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# Review of museums' indoor environment conditions studies and guidelines and their impact on the museums' artifacts and energy consumption

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ABSTRACT

Museums are the main link between the past, the present and the future.

The presence of ancient historical artifacts is the main factor differentiating museums' environment from the environments of other types of buildings.

This review paper, is focused on the indoor environment quality of the exhibition halls in the museums. The information presented is based on three main aspects. Gathering the required indoor environmental parameters related to the indoor exhibition spaces in the museums then discuss in terms of temperature, relative humidity, lighting, and indoor air quality (air pollutants and ventilations); this is done while considering the museum's artifacts, visitors and personnel. The second aspect focuses on the different researches carried out within the museum indoor environment focusing on temperature (T), relative humidity (RH), lighting (artificial lighting and daylight) as well as the studies conducted within the subject of indoor environment quality of museums (IEQ). The third aspect focuses on studies and guidelines designed for upgrading existing museums into more sustainable projects by focusing on energy efficiency part of museums. This review paper provides a rich guide of all the needed information in terms of museums indoor environments parameters for the museum officials to implement strategies and enhance the current conditions of the museums. It also highlights some of the remaining issues that researchers can look at in the future.

## 1. Introduction

According to the International Community of Museums (ICOM) [1]: “A museum is a non-profit, permanent institution in the service of society and its development, open to the public, which acquires, conserves, researches, communicates and exhibits the tangible and intangible heritage of humanity and its environment for the purposes of education, study and enjoyment.” As such museums are the main link between the past, the present and the future. They are a reliable source of information for researchers, and a good entertainer for children teaching them history and other topics. In addition, they allow people to see different but original ancient artworks and artifact. Most importantly, museums are a main destination for tourists for learning the culture and history of the country they are visiting.

The museums' environments are different from other built environments, because of the presence of ancient and historical artifacts that require specific environmental conditions for preservation. This paper focusing to highlight the Indoor Environmental Quality (IEQ), parameters that should be considered within the museum's environment. This includes temperature, humidity, lighting levels and UV levels. This paper is intended to help guide for the museum sector and museum's officials on potential strategies for enhancing the indoor environmental quality and energy performance of museums. Researchers will also be able to use the information reported as a base to further new researches within the related subjects presented here.

## 2. Museums, the need for a special IEQ

Artifacts, visitors and museum personnel are the three different categories within the museum environment, each of which has different indoor quality requirements. Depending on the type of the artifacts, the environmental conditions for their preservation will differ. Research about artifacts have been focusing on the objects nature. Generally, artifacts are divided into the three categories: organic, inorganic and mixed materials [2]. Organic objects are those coming from plants, animals or natural elements; paper and leather are examples of them. Inorganic materials refer to the items like stones, metal and bronze. Mixed material objects are a combination of organic and inorganic materials.

To be more specific, each ancient item usually requires certain

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**Table 1**
Temperature and Relative Humidity Parameters for museums indoor environments.by different standards [3,5,10,11].

| | T °C | T (24 h) | T Seasonal | RH % | RH (24 h) | RH Seasonal |
|---|---|---|---|---|---|---|
| **AICCM 2014** | 15C–25C | ± 4C | – | 45–55% | ± 5% | 40–60% |
| **UK standard 2012** | 18C–24C | ± 4 °C | | 50% | ± 10% | |
| **ASHRAE AA 2011** | 15C–25C | ± 2 °C | Up 5 °C<br>5 °C Down | 50% | ± 5% | No change |
| **ASHRAE A 2011** | 15C–25C | ± 2 °C | Up 5 °C<br>Down 10 °C | 50% | ± 5% | Up 10%<br>Down 10% |
| **ASHRAE A 2011** | 15C–25C | ± 2 °C | Up 5 °C<br>Down 10 °C | 50% | ± 10% | No change |
| **ASHRAE B 2011** | 15C–25C | ± 5 °C | Up 10 °C (but not above 30 °C)<br>Down as low as necessary to maintain RH control | 50% | ± 10% | Up 10% Down 10% |
| **ASHRAE C 2011** | Rarely over 30 °C, usually below 25 °C | – | – | Within range<br>25–75% RH<br>Year round. | – | – |
| **ASHRAE D 2011** | – | – | – | Reliably below 75% RH | – | – |
| **HCC (Hot Humid) 2002** | 22C–28C<br>Daily | – | 10% acceptable<br>20% dangerous<br>40% Destructive | 55% – 70%<br>Daily | – | Not to exceed 70%<br>Not below 40% |
| **HCC (Hot Dry) 2002** | 22C–28C<br>Daily | – | | 40%–60%<br>Daily | – | |
| **HCC (Temperate) 2002** | 14C–24C<br>Daily | – | | 45%–65%<br>Daily | – | |

environmental conditions depending on its status when it was found and how it should be preserved and displayed [3–5]. When the microclimatic conditions, like temperature or relative humidity are not controlled or properly set, damage to ancient items can be significant over a short period of time, or could cause small invisible changes like: accelerating the deterioration of the object or shortening their life [2,3,6].

Having visitors is one of the main purposes of establishing a museum is to introduce the history and culture. They visit the museums individually or in groups and in the relatively short visit conducted, they can leave their impact on the museum's environment. Thus, the indoor environment of the museums should be controlled and monitored in order to mitigate any negative impact from the visitors onto the artifacts. The factors related to visitor satisfaction levels inside the museums are: Exhibition Environments in the Museums (Indoor Environments and Technology Use, Visual Locomotors and Signage Availability, Circulation Complexity), Ambient Environment (Density of the Visitors, Noise Levels), Thermal Comfort (Temperature and Humidity) As well as the Size of the museum [7].

In difference to the transient visitors, the museum's personnel are the permanent occupants of the museum spending most of their time within the museum environment. Depending on their position and job requirements, they are more likely to be affected by their working environment. Being in direct contact with ancient items with different origins might be a common daily task for some of them. Museums with their importance to history and culture have got special attention from researchers on their vast subjects.

