

Article

Preliminary Microclimate Monitoring for Preventive Conservation and Visitor Comfort: The Case of the Ligurian Archaeological Museum

Alice Bellazzi ^{*}, Benedetta Barozzi , Lorenzo Belussi , Anna Devitofrancesco , Matteo Ghellere ,
Claudio Maffè, Francesco Salamone  and Ludovico Danza 

ITC-CNR (Construction Technologies Institute of National Research Council of Italy), Via Lombardia 49, San Giuliano Milanese, 20098 Milano, Italy; b.barozzi@itc.cnr.it (B.B.); l.belussi@itc.cnr.it (L.B.); a.devitofrancesco@itc.cnr.it (A.D.); m.ghellere@itc.cnr.it (M.G.); c.maffe@itc.cnr.it (C.M.); francesco.salamone@itc.cnr.it (F.S.); l.danza@itc.cnr.it (L.D.)

^{*} Correspondence: a.bellazzi@itc.cnr.it

Abstract

The preservation of cultural heritage within museum environments requires systematic control and monitoring of indoor microclimatic conditions. Over the past four decades, scientific evidence has established the critical role of environmental parameters, including air temperature, relative humidity, light, and airborne pollutants, in the preventive conservation of artifacts. International standards and national guidelines mandate continuous, non-invasive monitoring protocols that integrate conservation requirements with the architectural and operational constraints of historic buildings. Effective implementation necessitates a multidisciplinary approach balancing artifact preservation, human comfort, and building energy efficiency. Recent international recommendations further promote adaptive approaches wherein microclimate thresholds are calibrated to site-specific “historical climate” conditions, derived from minimum one-year baseline datasets. While essential for long-term conservation management, the design and implementation of such monitoring systems present significant technical and logistical challenges. This study presents a replicable methodological approach wherein preliminary surveys and three short-term monitoring campaigns (duration: 2 to 5 weeks) supported design, sensor selection, and spatial deployment and will allow the validation of a long-term continuous monitoring infrastructure (at least one year). These preliminary investigations enabled the following: (1) identification of priority environmental parameters; (2) optimization of sensor placement relative to exhibition layouts and maintenance protocols; and (3) preliminary assessment of microclimate risks in naturally ventilated spaces in the absence of HVAC systems.

Keywords: environmental monitoring; preventive conservation; visitor comfort; multidisciplinary approach; museum



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1. Introduction

During the last forty years, awareness of the importance of controlling the indoor environment to ensure the preservation of collections and artifacts in museums has significantly increased [1]. Maintaining stable and appropriate microclimatic conditions is essential to preserve exposed or stored artworks and avoid different types of deterioration [2]. High temperatures, electromagnetic radiation (UV radiation, blue visible light), and several gas pollutants can accelerate the degradation rate of some materials, in particular the organic

ones; conversely, high humidity levels can improve hydrolysis in synthetics, corrosion of metal, and microbiological growth. Therefore, monitoring these parameters in museums is fundamental, seeking cost-effective commercial solutions [3,4]. Preventive conservation involves “all measures and actions aimed at avoiding and minimizing future deterioration or loss. They are carried out within the context or on the surroundings of an item, but more often a group of items, whatever their age and condition. These measures and actions are indirect—they do not interfere with the materials and structures of the items. They do not modify their appearance” [5,6]. This definition, also adopted by CEN/TC346 [7] with the EN 15898 Standard [8], emphasizes preserving artifacts indirectly through actions and measures carried out within the environment.

In Italy, Ministerial Decree 113 of 21 February 2018 [9] provides Uniform Quality Levels (LUQ) for museums, citing among the various minimum standards the requirement for continuous monitoring of the indoor microclimate (temperature, relative humidity, and lighting). The decree resulted from collaboration among the ministry, regions, local authorities, and museum professionals, including researchers and experts. It is based on the Decree of the Ministry of the Cultural Heritage and Activities of Italy, 10 May 2001 [10], and UNI 10829:1999 [11], which suggests parameters to be respected for the effective preservation of cultural heritage artifacts. These guidelines assist curators in identifying the optimal temperature and relative humidity ranges to preserve artifacts, even if each case must be carefully analyzed and ranges considered as an indication. In certain situations, particularly when an object has long been acclimated to specific historical climate conditions, it is preferable to maintain those established conditions rather than conform strictly to standardized values. Altering the environment in such cases may subject the artifact to climatic stress, potentially triggering deterioration due to sudden changes [12]. EN 15757 [13], based on Camuffo [14], defines “historical climate” as “climatic conditions in a microenvironment where a cultural heritage object has always been kept or has been kept for a long period of time (at least 1 year), and to which it has become acclimatized”. The standard explains that a material stored in a poor-quality environment could acclimate to that condition, and, even if a new condition appears better for preservation, changing from a historical climate could be problematic. The strategy is to maintain a microclimatic condition if it is proven not harmful. Since Camuffo’s theory, the tendency has been to adopt more tolerable ranges, tailored to the specific artifacts. For example, in 2023, members of the Bizot Green Protocol [15] stated that every museum should be encouraged to use innovative, tailor-made methodologies suited to its unique collection, architecture, and operational needs, moving away from blanket conditions toward customized criteria. Museums should adopt long-term, environmentally sustainable collection care approaches tailored to each artifact and local climate. The Australian Institute for the Conservation of Cultural Material—AICCM [16] ratified national environmental guidelines for Australian cultural heritage collections, emphasizing sustainability, resilience, and adaptive and proactive practices. They provide temperature and relative humidity ranges for humid and temperate climates and encourage setting temperature and relative humidity parameters that respond to local conditions. Similarly, ASHRAE [17] introduces five climate control classes, defining permissible ranges of temperature and relative humidity. This flexible classification system helps museums set control targets that are economically viable and energy efficient.

Planning the intervention is challenging, also because museums are often housed in historical or artistic buildings [12,18–20], especially in the Mediterranean Area [21]. In Italy, 71.6% are located in buildings with high historical and artistic value: for the 27.2% of interviewees, the buildings and the collections equally attract visitors, while 19.2% believe that the structure itself is the main attraction for the public [22]. These historical buildings typically have thick walls and limited glazing, ensuring more stable internal

temperatures and better lighting control, but often suffer from condensation problems, and it is difficult to manage the sudden microclimate changes due to many visitors when they are not properly ventilated. At the same time, their protected status as cultural heritage makes installing HVAC systems difficult [21,23]. Famous museums are more sensitive to these aspects, but smaller ones, representing the majority, often lack the resources to monitor internal environmental conditions and lack HVAC systems [23]. Improvement strategies must consider correlations between external climate, artifacts conservation status, building envelope characteristics, and existing technical systems. Every museum presents a distinct and individual scenario [21,23].

