *Environ. Sci. Technol.* **1986**, *20*, 924–934. [CrossRef]
39. Chen, C.; Zhao, B. Review of relationship between indoor and outdoor particles: I/O ratio, infiltration factor and penetration factor. *Atmos. Environ.* **2011**, *45*, 275–288. [CrossRef]
40. Abbatt, J.P.; Wang, C. The atmospheric chemistry of indoor environments. *Environ. Sci. Process. Impacts* **2020**, *22*, 25–48. [CrossRef] [PubMed]
41. Bennett, D.; Koutrakis, P. Determining the infiltration of outdoor particles in the indoor environment using a dynamic model. *J. Aerosol Sci.* **2006**, *37*, 766–785. [CrossRef]
42. 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] [PubMed]
43. Jamriska, M.; Morawska, L.; Ensor, D. Control strategies for sub-micrometer particles indoors: Model study of air filtration and ventilation. *Indoor Air* **2003**, *13*, 96–105. [CrossRef] [PubMed]
44. Diapouli, E.; Chaloulakou, A.; Koutrakis, P. Estimating the concentration of indoor particles of outdoor origin: A review. *J. Air Waste Manag. Assoc.* **2013**, *63*, 1113–1129. [CrossRef] [PubMed]
45. Emmerich, S.J.; Persily, A.K. *State-of-the-Art Review of CO_2 Demand Controlled Ventilation Technology and Application*; Diane Publishing Co.: Darby, PA, USA, 2003.
46. Loupa, G.; Zarogianni, A.-M.; Karali, D.; Kosmadakis, I.; Rapsomanikis, S. Indoor/outdoor $PM_{2.5}$ elemental composition and organic fraction medications, in a Greek hospital. *Sci. Total Environ.* **2016**, *550*, 727–735. [CrossRef]
47. Mølhave, L. Organic compounds as indicators of air pollution. *Indoor Air* **2003**, *13*, 12–19. [CrossRef]
48. Dabanlis, G.; Loupa, G.; Liakos, D.; Rapsomanikis, S. The Effect of Students, Computers, and Air Purifiers on Classroom Air Quality. *Appl. Sci.* **2022**, *12*, 11911. [CrossRef]
49. Zarogianni, A.M.; Loupa, G.; Rapsomanikis, S. Fragrances and Aerosol during Office Cleaning. *Aerosol Air Qual. Res.* **2018**, *18*, 1162–1167. [CrossRef]
50. Halios, C.H.; Landeg-Cox, C.; Lowther, S.D.; Middleton, A.; Marczylo, T.; Dimitroulopoulou, S. Chemicals in European residences—Part I: A review of emissions, concentrations and health effects of volatile organic compounds (VOCs). *Sci. Total Environ.* **2022**, *839*, 156201. [CrossRef]
51. Chiantore, O.; Poli, T. Indoor Air Quality in Museum Display Cases: Volatile Emissions, Materials Contributions, Impacts. *Atmosphere* **2021**, *12*, 364. [CrossRef]
52. 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]
53. Marchetti, A.; Pilehvar, S.; Hart, L.T.; Leyva Pernia, D.; Voet, O.; Anaf, W.; Nuyts, G.; Otten, E.; Demeyer, S.; Schalm, O.; et al. Indoor environmental quality index for conservation environments: The importance of including particulate matter. *Build. Environ.* **2017**, *126*, 132–146. [CrossRef]
54. Persily, A.K.; Emmerich, S.J. Indoor air quality in sustainable, energy efficient buildings. *HVACR Res.* **2012**, *18*, 4–20. [CrossRef]

55. Sakiyama, N.R.M.; Carlo, J.C.; Frick, J.; Garrecht, H. Perspectives of naturally ventilated buildings: A review. *Renew. Sustain. Energy Rev.* **2020**, *130*, 109933. [CrossRef]
56. Wilson, M. Lighting in museums: Lighting interventions during the European demonstration project 'Energy efficiency and sustainability in retrofitted and new museum buildings'(NNES-1999-20). *Int. J. Sustain. Energy* **2006**, *25*, 153–169. [CrossRef]
57. Grzywacz, C.M. *Monitoring for Gaseous Pollutants in Museum Environments*; Getty Publications: Los Angeles, CA, USA, 2006.
58. Cass, G.R.; Druzik, J.R.; Grosjean, D.; Nazaroff, W.W.; Whitmore, P.M.; Wittman, C.L. *Protection of Works of Art from Atmospheric Ozone*; Getty Publications: Los Angeles, CA, USA, 1989.