As for the practices in the museum indoor environments, a compromise should be achieved to make the best balance between the artifacts preservation and the human comfort level while still keeping in mind that the collections' conditions is a priority that should never been underestimated [3,8]. The IEQ parameters can be divided into: Thermal conditions, Lighting, and pollution which are discussed in detail in the coming sections. Moreover, the requirements for preserving the ancient artifacts usually leads to different energy consumption patterns compared to other types of buildings. This aspect will be discussed in this paper. Additionally, the development of museum practices overtime in terms of considering energy efficiency and sustainable methods have been focused at.

## 3. Thermal requirements

Depending on the regional local climatic conditions and the standards adopted by different museums, RH and T set points might be strictly controlled, or they can vary by seasons and times. If properly set, providing uniform environmental conditions with minimum fluctuations favors the durability and long life of the exhibits. In countries with cold climates and having significant seasonal weather variations, stabilizing the RH in the indoor environment becomes a challenge especially during winter when the temperature drops the RH becomes high.

Having RH higher than what is needed can cause serious damage to the collection like detaching the different parts of an object. Moisture contributes to mould growth and fungi. In organic objects with some moisture content like wood, inflation is a result of high humidity as well. High RH also accelerates the corrosion process of different metals in the exhibits, like bronze. On the other hand, low RH is harmful when it reaches low values. Low RH can cause cracks, size shrink, or breaking the item. Additionally, when the RH rises in higher temperature the environment becomes more ideal for microorganism and mould growth [2,3].

Through the different studies carried about the museum's environments, temperature range is usually correlated with RH [2,3,6]. Temperature fluctuations may weaken the materials particulate, resulting in having more fragile items. According to ASHRAE the ideal percentage of the required RH for museum exhibits has changed over time [3].

As mentioned earlier there is no exact set point that is followed by all museum parties. RH of 50%–55% was known as ideal percentage for museum environments before [2]. However, the range was later reduced to 45% ± 5% [2]. Other guidelines, like the British government guideline after 2012, changed the requirements to make the RH and T more flexible. This flexibility contributed to reducing the energy required for humidification or dehumidification processes. Based on earlier studies, keeping the RH of the indoor environment within the 50% range was hard to achieve [8].

Table 1 summarizes the hygrothermal conditions in terms of T and RH gathered from different guidelines in different regions. As shown in the table, the range of T varies based on the different guidelines, as well as different climate conditions. Fluctuation allowance for T ranged from ± 2 °C to ± 5 °C. The variation of set points in RH was mostly 50% with the two options of ± 5% or 10% daily. As shown earlier the more allowance in variation of RH, the more energy could be saved [8,9]. However, the type and origin of collections should be considered as well.

The Australian guidelines developed by Heritage Collections Council (HCC) in the ministry of arts in Australia in 2002 defined the standards differently based on the climate of each region by depending on hot and dry, hot and humid and temperate regions [10]. In 2014, the Australian Institution for the Conservation of Cultural Material (AICCM) developed their guidelines from 2009 and specified tighter range in comparison to the 2002 HCC specifications [11]. Additionally, AICCM had a general approach and did not specify conditions based on the climate of each region.

As for ASHRAE standards [3] six different conditions were identified based on the sensitivity of the artifacts and the required control level for them. All shown in the following table. (D: to Prevent dampness only. C: Prevent all high risk extremes, B: Precision control, some gradients plus winter temperature setback, A: Precision control, some gradients or seasonal changes, not both, with system failure fall back. AA: Precision control, no seasonal changes, with system failure fall back).

## 4. Lighting requirements

Another key parameter for the museum environment is the lighting level. The exposure of light is very crucial for the collections. As for the collections requirements it is favorable not to be exposed to light, as the different radiations from light contribute in the deterioration of the collections. The Ultra Violet (UV) and Infra-Red (IR) radiations are the main harmful radiations from the light to the artifacts. UV contributes to the degradation of the object and colour change. Daylight is a main source for allowing big amount of UV radiations from the sun into the environment. Moreover, IR causes a rise in the temperature of the environment, which can be harmful to the collections [2,12].

However, having proper lighting is a must in the museums environments for viewing the collections to the visitors and it cannot be avoided. Nevertheless, lighting should not be a reason to cause damages to the valuable collections. Thus, a safe compromise should be achieved in a way to make the possibility for visitors to view and appreciate the artifacts without jeopardizing the collection's needs.

According to Melendez et al. [12] the current accepted values of UV radiation range between 35 and 75 μW per lumen (W/lm) for highly sensitive and moderately sensitive objects, respectively. Recently LED lighting has been the focus for museum environments, as they have less UV radiation, moreover they reduce energy consumption. Organic materials like papers are more sensitive to IR and UV radiation and require special care. Light can fade them or change their colour to yellow [2]. Daylighting in the museums was the focus of many different researchers [12–16]. However, according to [15] daylighting's main challenge to the museums is the deterioration of artifact as well as causing glare, which affects the visitors. A summary of these studies is included in section 4.1.

Table 2 is a summary of the allowed lux levels for different types of materials as defined by different international standards; based on the object origin. HCC defined the sensitivity level of material as:

**Table 2**
Lux and UV limits for museums indoor environments by different standards [5,10,17,18,19].

| | Very Sensitive Objects | | Sensitive | | Insensitive | |
|---|---|---|---|---|---|---|
| | Lux lumen/$m^2$ | UV μwatt/lumen | Lux lumen/$m^2$ | UV μwatt/lumen | Lux lumen/$m^2$ | UV μwatt/lumen |
| **UK Standard 2012** | 50 | | 200 | | 300 | |
| **HCC 2002** | 50 | 30 | 200 | 75 | 300 | 200 |
| **ASHARE** | 50–80 | 0–75 | 200–250 | 0–75 | Can be higher but not recommended | 0–75 |
| **Havells Sylvania 2015** | 50 | | 100 | | 300 | |
| **IESNA Museum and Art Gallery Lighting 1996 p14** | 50 | 0 | 200 | 0 | Depending on the exhibition | 0 |

- Very Sensitive: Includes textiles, water colours, prints and drawings, manuscripts, ethnographic objects
- Sensitive: Oil and tempera paintings, undyed leather, horn, oriental lacquer
- Insensitive: Metal, stone, ceramics and glass, jewellery [10].