EN 16893 [24] specifies building requirements for cultural heritage preservation, including structural, environmental, and safety aspects. Renovation must prioritize sustainability, considering the whole life cycle cost, energy use, water consumption, carbon emissions, and maintenance costs during the building's useful life. The standard emphasizes assessing risks associated with both the building and collections, including environmental conditions (temperature, humidity, light, and pollution), biodeterioration (pests and mold), theft, vandalism, fire, water, and natural events. Developing an environmental management strategy requires evaluating collection needs, duration, and the energy requirements, considering sensitivity and importance: value, use, state of conservation, previous environmental conditions, and vulnerability. The standard highlights how continuous monitoring is essential for collection protection. At the same time, it is important to guarantee adequate environmental conditions not only to preserve artifacts but also to ensure the comfort of visitors and staff [25,26]. Museums are visited by numerous people and are becoming increasingly dynamic spaces, making visitors protagonists of immersive experiences. Balancing artwork preservation with occupant comfort is crucial [27]. When the museum is a historical building, preserving the structure itself is also important [25]. There is increasing interest in this topic [28–34], highlighting that conservation, human comfort, and energy efficiency are compatible through rational planning, interdisciplinary cooperation, and a deep understanding of the building and its collections [26].

This research outlines a preliminary phase conducted at the Ligurian Archaeological Museum in Genoa (Italy), comprising surveys and three short-term monitoring campaigns aimed at characterizing the indoor environment, artifacts, conservation practices, and the dynamics of key environmental parameters. The primary purpose of this phase was to generate a robust knowledge base for the design, validation, and implementation of a long-term monitoring system compliant with EN 15757 [13], enabling the reconstruction of historical climate conditions. These investigations also informed the selection of parameters and sensors and their optimal placement, while identifying critical issues and potential intervention strategies, thereby substantiating the necessity of continuous environmental monitoring [23].

2. Materials and Methods

The methodology followed to design the long-term monitoring campaign is divided into the following four steps:

1. Surveys and inspections: identification of critical/significant artifacts and monitoring needs, involving the curator in the process. During this phase, artifacts' location (showcases or open environment) and the space logistics (visitor flow, HVAC systems) were analyzed. Technical challenges include installation constraints (size, security, and power source), which heavily influence sensor choice.
2. Monitoring parameters and target values: preliminary ranges for human comfort and artifact preventive conservation were defined based on the information collected

during surveys and inspections and the main standards requirements. This range will be adjusted after one year of data analysis.

3. Sensors selection and installation: selection of the sensors to monitor the selected parameters, ensuring compliance with exhibition requirements and technical feasibility.
4. Data analysis: preliminary analysis of daily trends, fluctuations, and compliance with selected ranges.

All the information collected supported the design of the long-term monitoring campaign, especially in the selection of the best sensors to be integrated into the showcase respecting the exhibit requirements, placement, costs, and technical feasibility.

2.1. Surveys and Inspections

Surveys and inspections permit us to determine and know exactly what needed to be monitored and to identify the main logistical and technical constraints (Table 1). Each artifact was analyzed, its constituent materials cataloged, and its display conditions recorded (open environment or display case, airtightness, accessibility for maintenance, internal lighting, and electrical connections). The layout of the rooms, visitor flows, and the presence of HVAC systems were also assessed. The main constraints concerning the future feasibility of installing sensors are listed.

Table 1. Survey framework for sensors selection.

Survey Domain	Relevant Survey Parameters	Technical and Operational Constraints
Kind of artifacts	Type and complexity of artifacts (different materials, significance) to identify the technical requirements of the sensors to be installed	Technical requirements of the sensors typology to be installed: accuracy, range of measurements, resolution
Typology of show cases and environmental layout and features (Hvac and lighting systems)	Aesthetics, Invasiveness, Exhibition requirements, Security, Connections, Superintendency interventions and requirements	Technical requirements of the sensors network to be installed: type of power management, type of connection etc

The Ligurian Archaeological Museum is located in Genoa, in the western part called Pegli, and is housed in the Villa Durazzo Pallavicini park and Museums. The historic villa was donated to the Municipality of Genoa in 1928 by the Pallavicini heirs on the condition that it be used for cultural purposes. This led to the creation of the most important archeological museum in Liguria, inaugurated in 1936. Exhibited remains and artifacts include Paleolithic burials, the rich grave goods of the necropolis of Genoa, and the famous “Table of Polcevera” [35]. The museum has a massive brick structure and, except for one room, it is not air-conditioned. It is open Tuesday to Friday from 9:00 a.m. to 5:00 p.m. and Saturday and Sunday from 11:00 a.m. to 5:00 p.m. Visitors are often small school groups: typically two classes in the morning and one in the afternoon.

The monitoring campaign was carried out in two different environments: a first-floor room identified by the museum curator for the importance of the remains it contained, such as several tomb remains inside showcases, including the skeleton of the Prince of Arene Candide, hereinafter called the “PoAC room”, and the third-floor deposit, noted for the importance of the artifacts stored and infiltration problems.

The PoAC room measures 74 m² with a ceiling height of 6.15 m (Figure 1). The room is not air-conditioned and has 3 windows that are always covered by curtains. There are four showcases containing tomb remains dating to the Paleolithic period. Two are particularly noteworthy: one holds the remains of the Prince of Arene Candide and another contains the remains of a child.