59. Mouratidou, T.; Samara, C. $PM_{2.5}$ and associated ionic component concentrations inside the archaeological museum of Thessaloniki, N. Greece. *Atmos. Environ.* **2004**, *38*, 4593–4598. [CrossRef]
60. Nazaroff, W.W. *Airborne Particles in Museums*; Getty Publications: Los Angeles, CA, USA, 1993.
61. Wold Health Organization. *WHO Global Air Quality Guidelines: Particulate Matter (PM2.5 and PM10), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide*; WHO: Geneva, Switzerland, 2021.
62. Brimblecombe, P.; Blades, N.; Camuffo, D.; Sturaro, G.; Valentino, A.; Gysels, K.; Van Grieken, R.; Busse, H.J.; Kim, O.; Ulrych, U. The indoor environment of a modern museum building, the Sainsbury Centre for Visual Arts, Norwich, UK. *Indoor Air* **1999**, *9*, 146–164. [CrossRef]
63. Camuffo, D.; Brimblecombe, P.; Van Grieken, R.; Busse, H.-J.; Sturaro, G.; Valentino, A.; Bernardi, A.; Blades, N.; Shooter, D.; De Bock, L.; et al. Indoor air quality at the Correr Museum, Venice, Italy. *Sci. Total Environ.* **1999**, *236*, 135–152. [CrossRef] [PubMed]
64. Hisham, M.W.; Grosjean, D. Sulfur dioxide, hydrogen sulfide, total reduced sulfur, chlorinated hydrocarbons and photochemical oxidants in southern California museums. *Atmos. Environ. Part A Gen. Top.* **1991**, *25*, 1497–1505. [CrossRef]
65. 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.
66. 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]
67. De Santis, F.; Di Palo, V.; Allegrini, I. Determination of some atmospheric pollutants inside a museum: Relationship with the concentration outside. *Sci. Total Environ.* **1992**, *127*, 211. [CrossRef]
68. Deng, J.; Jiang, L.; Miao, W.; Zhang, J.; Dong, G.; Liu, K.; Chen, J.; Peng, T.; Fu, Y.; Zhou, Y.; et al. Characteristics of fine particulate matter ($PM_{(2.5)}$) at Jinsha Site Museum, Chengdu, China. *Environ. Sci. Pollut. Res. Int.* **2022**, *29*, 1173–1183. [CrossRef]
69. 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]
70. Krupińska, B.; Worobiec, A.; Rotondo, G.G.; Novaković, V.; Kontozova, V.; Ro, C.-U.; Van Grieken, R.; De Wael, K. Assessment of the air quality (NO_2, SO_2, O_3 and particulate matter) in the Plantin-Moretus Museum/Print Room in Antwerp, Belgium, in different seasons of the year. *Microchem. J.* **2012**, *102*, 49–53. [CrossRef]
71. Saraga, D.; Pateraki, S.; Papadopoulos, A.; Vasilakos, C.; Maggos, T. Studying the indoor air quality in three non-residential environments of different use: A museum, a printery industry and an office. *Build. Environ.* **2011**, *46*, 2333–2341. [CrossRef]
72. 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* **2022**. [CrossRef]
73. 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]
74. Zorpas, A.A.; Skouroupatis, A. Indoor air quality evaluation of two museums in a subtropical climate conditions. *Sustain. Cities Soc.* **2016**, *20*, 52–60. [CrossRef]
75. Watt, J.; Tidblad, J.; Kucera, V.; Hamilton, R. *The Effects of Air Pollution on Cultural Heritage*; Springer: Berlin/Heidelberg, Germany, 2009; Volume 6.