As shown in Table 2, some standards specified the UV limits while others did not mention, it could be due to the fact of considering 0 UV levels in all conditions where not mentioned. Moreover, based on the defined lux levels in IESNA has defined light exposure limit through the year based on different materials. According to [14] in IESNA 50000 lux h/year is the annual exposure limit set for items being exposed to 50 lux. As for the 200–300 lux exposure level, this limit is 480000 lux h/year.

The crucial point to be considered in regards to the information presented in Table 2 as well as the previous part through the shown references, there was no clear indication of IR impact or IR levels limits.

### 4.1. Studies focused on museum lighting

As highlighted earlier, museum lighting is another key element in the museum indoor environment. Lighting is a main element for viewing the artworks and artifacts in the museums. Accordingly, it is directly related to artifact and visitors perception. As mentioned in previous Section (4), in terms of artifact preservation the ideal condition is the total darkness but this is not feasible for viewing purposes. As for the studies about lighting in museum environments, it is a very vast area with many researches in the field. However, the most recent studies have significantly focused on the energy optimization of lighting and potential ways to reduce energy consumption inside museums through adapting new lighting technologies. Section 6.1 is discussing the studies related to energy reduction through lighting systems.

Following part is mainly showing other research topics focused on item degradation, visual appearance and other aspects not related to energy topic.

The study by Wahab and Zuhardi [20] focused on visual quality in terms of lighting. They discussed the following variables in terms of visual performances and quality: Light distribution, Visual size and location of the target, Luminance and luminance contrast, Colour difference, Glare, Shadow, Veiling reflections. Their study mainly focused on the aesthetic purpose of light and how visitors responded to the lighting of the museum's artworks. The results were based on walk through observation made at a chosen art museum in Kuala Lampur. Authors in their study, focused on three main components extracted from the literature review made for the research. The three factors were: Luminaire effect, interior material and finishes and space planning. Based on these The walk through observation results were discussed. The discussion identified the problems in viewing and artwork and how it can be avoided. The solutions proposed included changing the direction of the light, type of the light fixture design of the exhibition and what is surrounding that is causing reflection/shadow or other factors.

Delgado et al. [21] studied how to make the lighting systems for museums safer by testing and examining different methods to improve luminance efficiency L/W of light. LED lights have been used in many types of projects.In museum practices and researches, they became centre of attention as well.As these lightings have longer lifecycle, require less energy, and produce enhanced quality of lights. This study mainly aimed in enhancing the luminance efficiency of the spectral profile through maintaining the proper colour rendering and removing the light not contributing in colour perception or brightening. The use of LED lighting was also investigated by many other researchers [22–25].

Tuzikas et al. [22] in their study have introduced a new solid-state lighting engine with control of photochemical safety. The study considered the artwork and artifact requirements alongside the viewing requirements. Colour temperature, flexibility of colour saturation and chromaticity are some factors discussed for reaching the proper visual appearance with considering constant damage irradiance. The research established the advancement of LED light and the flexibility of providing smart controllable systems for museums with control over photochemical effect. Mayorga Pinilla et al. [24] and Viénot et al. [25] in their studies proposed LED lights as best option for better visual quality with minimal damage to artworks. Moreover, Viénot et al. [25] proved that LED improves the visual quality and colourfulness for moderately degraded colour objects, and present them in a condition better than their current state. On the other hand [26], aimed to set some standards for lighting in cultural heritage, to limit the degradation process to artifacts. Different types of lights were selected and compared in terms of their specification. An experiment was carried out to measure the Effective Illuminance (lux) for each type of light and to compare the degradation process of the sample.

Benefiting from daylight within the exhibition environments is another subject of interest for different researchers [12-16and27]. Kim and Seo [13] and Kim and Chung [15] considered daylight as a main topic for their studies. Daylight also was considered as a main factor contributing to energy savings in the museums. Studies related to daylight and energy conservation are explained in 6.1 section. Kaya [16] examined daylight on visitors' perception from a satisfaction point of view in the museums in terms of the visual quality in the museum environment. In the study, daylight exposure was measured and guidelines to successfully implement daylight in a selected art museum was simulated and presented to be adopted without causing any harms to the art collection of the museum.

Kim and Seo [13] studied the possibilities of benefiting from the available skylight in the building and evaluated the possibilities of reusing it for the museum. Their study measured the amount of daylight entering from the skylight and based on the measurement results, they simulated different possibilities to safely integrate daylight in the environment. Based on the findings, the existed skylight is not safe and it should be redesigned to reduce the high level of lights to avoid the damages to the collection. Their study concluded the necessity of considering daylight factor from early architectural design phase in order to have efficient and beneficial light for museums. This indicates the possibility for purpose built buildings to be as museums.While, other studies evaluated the existing conditions for a non-purpose built historical building, later used as a museum.

Likewise, Al-Sallal and Bin Dalmouk [14] have studied the daylight factor as well. Their study was about the old heritage houses adopted into museum function. Although, their study was about studying the impact of daylight, the focus was the windows rather than skylight. They also concluded with the negative impact of daylight that is resulting damages to the museum indoor environment in terms of artifacts. Kim and Chung [15] proposed alternative top light to the existing skylight of a museum in their study. They concluded that daylight should be evaluated from early design stage of museums in order to be beneficial in terms of indoor environment.

Del Hoyo-Meléndez et al. [12] have noted the amount of daylight entering the museum is within the acceptable light level in comparison to the standards by measuring the lighting level of a museum. However, that condition did not last during the summer period as stronger solar radiation changed the results. Franzitta et al. [27] in their study of the impact of daylight on the exhibited artworks have provided guidebook for exhibition managers of the case study building to consider the areas of the museum that would not be negatively impacted by daylight through different time and seasons.