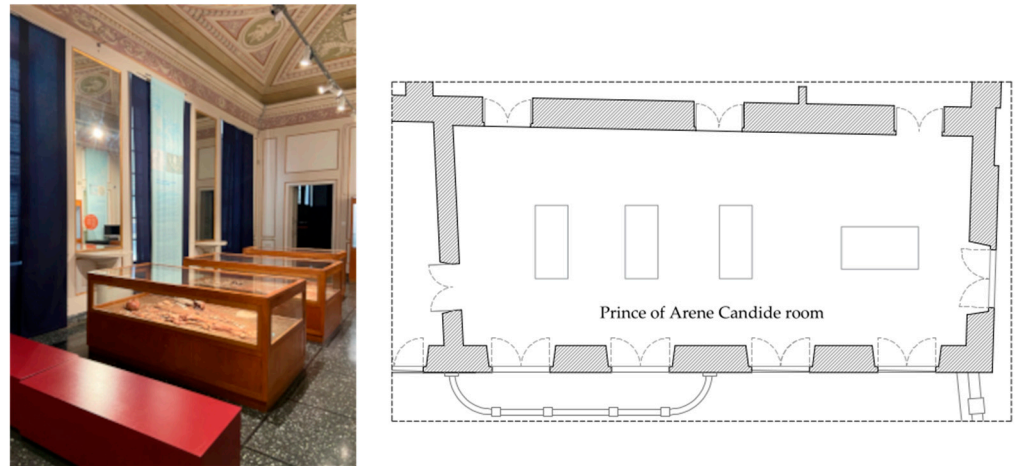


Figure 1. Prince of Arene Candide room view.

The Prince of Arene Candide was a young hunter–gatherer dated to approximately 28,000 years ago (Upper Paleolithic). He was discovered in the Arene Candide Cavern, in Finale Ligure, Savona, Liguria, Italy. The burial is remarkable for its rich grave goods: thousands of pierced shells sewn onto a headdress, mammoth ivory pendants, four “pierced staffs,” and a long flint blade.

The showcases are not airtight, and they do not have internal lighting, so it is possible to consider that they reflect the microclimate condition of the room [23]. For this short-term monitoring campaign, it was possible to monitor the environmental conditions of the room, assuming they correspond to those inside the showcases, but with the long-term monitoring campaign, this will be verified by comparing showcase internal and external data measurements, with the support of a portable sensor.

The deposit located on the third floor is important because it preserves metal materials, ashes, wooden poles, and other easily perishable organic material. The room measures 21 m² with an average height of 2.73 m and has two small, shaded windows (Figure 2). This area requires particular attention due to severe water infiltration from the roof, which has led to mold formation.



Figure 2. Deposit view.

The three short-term monitoring campaigns were conducted in the following different seasons:

1. Spring: from 16 April to 8 May 2024 in the PoAC room and from 16 to 23 April in the deposit.
2. Summer: from 23 July to 27 August 2024 in the PoAC room and deposit.
3. Winter: from 8 to 22 January 2025 in the PoAC room and deposit.

2.2. Monitoring Parameters and Target Values

Maintaining artifacts within specific environmental ranges supports their preventive conservation, although these ranges should be treated as guidelines. Numerous standards provide suggested environmental target ranges, but selecting the most appropriate parameters requires careful consideration. An artifact may consist of different materials with varying requirements, or the same showcase may contain multiple artifacts made of different materials. This complexity increases when it is necessary to ensure both the preventive conservation of artifacts and human comfort.

Based on standards for human comfort and artifact conservation and considering the specific requirements of each artifact and context, distinct target ranges were defined for each showcase and environment. These ranges support data analysis and the configuration of alert systems, useful in the data analysis and in the definition of alerts for museum curators as follows:

- Green: the measured value falls within the established value;
- Yellow: the measured value is within an alert range;
- Red: the measured value is outside the required range.

2.2.1. Range of Parameters for Human Comfort

For rooms with visitors, the Category II comfort class of EN 16798-1:2019 [36] for hygrothermal requirements ($PPD < 10$; $-0.5 < PMV < +0.5$ [37]) was considered. Temperature set points were 20 °C in winter and 26 °C in summer, with a humidity range of 50–60%. CO₂ (carbon dioxide), primarily emitted by human respiration, has no significant effect on artifacts, but values above 1000 ppm indicate inadequate ventilation and may lead to adverse effects on humans, particularly during prolonged exposure [19]. EN 16798:2019 also provides a maximum indoor CO₂ concentration difference for each category compared to outdoor levels. For example, to meet Category I, the maximum delta is 550 ppm, assuming an outdoor concentration of 400 ppm and a standard emission rate of 20 L/h per person. Considering an outdoor concentration of 400 ppm, the threshold limit was set to 950 ppm.

Regarding Indoor Air Quality (IAQ), the WHO Global Air Quality Guidelines (AQG) (<https://www.who.int/publications/i/item/9789240034228>, accessed on 20 June 2025)—Particulate Matter (PM) [38] recommend annual and 24 h average levels of PM and propose incremental targets for highly polluted outdoor environments. The following thresholds were selected: the recommended PM_{2.5} AQG annual level is 5 µg/m³, and the 24 h level is 15 µg/m³; the PM₁₀ AQG annual level is 15 µg/m³, and the 24 h level is 45 µg/m³.

Focusing on lighting aspects, EN 12464 [39] specifies the minimum illuminance (E) requirement for the museum of 300 lux. While exhibition lighting is determined by display requirements, a value between 300 and 500 lux can be considered acceptable for visitors. Higher values could cause glare and excessive brightness, while lower levels could impair the ability to perceive objects' shapes and colors correctly. A compromise is necessary: sufficient light is required for visitors to enjoy the exhibitions, but it must be controlled to

preserve artifacts, as light can cause cumulative and irreversible deterioration of a wide range of materials [40].

Combining all this information, the range in Table 2 was selected.

Table 2. Target ranges—users comfort.

	Ta _{winter} (°C)	Ta _{summer} (°C)	RH _{winter} (%)	RH _{summer} (%)	CO ₂ (ppm)	PM _{2.5,24h} (µg/m ³)	PM _{10,24h} (µg/m ³)	E (lux)
	19–22	24–26	40–50	50–60	<950	<15	<45	300–500
	<19 or >22	<24 or >26	<40 or <60	<50 or <70	<1200	<20	<50	<300 or >500
	<18 or >23	<23 or >27	<30 or >60	<40 or >70	>1200	>20	>50	<200 or >1000

2.2.2. Range of Parameters for Artifacts

Regarding artifact preservation, each material was compared with the environmental range required by D.M. 10.05.2001 [10] and UNI 10829:1999 [11]. Since an artifact may be composed of different materials, it can be challenging to define the optimal range to be respected. In consultation with the museum curator, artifacts were classified based on their composition and materials, as well as age, state of preservation, and historical value. This approach made it possible to define a scale of priority that determines the range to be maintained.