76. Wang, L.; Xiu, G.; Chen, Y.; Xu, F.; Wu, L.; Zhang, D. Characterizing particulate pollutants in an enclosed museum in Shanghai, China. *Aerosol Air Qual. Res.* **2015**, *15*, 319–328. [CrossRef]
77. Abdul-Wahab, S.A.; Salem, N.; Ali, S. Evaluation of indoor air quality in a museum (Bait Al Zubair) and residential homes. *Indoor Built Environ.* **2015**, *24*, 244–255. [CrossRef]
78. Druzik, J.R.; Adams, M.S.; Tiller, C.; Cass, G.R. The measurement and model predictions of indoor ozone concentrations in museums. *Atmos. Environ. Part A Gen. Top.* **1990**, *24*, 1813–1823. [CrossRef]
79. 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]
80. Katsivela, E.K.; Raisi, L.; Lazaridis, M. Viable Airborne and Deposited Microorganisms inside the Historical Museum of Crete. *Aerosol Air Qual. Res.* **2021**, *21*, 200649. [CrossRef]
81. 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]
82. Winkler, A.; Contardo, T.; Lapenta, V.; Sgamellotti, A.; Loppi, S. Assessing the impact of vehicular particulate matter on cultural heritage by magnetic biomonitoring at Villa Farnesina in Rome, Italy. *Sci. Total Environ.* **2022**, *823*, 153729. [CrossRef]
83. Licina, D.; Tian, Y.; Nazaroff, W.W. Emission rates and the personal cloud effect associated with particle release from the perihuman environment. *Indoor Air* **2017**, *27*, 791–802. [CrossRef]

84. Qian, J.; Peccia, J.; Ferro, A.R. Walking-induced particle resuspension in indoor environments. *Atmos. Environ.* **2014**, *89*, 464–481. [CrossRef]
85. Loupa, G.; Karali, D.; Rapsomanikis, S. Aerosol filtering efficiency of respiratory face masks used during the COVID-19 pandemic. *medRxiv* **2020**. [CrossRef]
86. Fenske, J.D. Human breath emissions of VOCS. *J. Air Waste Manag. Assoc.* **1999**, *49*, 594. [CrossRef]
87. Destaillats, H.; Lunden, M.M.; Singer, B.C.; Coleman, B.K.; Hodgson, A.T.; Weschler, C.J.; Nazaroff, W.W. Indoor Secondary Pollutants from Household Product Emissions in the Presence of Ozone: A Bench-Scale Chamber Study. *Environ. Sci. Technol.* **2006**, *40*, 4421–4428. [CrossRef] [PubMed]
88. Vicente, E.D.; Vicente, A.M.; Evtyugina, M.; Calvo, A.I.; Oduber, F.; Blanco Alegre, C.; Castro, A.; Fraile, R.; Nunes, T.; Lucarelli, F.; et al. Impact of vacuum cleaning on indoor air quality. *Build. Environ.* **2020**, *180*, 107059. [CrossRef]
89. Tetreault, J. The Evolution of Specifications for Limiting Pollutants in Museums and Archives. *J. Can. Assoc. Conserv.* **2018**, *43*, 21–37.
90. Godoi, R.H.M.; Carneiro, B.H.B.; Paralovo, S.L.; Campos, V.P.; Tavares, T.M.; Evangelista, H.; Van Grieken, R.; Godoi, A.F.L. Indoor air quality of a museum in a subtropical climate: The Oscar Niemeyer museum in Curitiba, Brazil. *Sci. Total Environ.* **2013**, *452–453*, 314–320. [CrossRef] [PubMed]
91. Hisham, M.W.M.; Grosjean, D. Air pollution in Southern California museums: Indoor and outdoor levels of nitrogen dioxide, peroxyacetyl nitrate, nitric acid, and chlorinated hydrocarbons. *Environ. Sci. Technol.* **1991**, *25*, 857. [CrossRef]
92. Zhuo, M.; Ma, S.; Li, G.; Yu, Y.; An, T. Chlorinated paraffins in the indoor and outdoor atmospheric particles from the Pearl River Delta: Characteristics, sources, and human exposure risks. *Sci. Total Environ.* **2019**, *650*, 1041–1049. [CrossRef]
93. Oreszczyn, T.; Cassar, M.; Fernandez, K. Comparative study of air-conditioned and non air-conditioned museums. *Stud. Conserv.* **1994**, *39*, 144–148. [CrossRef]