Having shading devices, adjustable louvers are other techniques identified by Delgado et al. [21] to have the right amount of light without raising the temperature inside the exhibition environment and reduce the UV radiation as much as possible. In order to block the UV radiation from daylight or other types of lights, filters are used in museums. Lighting filters beside lighting systems are another strategy that can be considered in museum indoor environments. Delgado et al. [21] proposed different types of light filters by enhancing the luminance efficiency to have safer lighting systems for sensitive works.

From the reviewed literature, it can be concluded that daylight in existing buildings transformed to museums is not successful because of the harm and damages they cause to the artifact, as they were not planned to serve a museum building. In purpose built museums, capturing daylight was well studied and considered from different aspects, and considered from early design stages with keeping the artifacts requirements as a priority in the process. Thus, it had successful implementations. However, it should be noted that, in all of these studies, skylights were implemented instead of windows, without mentioning specific reasons for that.

## 5. Pollution and indoor air quality (IAQ)

Within the museum's indoor air quality, airborne particulates should not be ignored. They can negatively impact the artifacts. Aside from dust and other suspended solid particulates, chemical/gaseous pollutants like Ozone, Sulphur dioxide cause serious damages in the museum's indoor environment. They contribute in deoxidization, significant deterioration, as well as corrosion of metal. These pollutants should be blocked from entering the museums or removed from the environment.

One of the most common way to remove the atmospheric pollutant is to use the air filters. However, according to [2] some air filters can only remove the diameters of more than 2 mm, which form almost 80% from the total pollutants in the environments. The finer pollutants will stay in the environment, which can cause to chemical reactions and damage the collections [2]. Electrostatic filters can remove these fine particulates however, they produce ozone and they are forbidden to be used in the museums due to this.The most common way is benefitting from HVAC systems that are equipped with fine filters to remove these particulates from the environments by filtering the air in the safe way without causing any side effects to the museum environments.

### *5.1. Studies focused on museum indoor air quality (IAQ)*

Indoor air quality of museum environments topic remains a crucial scope of research over time [27–34]. Atmospheric air pollutants were also covered in many recent publications [28-30,33and35-37].

Chianese et al. study was about monitoring and measuring the air pollutants of a museum in Italy [35].The paper showed the values that should not be exceeded in terms of chemical/gaseous pollutants as well as the particulate matters in the environment in the Italian Law standards and the results of the measurements were compared to them. The monitoring results showed the average PM10 (particulate matters 10 µm in diameter or smaller) concentration exceeded the highest limit of standards (30 µg/m3) by 62%, which was significant, while the average PM2.5 (particulate matters 2.5 µm in diameter or less) did not exceed this limit as well. The study also included measurements of outdoor environment and results were compared with indoor. The research showed the impact from outside on the indoor environment in terms of PM and other pollutants were transported to the indoor environment by visitors. Also the location of the museum played a role in having the pollutants inside. The use of High efficiency particulate air (HEPA) filters can be used to effectively control small PM2.5 particular matter [38,39].

Marchetti et al. unlike others, in their study showed the importance of including all IEQ parameters including the airborne particulates when monitoring and measurements campaigns were carried out. Their study resulted in developing ways to recognize any future potential damages to artifacts through monitoring of different PM. According to Marchetti et al. The presence of sudden events could not be identified through T, RH or light monitoring. By measuring the different PM sizes and considering their chemical reactions in the environments big damages could be prevented on their chosen case study. However, their study needed further development in order to find ways for prevention in the galleries where the environments are not fully controlled like the storage areas because of the presence of visitors [40].

Likewise, Krupińska et al. [29] and Hu et al. [36] also had similar research focus on measuring the NO2, SO2, O3 and particulate matter. While Andretta et al. [41] measured the concentration of NO2, O3 and Wang et al. [30] focused on Nitrogen only. The study by Krupińska et al. [29] showed very low concentration in the indoor environment in comparison to the outdoor in one museum. Hu et al. [36] considered 5 museums with various locations and concluded the inefficient indoor environment dues to lack of proper control from outer environment. Comparing the 3 mentioned studies [30] is a stronger study in terms of showing the result because of the comparison to the standards. While the study of Hu et al. [36] depended only on comparing the results with other similar studies conducted earlier. These studies referred to also might not be having satisfactory conditions. On the other hand, the study by Krupińska et al. [29] lacked providing the standard of the volume limit for the indoor environment or comparing them with other studies. The results were mainly based on comparing the pollutants volume indoor vs outdoor concentrations by showing the significant lower pollutant concentration in the indoor environment, which resulted in safe conditions. Even though, the measured volumes had significant differences between the outdoor and the indoor, the indoor concentrations might remain higher than the safe situation in the standards.

Similarly, Andretta et al. focused on the measurements and comparison between indoor and outdoor pollutants concentration ratio, in a chosen ancient library building in Italy. However the strong point of this study is the comparison made for the results of measurements to the standards to show the condition of the IAQ for this case as well as comparing it to the results obtained from other similar studies. The measurements were carried out to cover the two extreme seasons in the year (winter/summer). Results showed the indoor and outdoor ratio for NO2 in winter was 0.06 +_ 0.02 which was much lower comparing to summer with 0.3 +_0.1. Since this study also measured RH and T for the indoor and outdoor environments, the reason for this big difference in ratio for summer and winter could be identified. Measurement results for indoor RH in winter was 66.7% while in summer this percentage was 58.1%. According to the authors, this high RH can favor the chemical reactions of NO2 into HONO or HNO3, which was the reason for having lower NO2 concentration ratio [41].

Abdul-Wahab et al. [37] in a leading study for the GCC region have measured the IAQ parameters of Bait Al Zubair building in Oman. The building contained one level of museum exhibition and two residential blocks. The study focused to measure the concentration of the air pollutants in the environment. In the result of this study, a comparison was made to show the actual the measurement results from the chosen building and how far it is from the standard rates. This comparison made the study stand out among the other mentioned studies by defining the status of the results.