The reference parameters recommended by UNI 10829 and D.M. 10.05.2001 are air temperature (Ta, °C) and relative air humidity (RH, %). UNI 10829 also recommends maximum daily range ($\Delta T_{a,max}$ and ΔRH_{max}), maximum illuminance (E_{max} , lx), maximum amount of ultraviolet radiation (UV_{max} , mW/lm), and maximum annual light dose (LO_{max} , Mlx/h yr). For indoor air quality parameters, CO₂ and particulate matter concentrations are also considered. All the material inside the showcases was cataloged and compared with the ranges specified by UNI 10829 and D.M. 10.05.2001, as illustrated in Tables 3 and 4. An average value between the requirements of the different materials and the standard recommendation was selected, based on a comparison with the museum curator (Tables 5 and 6). This process was repeated for all the showcases and rooms.

The consultation with the curator of the museum made it possible to classify the different requirements of each artifact and determine the optimal range for each case, ensuring the protection of the most vulnerable items (Table 4).

The third-floor deposit contains open metal shelving and wooden crates, holding various materials. In collaboration with the museum curator and by analyzing the standard requirements (Table 5), the optimal ranges for protecting the stored artifacts were defined (Table 6).

Table 3. Parameters UNI 10829 Standard—display case of the ‘Prince of Arene Candide’.

Material of Preserved Artifacts	Ta (°C)	ΔTa _{max} (°C)	RH (%)	ΔRH _{max} (%)	E _{max} (lx)	UV _{max} (μW/lm)	LO _{max} (Mlx/h yr)	Ref. Standard UNI 10829:1999	Ta (°C)	RH (%)	Ref. D.M. 10.05.2001
Skeletal remains	<4	-	Into saturated air	-	-	-	-	Organic materials from wet excavation areas (before treatment)	19–24	45–65	Ivories and bones
	21 ÷ 23	1.5	20 ÷ 35	-	50	75	0.2	Dried animals, anatomical organs, and mummies			
Faunal remains	21 ÷ 23	1.5	20 ÷ 35	-	50	75	0.2	Dried animals, anatomical organs, and mummies	15–21	45–60	Furs and feathers
	4 ÷ 10	1.5	30 ÷ 50	5	50	75	0.2	Furs and feathers, taxidermied animals, and birds			
Mammoth ivory ornaments Elk horn artifacts, shell, and deer-element ornaments Marine shells and faunal elements	19 ÷ 24	1.5	40 ÷ 60	6	150	75	0.5	Ivories, horns, malacological collections, eggs, nests, and corals	19–24	45–65	Ivories and bones
Soil and rocks from the burial excavation	19 ÷ 24	-	40 ÷ 60	6	NR *	-	-	Stones, rocks, minerals, meteorites (non-porous), fossils, and stone collections	≤30	45–60	Mineralogical collections, marbles, and stones

* NR: Not Relevant.

Table 4. Parameters UNI 10829 Standard—deposit.

Material of Preserved Artifacts	Ta °C	ΔTa _{max} °C	RH %	ΔRH _{max} %	E _{max} lx	UV _{max} μW/lm	LO _{max} Mlx/h anno	Ref. Standard UNI 10829:1999	Ta (°C)	RH (%)	Ref. D.M. 10.05.2001
Ceramics	NR	-	NR	10	NR	-	-	Porcelains, ceramics, stoneware, terracotta, and tiles (non-excavated, and excavated if demineralized)	-	-	-

Table 4. Cont.

Material of Preserved Artifacts	Ta °C	$\Delta T_{a_{max}}$ °C	RH %	ΔRH_{max} %	E_{max} lx	UV_{max} $\mu W/lm$	LO_{max} Mlx/h anno	Ref. Standard UNI 10829:1999	Ta (°C)	RH (%)	Ref. D.M. 10.05.2001
Bronze, Iron, and Silver Artifacts (or Metal Artifacts)	NR *	-	<50	-	NR *	-	-	Metals, polished metals, metal alloys, silver items, armors, weapons, bronzes, coins, marble objects, tin, iron, steel, lead, and pewters	-	-	-
Faunal Remains and Bone Artifacts	21 ÷ 23	1.5	20 ÷ 35	-	50	75	0.2	Animals, dried anatomical organs, and mummies	19–24	45–65	Ivories and bones
Vegetal Remains (Wood, Seeds, and Charcoals)	19 ÷ 24	1.5	45 ÷ 60	4	150	75	0.5	Unpainted wood sculptures, wicker objects, and wood or bark panels	19–24	40–65	Wood
Stone Artifacts and Amber Objects	19 ÷ 24	-	40 ÷ 60	6	NR *	-	-	Stones, rocks, minerals, meteorites (non-porous), fossils, and stone collections	≤30	45–60	Mineralogical collections, marbles, and stones
Glass Paste Objects	20 ÷ 24	1.5	40 ÷ 45	-	150	75	0.5	Unstable glass, iridescent, sensitive, and sensitive glass mosaics		25–60	Glass and stable glazing

* NR: Not Relevant.

Table 5. Target ranges—display case of the ‘Prince of Arene Candide’.

	Ta (°C)	$\Delta T_{a_{max}}$ (°C)	RH (%)	ΔRH_{max} (%)	CO ₂ (ppm)	PM _{2.5} _{24h} ($\mu g/m^3$)	PM ₁₀ _{24h} ($\mu g/m^3$)	E_{max} (lux)	UV_{max} ($\mu W/lm$)
	20–23	1.5	45–55	6	<950	<15	<45	<50	<10
	<20 or >23	1.5	<45 or >55	6	<1200	<20	<50	<70	<75
	<19 or >24	1.5	<30 or >60	>6	>1200	>20	>50	>70	>75

Table 6. Target ranges—deposit.

	Ta (°C)	ΔTa _{max} (°C)	RH (%)	ΔRH _{max} (%)	CO ₂ (ppm)	PM _{2.5,24h} (μg/m ³)	PM _{10,24h} (μg/m ³)
	20–23	1.5	45–60	<4	<950	<15	<45
	<20 or >23	1.5	<45 or >60	>4	<1200	<20	<50
	<19 or >24	1.5	<40 or >65	>6	>1200	>20	>50

2.3. Sensor Selection and Installation

Sensors must comply with the performance requirements suggested by standards such as UNI EN 7726 (general monitoring [41]), UNI 10829 [11], and UNI EN 15758 [42], which provide additional guidance on temperature measurements for monitoring campaigns within the museum.