94. On, M. Heating Accounts For 70% of Museum's Energy Savings. *ASHRAE J.* **2020**, *62*, 40–45.
95. Camuffo, D.; Van Grieken, R.; Busse, H.-J.; Sturaro, G.; Valentino, A.; Bernardi, A.; Blades, N.; Shooter, D.; Gysels, K.; Deutsch, F. Environmental monitoring in four European museums. *Atmos. Environ.* **2001**, *35*, S127–S140. [CrossRef]
96. Gysels, K.; Delalieux, F.; Deutsch, F.; Van Grieken, R.; Camuffo, D.; Bernardi, A.; Sturaro, G.; Busse, H.-J.; Wieser, M. Indoor environment and conservation in the royal museum of fine arts, Antwerp, Belgium. *J. Cult. Herit.* **2004**, *5*, 221–230. [CrossRef]
97. Ferdyn-Grygierek, J. Indoor environment quality in the museum building and its effect on heating and cooling demand. *Energy Build.* **2014**, *85*, 32–44. [CrossRef]
98. Bernardi, E.; Carlucci, S.; Cornaro, C.; Bohne, R.A. An analysis of the most adopted rating systems for assessing the environmental impact of buildings. *Sustainability* **2017**, *9*, 1226. [CrossRef]
99. Licina, D.; Langer, S. Indoor air quality investigation before and after relocation to WELL-certified office buildings. *Build. Environ.* **2021**, *204*, 108182. [CrossRef]
100. Fouseki, K.; Cassar, M. Energy Efficiency in Heritage Buildings—Future Challenges and Research Needs. *Hist. Environ. Policy Pract.* **2014**, *5*, 95–100. [CrossRef]
101. Katsaprakakis, D.A.; Georgila, K.; Zidianakis, G.; Michopoulos, A.; Psarras, N.; Christakis, D.G.; Condaxakis, C.; Kanouras, S. Energy upgrading of buildings. A holistic approach for the Natural History Museum of Crete, Greece. *Renew. Energy* **2017**, *114*, 1306–1332. [CrossRef]
102. Bakry, M.S.; Hamdy, M.; Mohamed, A.; Elsayed, K. Energy saving potential in open museum spaces: A comparative hygrothermal microclimates analysis. *Build. Environ.* **2022**, *225*, 109639. [CrossRef]
103. 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]
104. 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]
105. 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]
106. Efthymiou, C.; Barmparesos, N.; Tasios, P.; Ntouros, V.; Zoulis, V.; Karlessi, T.; Salmerón Lissén, J.M.; Assimakopoulos, M.N. Indoor Environmental Quality Evaluation Strategy as an Upgrade (Renovation) Measure in a Historic Building Located in the Mediterranean Zone (Athens, Greece). *Appl. Sci.* **2021**, *11*, 10133. [CrossRef]
107. Kramer, R.P.; Schellen, H.L.; van Schijndel, A.W.M. Impact of ASHRAE's museum climate classes on energy consumption and indoor climate fluctuations: Full-scale measurements in museum Hermitage Amsterdam. *Energy Build.* **2016**, *130*, 286–294. [CrossRef]
108. Chatzidiakou, L.; Mumovic, D.; Summerfield, A.J.; Hong, S.M.; Altamirano-Medina, H. A Victorian school and a low carbon designed school: Comparison of indoor air quality, energy performance, and student health. *Indoor Built Environ.* **2014**, *23*, 417–432. [CrossRef]
109. NEMO. Statement on the Impact of the Energy Crisis on Museums in Europe. Available online: https://www.ne-mo.org/fileadmin/Dateien/public/NEMO_Statements/NEMO_Statement_Energy_Crisis_in_Europe_16092022.pdf (accessed on 25 March 2023).

110. van Schijndel, A.W.M.J.; Schellen, H.L.H. Mapping future energy demands for European museums. *J. Cult. Herit.* **2018**, *31*, 189–201. [CrossRef]
111. 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]
112. Lucchi, E. Simplified assessment method for environmental and energy quality in museum buildings. *Energy Build.* **2016**, *117*, 216–229. [CrossRef]
113. Battle, G.; Yuen, C.; Zanchetta, M.; D'Cruz, P. Energy efficiency in new museum build: THEpUBLIC. *Int. J. Sustain. Energy* **2006**, *25*, 185–198. [CrossRef]
114. Lundqvist, R.C. *Investigation of Stabilizing the Indoor Environment Using Building Technologies-A Case Study: Viking Age Museum in Norway*; NTNU: Trondheim, Norway, 2018.
115. Hassanizadeh, N.; Noorzai, E. Improving lighting efficiency in existing art museums: A case study. *Facilities* **2020**, *39*, 366–388. [CrossRef]
116. Zannis, G.; Santamouris, M.; Geros, V.; Karatasou, S.; Pavlou, K.; Assimakopoulos, M.N. Energy efficiency in retrofitted and new museum buildings in Europe. *Int. J. Sustain. Energy* **2006**, *25*, 199–213. [CrossRef]
117. Fabbri, K.; Bonora, A. Two new indices for preventive conservation of the cultural heritage: Predicted risk of damage and heritage microclimate risk. *J. Cult. Herit.* **2021**, *47*, 208–217. [CrossRef]
118. Ge, J.; Luo, X.; Hu, J.; Chen, S. Life cycle energy analysis of museum buildings: A case study of museums in Hangzhou. *Energy Build.* **2015**, *109*, 127–134. [CrossRef]
119. Arroyo, P.; Tommelein, I.D.; Ballard, G.; Rumsey, P. Choosing by advantages: A case study for selecting an HVAC system for a net zero energy museum. *Energy Build.* **2016**, *111*, 26–36. [CrossRef]
120. Davis, J. Museums and climate action: A special issue of Museum Management and Curatorship. *Mus. Manag. Curatorship* **2020**, *35*, 584–586. [CrossRef]
121. Sutton, S. The evolving responsibility of museum work in the time of climate change. *Mus. Manag. Curatorship* **2020**, *35*, 618–635. [CrossRef]