Proietti et al. [33] concentrated on dust as pollutants and the contribution of dust on degradation process of the materials and artifacts. The study by Lee et al. [28] focused only to identify the sources of pollutants by measuring PM10, CO2, HCHO, CO, NO2, TVOCs, O3, Rn, and SO2, as well as temperature and relative humidity. In a chosen museum. The results showed, temperature, relative humidity, PM10, and TVOCs existed were not in the safe range and were causing damage to the collection. Moreover, the study identified NO2, SO2, O3 and HCHO as the major pollutants in the museum. Authors identified the cause of this insufficient museum environment was due to following guidelines which was set for visitors comfort only and not considering the collections requirements. Muller, Seng and Satienrattanakul [42] recommended the use of adsorbent based or gas-phase filtration systems can be used to remove gaseous contaminants. Still more detailed research is needed to assess the long term effectiveness of such systems.

Other researchers focused on the mould and fungus within the museum environment and their causes [43–45]. Paner [43] in his study examined ways and approaches to restore fungi and mould infested paintings of University of Santa Tomas museum in the Philippines by experimenting different fungicides and their impacts on the artworks. Harkawy et al. [39] focused their study on a later stage of conservation by checking the possibility of microbial recontamination in artifacts after going through the disinfection process. The study was conducted 10 years after the disinfection process of the artifacts as well as their environment. Disinfection was done through a complex chemical process, to sterilize contaminated objects and to help stop the microorganism reaction in manuscripts and ancient papers over long periods of time. The findings of [44] study proved the occurrence of microbial recontamination and concluded the need for enhancing the indoor environment and to have full control over it.

Natural ventilation was studied by Harkawy et al. [44] and Lopez-Aparicio et al. [46]. Their studies showed when the environment was naturally ventilated without controlling and filtering the air, it is not safe because due to the pollutants, coming from outside and as well as the mould growth and fungus. In the chosen case study, natural ventilation was providing the desired temperature for the collection, however, it was causing damages because the air entering should have been filtered or treated appropriately to match the requirements of the artifacts.

As for recent studies, Din, Husin and Othman [47] provide literature on a very focused topic in terms of the relationship of chemical characteristics of airborne particulates with the soiling defect of the inorganic artifact. This is done by presenting and analyzing the case studies qualitatively. The mentioned review provided detailed information on the chemical specification for the different airborne particulates that produce black crust or soiling defect when they react with the historical item's surface. This paper helps other researchers to understand the whole process and chemical characterization in order to provide proper and suitable solutions.

Whereas in the study of Skytte et al. [48] study a new method was developed in order to monitor the and measure the water soluble pollutants on the cultural heritage items without taking any samples from the object itself. This method included flushing water on the nearby objects like the showcase wall or a space beside it. Then the flushed water was analyzed (with Ion Chromatography and Inductively Coupled Plasma Mass Spectrometry). This method measured vertical surfaces and cover areas 0.03–0.07 $m^2$ in size. Tested on different locations and different surfaces. Results of the study showed clear results gathered from smooth or well defined surfaces. The results get more complex situations when the tested surface itself contributes to the flush water. However, this method was very easy and cheap to implement and it provide realistic results in terms of the existing situations.

Aside from indoor air pollutants, hygrothermal condition is a crucial parameter for museums indoor environment. They are directly related to ventilation and air conditioning systems of the museums. The study of D'Agostino and Congedo [32] was about museum ventilation showed the natural ventilation effect on a chosen historical cathedral in Italy with no HVAC systems. Results of the study and the software simulations made concluded that two of the windows from the building should be walled up. And to have a safer case all the windows should be kept closed and only get ventilation from the entrance door. However, the study confirmed high level of relative humidity is not providing safe condition for the conservation of the building and necessity of adopting other ventilating systems (HVAC) in the building specially when is open to public.

Coelho et al. [49] in their recent study mainly focused on hygrothermal simulation optimization for historic buildings in order to provide best option to depend on for validating historic building simulations. Their study depended on using pre-monitored microclimatic data of the building and mainly used T and water-vapor pressure data for validation the simulation model. Research included testing various weather files for the chosen city.

Results showed different weather files provide different accuracy. The best fit was from the weather files provided by IPMA from 71.8% and for water-vapor pressure was 71.5% which allowed validation of the model. While WUFI had 48.8% and 33.5% and Energy Plus database could only reach to max 56.5% and 40.1% of accuracy for the same year environmental monitoring were carried out. Study concluded that depending on monitoring data could provide the best accuracy for validation [49].

On the other hand, Martinez-Molina et al. [50] in their study considered the visitor's satisfaction level inside the museum rather than focusing on the required conditions for artifacts. In their selected museum building they have qualitative as well as quantitative data collection, and they studied visitors' Thermal Sensation Votes (TSV), and visitors' Predicted Mean Vote (PMV) as well as considering visitor's clothing levels. Results of the study showed high discomfort level among most visitors during cooling season (July–September). According to authors it was due to the high difference between indoor and outdoor temperature. Also, it depended on the clothing level of visitors. As normally people dress up according to the outdoor conditions not considering the indoor environment.

Considering archeological museums, where there are some indoor as well as outdoor exhibits, Luo et al. [51] in their study for a selected archeological museum investigated the conditions during winter, which showed significant fluctuation in T and RH when heating system is not working and caused damages to the pit area of the museum where the artifacts are unearthed they were freezing. Through their research they experimented different possibilities for winter and summer conditions for both areas of visitors and pit area. Study showed installing radiant heating system for winter and air conditioning systems for summer provided the best option for artifact preservation. However, energy consumption was high. To preserve energy and provide suitable environment for artifacts and visitors, the best option was to install air curtain to make insulation with the layer of warm air layer in the environment to prevent the T and RH fluctuations.