For short-term monitoring, where larger equipment can be tolerated for limited periods, it is easier to identify sensors that meet the required specifications. Portable dataloggers connected to high-performance probes can be installed in selected areas of the environment to be monitored, balancing representativeness, security, and exposure needs.

Short-term monitoring was carried out using a microclimatic station and two indoor air quality stations (Figure 3) capable of measuring not only temperature, relative humidity, and air velocity, but also the concentration of CO₂, PM_{2.5}, and PM₁₀.

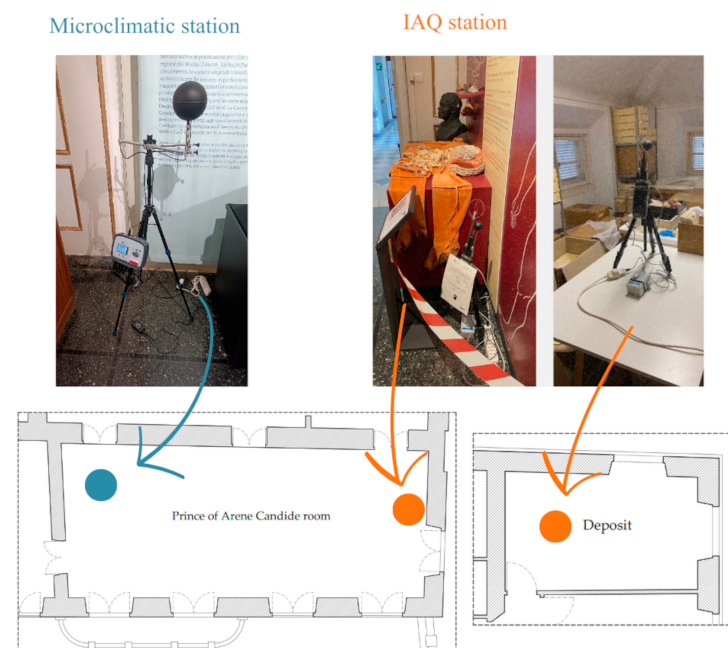


Figure 3. Position of the monitoring stations.

1. Microclimatic Station [43]: a datalogger with a globe thermometer probe [44] (PT100 sensor), $\Phi 150$, for measuring the globe temperature; a combined temperature and relative humidity probe [45], capacitive RH sensor (5–98%, $\pm 0.1\%$), Pt100 temperature sensor ($-10\text{ }^{\circ}\text{C}/80\text{ }^{\circ}\text{C}$, $\pm 0.01\text{ }^{\circ}\text{C}$); an omnidirectional hot-wire probe [46] for measuring air velocity (0–5 m/s, $\pm 0.3\text{ m/s}$); a photometric probe [47] for measuring illuminance (0.1–200,000 lux). One of these was placed in a corner of the PoAC Room.
2. IAQ Station [48]: a datalogger with Particulate Matter PM₁, PM_{2.5}, and PM₁₀ Transmitter and a combined CO₂ (0–5000 ppm, $\pm 50\text{ ppm} + 3\%$), relative humidity (0 ÷ 100%, $\pm 2\%$), temperature ($-20\text{ }^{\circ}\text{C}/80\text{ }^{\circ}\text{C}$, $0.1\text{ }^{\circ}\text{C}$), radiant temperature ($-30\text{ }^{\circ}\text{C}/120\text{ }^{\circ}\text{C}$, $0.1\text{ }^{\circ}\text{C}$), atmospheric pressure probe (300 ÷ 1250 hPa, $\pm 0.5\text{ hPa}$), TVOCs index (0–500). One of these was placed in a corner of the PoAC Room and one in the middle of the deposit.

These stations were supplemented by spot measurements of illuminance and UV radiation (Figure 4) using the portable luxmeter HD2102.2, equipped with a combined probe for measuring illuminance (E, 0.3–200 klux) and irradiance (UV, 0.1–2000 W/m²) in the UV-A spectral range (315–400 nm). The probe provides both the direct measurement of UV irradiance in $\mu\text{W}/\text{cm}^2$ falling on the sensor and the relative UV index in $\mu\text{W}/\text{lm}$ associated with the illuminance. Measurements were taken using a tripod on a grid of points representative of the room and of the illumination on the showcases.

With the long-term monitoring design, the selection process is more complex. Sensors must meet the required performance standards while also complying with the museum's display constraints. It is important to consider the limitations imposed by the size of the showcases, the visual impact of the sensors, maintenance requirements, and necessary connections. As described in Section 3.3, the short-term monitoring presented in this paper, combined with the knowledge gained about the environments and the artworks, led to the choice of sensors and their placement.

2.4. Data Analysis

Data are collected every 15 min, and hourly averages are calculated. In accordance with UNI 10829 [11]. The following indices are computed:

- The Deviation Index (DI) relates to conservation conditions and is evaluated as the percentage of time (or the percentage of measured data points) during which the detected environmental parameters fall outside the acceptable range of values.
- Frequency percentage describes the percentage of time in which a parameter falls in a specific range.

As described in [49], the Global Performance Index (PI) is also calculated, representing the percentage of time both Ta and RH remain within a specific range. For air temperature and relative humidity, daily gradients are calculated and compared with the limits required by the UNI 10829. Additionally, variations in internal temperature and relative humidity with respect to the external conditions are analyzed to assess the influence of the building envelope. Due to historical and conservation restrictions, it was impossible to install a weather data logger on the museum's roof, so data provided by the Regional Agency for Environment Protection of Liguria Region (ARPAL) were used [50].

Hourly average IAQ parameters were analyzed. For CO₂, the hourly data are compared with the required limits. For particulate matter, daily values are calculated and analyzed.

For lighting analysis, the distribution of illuminance and UV values across a grid of points is compared with human comfort ranges and artifact preservation requirements. In cases where only artificial light is present, annual light exposure is calculated by multiplying the maximum illuminance by the number of working hours.

3. Results

In parallel with the analysis of the indoor data, the external weather conditions of each monitoring period were examined (Table 7).

Table 7. Weather data—ARPAL meteorological data.

Period	T _{mean} (°C)	T _{max} (°C)	T _{min} (°C)	ΔTa _{24h,max} (°C)	RH _{mean} (%)	RH _{max} (%)	RH _{min} (%)	ΔUR _{24h,max} (%)	Rad _{max} W/m ²	Rain
Spring	13.5	25.5	6.0	11.2	68.2	96	15	60	780	Cumulative: 101 mm, with 56 mm on May 1st–2nd and a peak on 7th with 17 mm
Summer	26.6	35.0	19.5	11.40	68.9	91	36	47	742	Cumulative: 18 mm
Winter	8.61	16.9	3.0	8.90	65.2	92	27	50	394	Cumulative: 66 mm

3.1. Prince of Arene Candide Room

Analyzing the DI and Frequency percentage [11] for air temperature and relative humidity (Figures 4–6, pie charts), air temperature meets the required ranges for only 4%

measurements during the intermediate season, and for 21% falls within the yellow range, but never during summer or winter. RH, however, remains within the green or yellow range at higher percentages in every season, revealing a critical issue, especially in summer, with 67% of values out of range. When both parameters are analyzed simultaneously, as suggested by Corgnati [49], the required range is practically never met, except for a few cases during spring, and never during summer and winter. Furthermore, human comfort ranges are not respected, with temperatures too high during the summer and too cold during the winter. During the summer monitoring period, air temperature lies within the 29–30 °C range for 82% of the measurements, exceeding 30 °C for 6% of the time. Relative humidity is within the 60–70% range for 83% of the recordings, exceeding 70% for 9%. Conversely, during winter, excessively low values are observed. Air temperature is consistently below 16 °C, with values dropping below 14 °C for 29% of the measurements. Relative humidity lies within the 20–40% range for 42% of the observations.

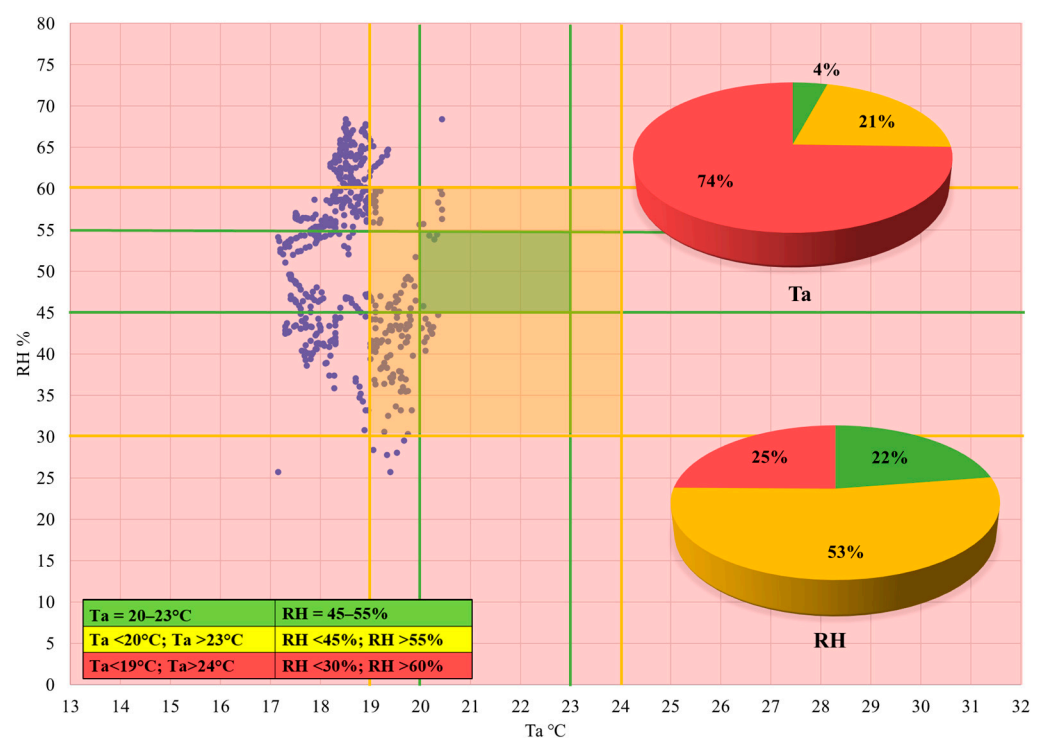


Figure 4. PoAC room—deviation index and frequency percentage, spring (16 April to 8 May). The colored areas indicate different compliance levels: green for conditions within the required range, yellow for the alert zone, and red for critical values outside the recommended limits.

However, analyzing the daily gradients (Table 8), temperature shows limited fluctuations, exceeding the daily limit of 1.5 °C only on three days during the summer period. The presence of very thick solid-brick walls, combined with the absence of ventilation, results in a high average indoor temperature with very limited fluctuations. Analyzing the maximum and minimum values during the summer monitoring period, the outdoor air temperature ranges from a maximum of 35 °C to a minimum of 19.5 °C (Table 7), whereas the indoor temperature shows a maximum of 30.9 °C and a minimum of 28.9 °C, with a very limited excursion in the period. RH is more critical, exceeding the limit for almost all the days during these monitoring campaigns. The presence of visitors and the absence of ventilation increase the internal fluctuations, with a maximum of 76.5% and a minimum of 30.6% in the period.