Other recent studies related to microclimatic conditions, HVAC systems and ventilation in general focused mainly on energy monitoring, performance and energy savings, which are discussed in section 6 below.

## 6. Energy consumption in museums

Even though there are thousands of museums around the word with more than 10 billion annual visitors, researchers believe the field of museums studies should develop more as there is high demand particularly in the context of sustainability within museums [8,52]. To have an energy efficient museum building means to reduce energy consumption without putting the museum's collections at any risk [53]. Maintaining the required environmental conditions for artifacts all the time might not lead to the desired reduction in energy consumption in museum buildings in comparison to other types of regular buildings.

In Museums it is expected to have lower reduction in energy consumption due to the artifacts limitations, this also could be another fact that derived specialists to avoid this field of study. According to different studies, energy efficiency wasn't considered a priority in the field of museums in earlier times [52–54]. In fact, in a study conducted by the Museums Association in UK covering 704 different cultural projects funded by the Arts Council England (ACE), the highest carbon foot print in 2012–2013 was assigned to museum projects with an average of 1346 tone per museum [55].

With all the development that have taken place in the field of sustainability, some still believe that museum sustainability is only a subject that is just being talked with no implementations or real actions within this context [56]. According to Padfield et al. [8] the attention to energy efficiency in museums increased from 2005 and led to higher number of research in the field in 2010. In the UK, the Museums Association is playing a key role in this field by actively initiating studies targeting different UK museums and awareness programs for moving towards more environmentally friendly museums. In addition, the Arts Council England (ACE), which provides funding for UK based cultural projects, set up plans for making their funded projects more sustainable including reducing their costs and different aspects.

When addressing sustainable intelligent museums as a research scope, it is important to consider all aspects of sustainability and intelligence within the museums. The information related to different areas of the museums was discussed in the previous section. The following section is dedicated to showing the definitions and guidelines of sustainable buildings and intelligent buildings. Similarities and differences of each scope will be presented and most importantly upgrading existing museums into such buildings will be discussed. In this section studies discussing the different areas of museum indoor environments will be presented with particular focus on the sustainable and intelligent methods for the exhibition's environments.

### 6.1. Studies focused on energy efficiency of museums

Research into museum energy efficiency is varied in scope. Polo López and Frontini [57] examined ways and approaches to enhance the energy consumption in historic buildings by choosing 3 case studies. Their study did not focus on the indoor environment as much as it focused on the exterior elements such as renewable energy (benefiting from solar panels), sealing of windows as well as the insulation of the facades.

De Santoli [58] investigated the landscaping of cultural heritage and their impact on energy consumption. In his paper presented guidelines for historical buildings in terms of evaluating energy consumption, as well as, improvement methods for enhancing the energy performance of these buildings. These guidelines were focused to respect the historical preservation requirements of such buildings. These guidelines target the design engineers as well as the authorities in charge of the cultural historic buildings to help them adopt the strategies needed in each required stage. De Santoli [58] divided the procedure of enhancing energy performance of the historical buildings into four main stages; in the energy auditing stage as the first and most important step, author shows 3 different levels of making the audit and the time frame, characteristics and results each level will give. Second stage is the analysis stage which includes the analysis of building envelop, as well as the systems system and based on it the energy modelling to be done. After this stage the possible enhancements should be identified and examined based on considering winter and summer conditions and measure the before and after energy consumption differences based on the proposed solutions. Last stage would be deciding on whether the successful identified enhancements are feasible and worth to be implemented, and applying the change. Museum energy efficiency from lighting point of view was investigated by many other researchers [59–61]. In general, benefiting from daylight is an important aspect in sustainable projects in order to save energy and enhance indoor environments by providing proper colour rendering and visual comfort. However, when it comes to museums, this aspect becomes very crucial and challenging as artifact degradation is heavily dependent on light exposure, particularly UV radiation.

As discussed in section 4.1, studies investigating daylight within museum indoor exhibition environments, proved the negative impact of the existing daylight in museums on the artifacts. Helping the museums to adopt strategies to treat or design based on the special requirements for museums [13-15and62]. Muller [62] showed the possibility of energy reduction by benefitting from daylight factor by referring to the “Emil-Schumacher-Museum, Hagen”. According to Muller, skylights can provide more manageable lighting in terms of artifact preservation [62]. Integrating movable shading devices and having full control over daylight entering the museum environment is a critical point to be integrated with benefitting from daylight. The study provided information of the needed energy for lighting however, it lacked information on how much the reduction in daylight is causing to the light electricity or total electricity. Also, how these systems could be integrated without negatively impacting artifacts was not specified in the paper.

In terms of energy savings through artificial lighting, the study by Salata et al. [59] focused on the exterior lighting, specifically the energy monitoring and maintaining of the facades of historical buildings. Salata et al. [59] in their research examined an alternative lighting system for a chosen case study historical building where the existing lighting systems included metal halides, compact fluorescent and halogen lamps. The suggested alternative light was LED and scenographic lighting of the monumental façade. The proposed light were examined through DIALux Evo 4.0 and ecoCALC softwares in terms of lighting levels, investment cost and maintenance cost. The findings showed enhanced lighting levels for the proposed LED light and they match the standards more than the existing lights. As for the cost the proposed lighting requires higher upfront investment but the lower maintenance cost of lighting compromise the different. The study identified the period of 7 years for payback time for the suggested alternative.

Tavares and Coelho [60] and Somasekhar and Umakanth [61] focused on the museums' indoor lightings in their research. Tavares and Coelho [60] compared the energy consumption's rate, cost as well as other electricity charges for three types of lighting; 35 W Halogen, 20 W Halogen and 6 W LED lights. The lighting specifications and their impacts on artifacts were examined through software simulation based on a chosen case study exhibition room. The study showed the adoption of LED light to be the best in comparison to the other lighting types examined. Moreover, investment cost, annual energy consumption costs, maintenance costs as well as annual CO2 emissions were compared. The result showed much better conditions when adopting LED lights in terms of annual energy consumption (kWh), annual energy cost, annual maintenance cost, as well as the annual CO2 emissions. Only the LED upfront investment was much higher in comparison to the other lights, exact figures are presented in Table 3. Halogen 20 W lights would need 1.1 year while LED lights would take 1.8 years for return on investment. However comparing the results showed LED lights would be more energy and cost efficient in the long run.

On the other hand, Somasekhar and Umakanth [61] reduced the energy consumption of a museum by adopting PIR (Passive Infrared) sensors, in which lighting systems were connected to a network and the PIR system detected the presence of the visitors. Lights will be at their best maximum intensity when visitors are present consuming 300 mA of current. When no visitors are present and the exhibition is empty the lights will be dimmed and consumption will reduce to around 150 mA. Somasekhar and Umakanth concluded that by adopting this method 100 MW per day would be saved specially if it is a large scale project with a lot of lightings in use [61].

**Table 3**
Study results for different types of light [61].

| | 35 W Hal | 20 W Hal | 6 W LED |
|---|---|---|---|
| Investment Cost (€) | 37.36 | 37.36 | 145.12 |
| Annual Energy Consumption (kWh) | 509.6 | 291.2 | 87.36 |
| Annual Energy Cost (€) | 86.63 | 49.5 | 14.85 |
| Annual Maintenance Cost (€) | 13.60 | 13.60 | 5.28 |
| Annual CO2 Emissions (kg) | 188.04 | 107.45 | 32.24 |
| Payback Period (year) | – | 1.1 | 1.8 |

Aside from studying energy reduction from lighting point of view, some studies focused on HVAC systems and possibilities of enhancing the energy performance of museums through the HVAC. With regards to air conditioning and HVAC, Silva and Henriques [6] highlighted the importance of considering the local climatic conditions when considering the energy savings. According to [6] this factor was not considered in earlier researches. Their study showed that the HVAC system was not effective to provide a safe indoor environment in terms of temperature and relative humidity. However, the authors have carried a risk assessment procedure and identified low risk is caused to the collection based on the current HVAC. To enhance the conditions dynamic method (FCT-UNL) was applied and minimized the RH fluctuations. Based on the study the T and RH set points were also changed within a safe range to contribute in energy reduction. Moreover, the study emphasized the need to carry out long data collection period (more than one year) to obtain proper results in terms of having more than one record of each season.

The 2015 study by Rota et al. [63] concentrated on a single focus point in terms of energy savings of the museum's indoor environments.

On the other hand, Kramer et al. [64] studied energy efficiency from the possibility of changing the indoor environment set points for T and RH rather than focusing on HVAC itself. Their study considered the different artifact class categorization by AHSRAE (explained in section 3) and simulating 20 different weather files for different countries in Europe by considering 5 different museum building quality levels (from historical existing building until purpose built museums). Their study resulted in developing a setpoint algorithm enabling control over seasonal changes adopting the acceptable daily fluctuations of T and RH. Their study simulation resulted in energy saving from 53% for class AA until 74% for class B in AHSRAE class categorizations.

Recent publications indicated the crucial role of assessing multiple systems in the museum in terms of enhancing the energy performance of the museum. They monitored energy efficiency of 36 museum in Italy by considering the building's HVAC systems, lighting, renewable sources and new technologies as well as safety and security systems adopted in each. Based on their study, they developed a handbook for museum management to follow in terms of enhancing the museum's conditions. Ascione et al. [65] emphasized the same in their study, which was aimed at investigating the structural and energy performances behavior.

Ge at al [66]. Conducted a life cycle energy analysis for a museum that considered all stages of construction and other phases of the project. While Farreny et al. [52] study was based on comparing the amount of energy resources consumed in the museums rather than examining and evaluating the indoor environment elements. This study categorized the types of museum buildings and considered different types of resources (e.g. Electricity, natural gas, oil, etc.). The study also examined the water flow of each museum.

In a recent study by Khodeir et al. [67] identified the different phases and actions that should be taken in order to make sustainable retrofitting in Historical buildings

1 Initiation: is by setting a vision of what is to be achieved and evaluating current status of the targeted project.
2 Planning: includes seeking of solutions and designs to overcome the stated problems.
3 Seeking of alternatives: evaluating different options and alternatives to check the best options through assessing the options via simulation software.
4 Implementation of the final decision: to start the application on HB based on the best examined option.
5 Performance assessment: includes Mock-ups assessment if there are design changes, Risk assessment, Sustainable performance assessment (process performance, system performance, building performance, market performance, financial performance).

The recommendation of Khodeir et al. [67] provide a holistic approach for focusing on all aspects of the HB from the earliest stage of thinking of enhancements to settings goals for all stages. The necessity of having holistic approach was also emphasized by Litti and Audenaert [68] study as well, where they found many problems related to the museum environment as well as the building envelop of a museum in Antwep. Seeking alternatives was the key stage in order to achieve best results, which is similar to the findings in the study by Arroyo et al. [69].

In a different scope, Schijndel and Schellen [70], developed a simulation method for European museums and predicted their energy demand targeting the near future (2021–2050) and the far future (2071–2100) based on their recent past (1961–1990) performance. The result of the study included developing a basic map of all building and control types based on seven performance indicators: Indoor T, Indoor RH, Heating demand, Cooling demand, Humidification demand, Dehumidification demand and Total energy demand.

Based on the analysis done in this study relative total energy use was calculated. For museums using only heating systems 40% reduction for total heating demand was achieved for entire Europe. And for museums having cooling and heating systems, the reduction in relative energy use was 10% for North Europe. And South Europe will have increase of energy demand by 20%.

Some researchers investigated the prospects of adding renewable energy systems to historical buildings such as solar thermal and PV systems [71–74]. Using renewable energy in historical building poses unique issues mainly in terms of the visual impact of such systems on the appearance of such buildings. There have been examples when such integration was successfully achieved [71], Fig. 1. Still such additions are not common and need to be looked at closely on case by case bases. Thus such additions will not be discussed further in this paper.