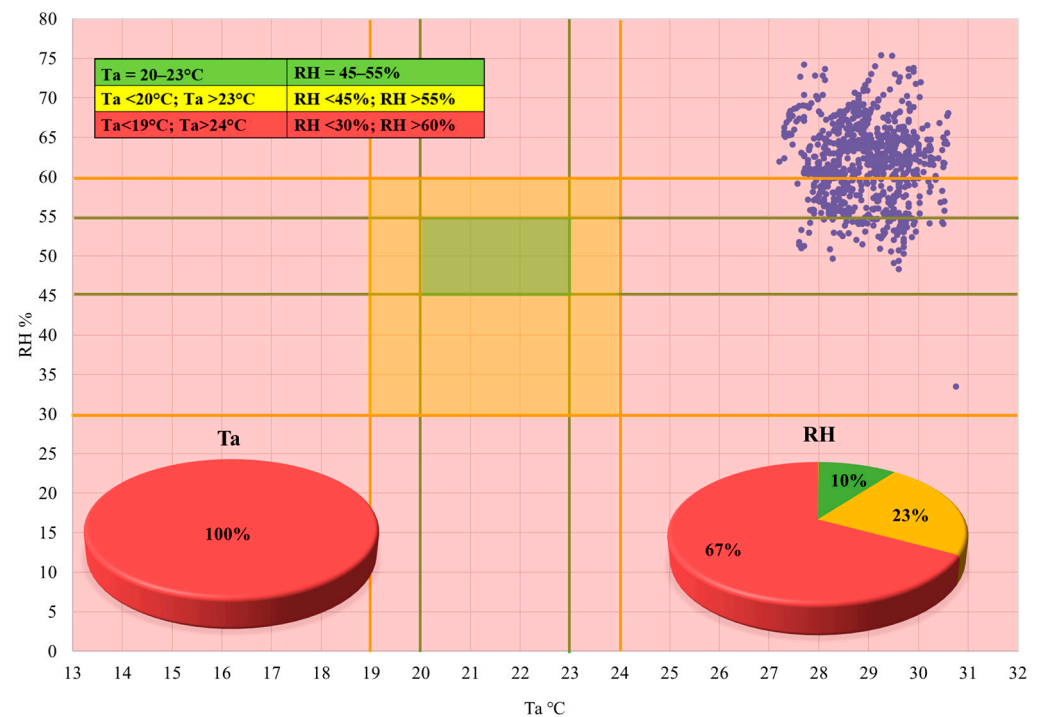


Figure 5. PoAC room—deviation index and frequency percentage, summer 23–27 July. The colored areas indicate different compliance levels: green for conditions within the required range, yellow for the alert zone, and red for critical values outside the recommended limits.

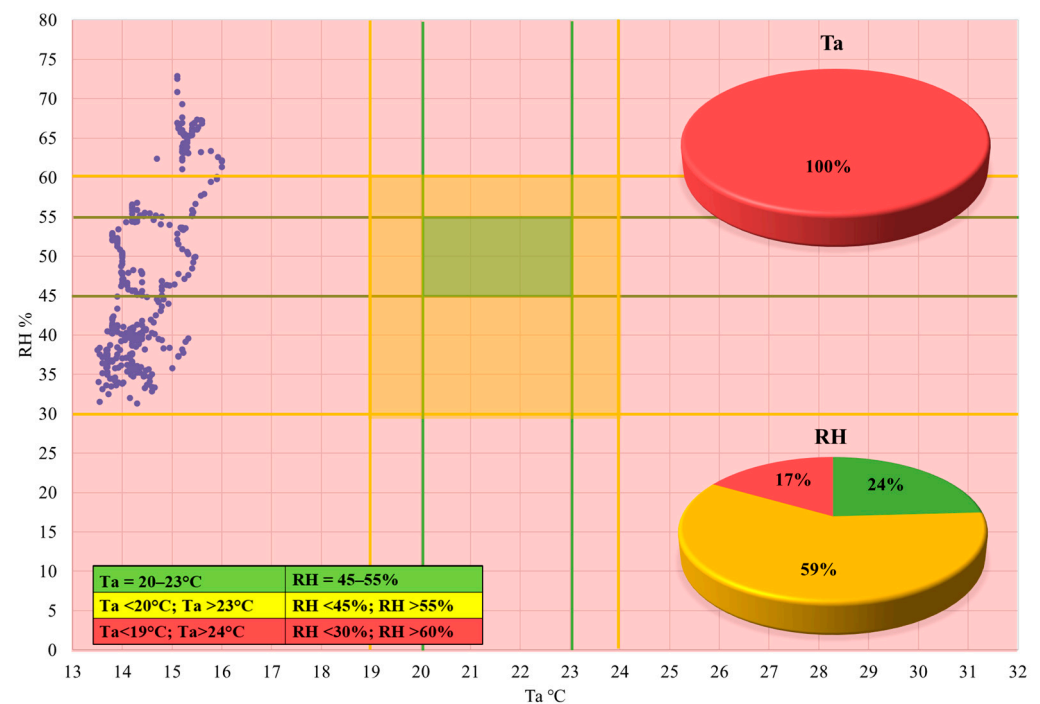
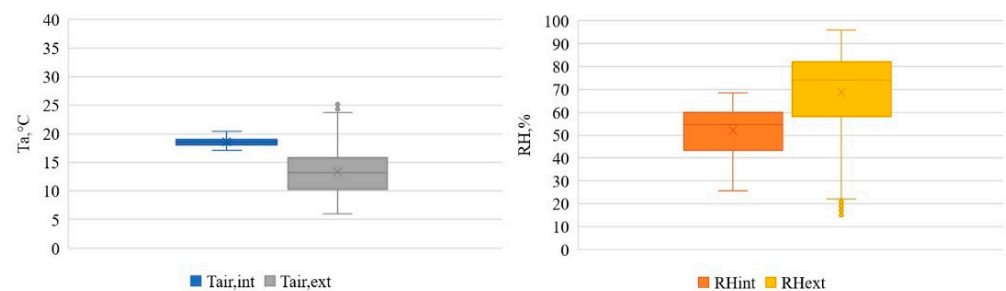
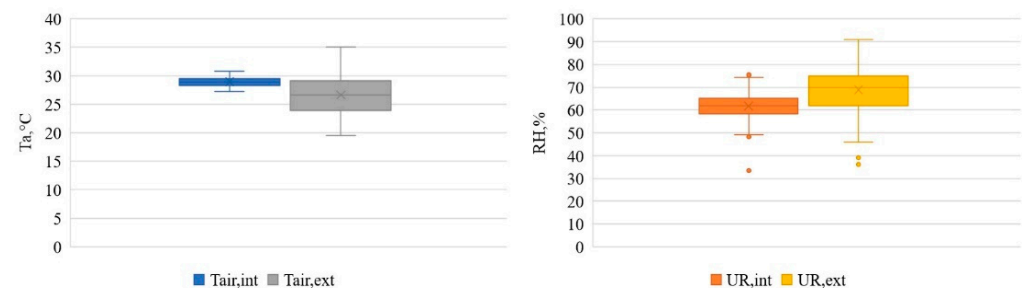
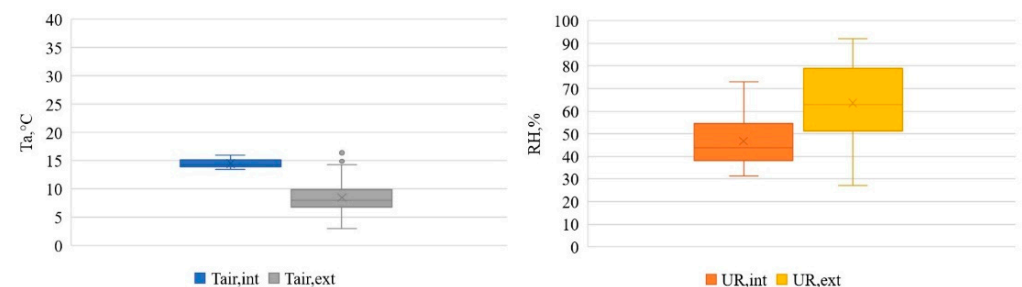


Figure 6. PoAC room—deviation index and frequency percentage, winter 8–22nd of January. The colored areas indicate different compliance levels: green for conditions within the required range, yellow for the alert zone, and red for critical values outside the recommended limits.