From this section, the practice of upgrading museums to be more energy efficient and intelligent is a common method that has been practiced and studied. It can be implemented on already established and running museums rather than adopting strategies only for new practices.

## 7. Guidelines for enhancing Museum's energy efficiency

Guidelines for turning existing museums into sustainable projects have been released by different parties. These guidelines consider the wide scope of sustainability and provide step-by-step procedure helping the museums adopt and follow in order to enhance their current conditions. The South West Federation of museums and art galleries (SW Fed) in their guide to help meeting the accreditation requirements for museums in UK have depended on the carbon footprint method to achieve this [47]. The accreditation scheme is set of standards and code of practices to show the minimum requirements of actions to be done in museums. Following them will define the level of good quality practices as well as elevate the quality of different museums. The SW Fed guide for achieving Environmental sustainability for museums targets the following areas within museums and shows how to address them:

- Utilities
- Materials used/products sold
- Energy conservation
- Waste
- Transport
- Public programmes
- Awareness of environmental sustainability issues

On the other hand, the green museums step-by-step guide was prepared by the Museums, Libraries and Archives East Midlands, and Renaissance East Midlands organization [48]. This guide shows how sustainability can be achieved in 5 stages:

1 Monitoring Data
2 Walk around tool
3 Target Scorecard
4 Action plan
5 Implementation

This guide was implemented on 6 chosen case study museums provided in the same guide to assess the enhancement levels in terms of savings. This helps other museums on how the guidelines can be followed in each of the mentioned stages.

The 2011 study by De Silva and Henderson [75] targeting sustainability in the conservation section of the museum, have covered a more general and wide scope as well, and it is not limited to a certain specific aspect (for example: only lighting, or only HVAC systems). Different areas of the museum are linked and various parties get involved. Even visitors of the museum who are not in direct interaction with the conservation staff were included in this study. A recent study by Pencarelli et al. [76] emphasized the importance of considering all sustainability dimensions related to museum practices. The museum of English Rural life developed a template for calculating the Carbon footprints of museums in rural areas and made it available to the public to benefit from. This calculator considers the following points:

- The annual consumption of electricity, gas and oil.
- The capital investments per year (Museum expenditure for building,

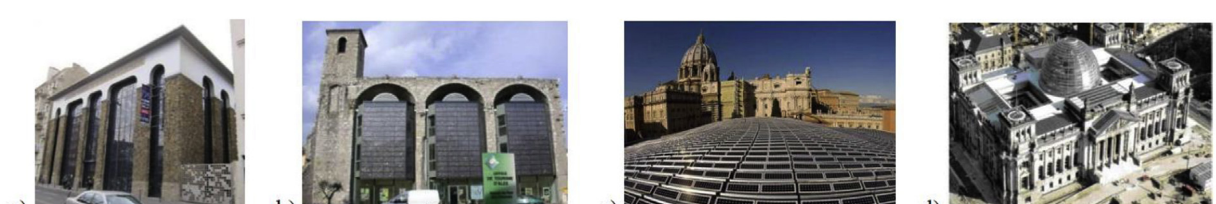

**Fig. 1.** Some examples of building integrated Photovoltaic system on historical buildings: (a) Hotel Industrial, Paris (France) (b) Tourist office, city of Alès (France) (c) Sala “Nervi”, Vatican City (Italy) (d) Reichstags building (Germany) [71].

equipment, etc)

- Commuting methods of staff.
- The commuting distances.
- The visitor's transportation method to reach to the museum.

Based on the mentioned points, the calculator shows the results of emission per square meter, per visitor and per full time staff. Additionally, from the mentioned guidelines and researches, it shows the practice of upgrading museums into sustainable projects, like other sustainability approaches, require wide scopes and it is not limited to a small area. Moreover, museums due to their cultural recognition and educational role can have a stronger impact for encouragements as well as driving the societies for adopting sustainable practices. Therefore, leading environmental friendly approaches are more expected form museums.

Other than the mentioned guidelines, organizations like the international community of museums (ICOM) in Europe are providing support and guidance for member museums in different aspects. The support is mostly in terms of helping the museums in their practices rather than provide funding opportunities. Depending on the museums and their conditions, experts from ICOM would help the museums upgrade their current conditions, get advises for best practices in terms artifact preservation and energy savings as well.

Beside the researches for setting guidelines for museum sustainability with their wide scope of activities, there are other studies conducted with detailed targets focusing on narrow subjects within the energy efficiency field.

## 8. Conclusions

This review paper has focused on the indoor environment quality of the exhibition halls in the museums. As shown, in the museums due to the presence of ancient artifacts having a well-controlled environment is a must. Based on different locations and the nature of the artifacts museums indoor environments conditions vary. These conditions also have changed over time based on different practices and conducting different researches. According to the UK standards [5] the thermal conditions are as follow:

- Temperature: min 18C to max 24C with allowing ± 4C change during the 24 h.
- Relative Humidity: average of 50% with allowing ± 10% change during the 24 h.
- Lighting Level: Very sensitive materials: 50 lux, sensitive materials 200 lux, insensitive materials: 300 lux.
- Pollutants: the most dangerous chemical/gaseous pollutants are Ozone, Sulphur dioxide and Nitrogen.

Moreover, due to the restricted and controlled environments the high energy consumption was a main concern for the researchers recently. As shown in this review paper, in term of lighting, there has been significant focus on changing from the halogen, tungsten light into using LED lights and more specifically to benefit from DALI systems. Allowing well studied and planned daylight to the indoor environment was a main focus to reduce energy consumption as well.

It is hoped that this review paper provides a rich guide with all the needed information in terms of museums indoor environments parameters for the museum officials to implement strategies and enhance the current conditions of the museums. And for researchers, to benefit from the researches reviewed as a base to further new researches within the related subjects presented here such as the IR impact and acceptable limits or the effectiveness of gas filters.

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