Table 8. Daily temperature and relative humidity gradients—PoAC room.

	T_{mean} (°C)	T_{max} (°C)	T_{min} (°C)	$\partial T_{24\text{h,max}}$ (°C)	N° Days $\Delta > 1.5$ °C	St.dev.T (°C)	RH_{mean} (%)	RH_{max} (%)	RH_{min} (%)	$\partial UR_{24\text{h,max}}$ (%)	N° Days $\Delta > 4\%$	St.dev.RH (%)
Spring	18.6	20.6	17.0	1.2	0	0.75	52.3	68.8	23.8	20.7	22/23	9.57
Summer	28.9	30.9	27.2	2.20	3	0.74	61.8	76.5	30.6	41.10	36/36	5.02
Winter	14.5	16.0	13.4	1.50	0	0.61	47.6	73.8	29.5	13.80	14/15	10.58

The box plots (Figures 7–9), clearly illustrate that, despite the more significant external variations in temperature and relative humidity, internal temperature fluctuations are reduced and contained, while relative humidity fluctuation are higher, especially during spring and winter. This is also confirmed by the standard deviation of temperature, which is 0.75 °C in spring, 0.74 °C in summer and 0.61 °C in winter (Table 8), while for RH it ranges from 5% during the summer to 10.58% during the winter.

**Figure 7.** PoAC room—temperature and relative humidity values distribution—spring (16 of April to 8 of May).**Figure 8.** PoAC room—temperature and relative humidity values distribution—summer (23–27 of July).**Figure 9.** PoAC room—temperature and relative humidity values distribution—winter (8–22 of January).

IAQ parameters are always within the required limits. The CO₂ emission trend shows a correlation with the visitors' presence, as illustrated in Figure 10; the values are lower during the closing days (indicated by gray bands). PM daily means are always below the target values (Figure 11).

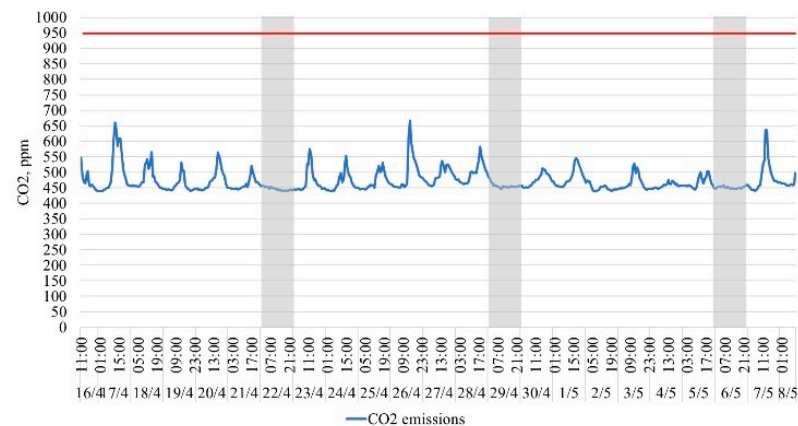


Figure 10. PoAC room—CO₂ concentration trend—spring (16 of April to 8 of May). The red line is the maximum concentration allowed as defined by the standard.

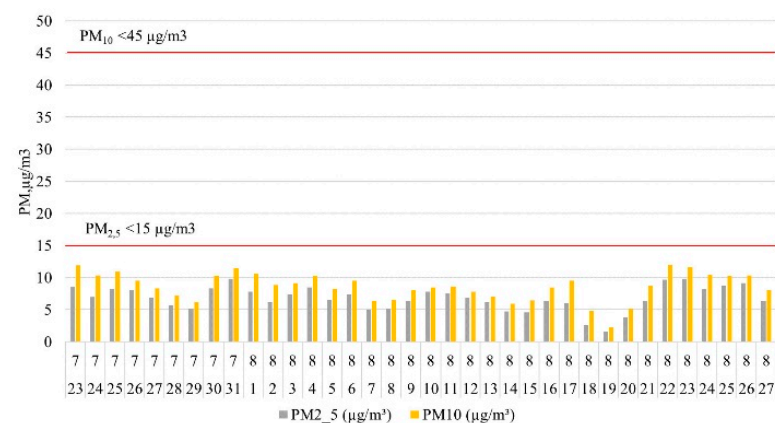


Figure 11. PoAC room—PM concentrations—summer (23–27 of July). The two red lines are the maximum concentrations allowed as defined by the standard.

Regarding lighting conditions, inside the room, there is only artificial light contribution as the windows are permanently shaded by opaque curtains. Measurements of illuminance indicate that values on the upper surfaces of the showcases are excessively high, ranging from 288 lx to 577 lx, while in the visitor circulation areas, they consistently remain below 300 lx (Figure 12). This uneven distribution can be primarily attributable to the use of spotlights, which concentrate light on specific points rather than ensuring uniform coverage. A spot measurement conducted in the presence of the “Superintendency for Archaeology, Fine Arts and Landscape”, confirmed that the illuminance outside and inside the Prince of Arene Candide showcase was identical (288–300 lx) and exceeded the recommended threshold (50 lx). Considering the opening hours of the museum (2800 h/year), the annual light exposure LO is 0.81 Mluxh/yr, higher than the 0.2 requested for skeleton or 0.5 requested for ivory. UV levels, however, remain below the limit of 75 µW/lm: throughout the room, UV is equal to 3 µW/lm, while on the top of the showcase (T_{1,H}) of Prince of Arene Candide, the value is 3 µW/lm, and 6 µW/lm on the top of the other three. The values depend on the orientation of the spotlights.

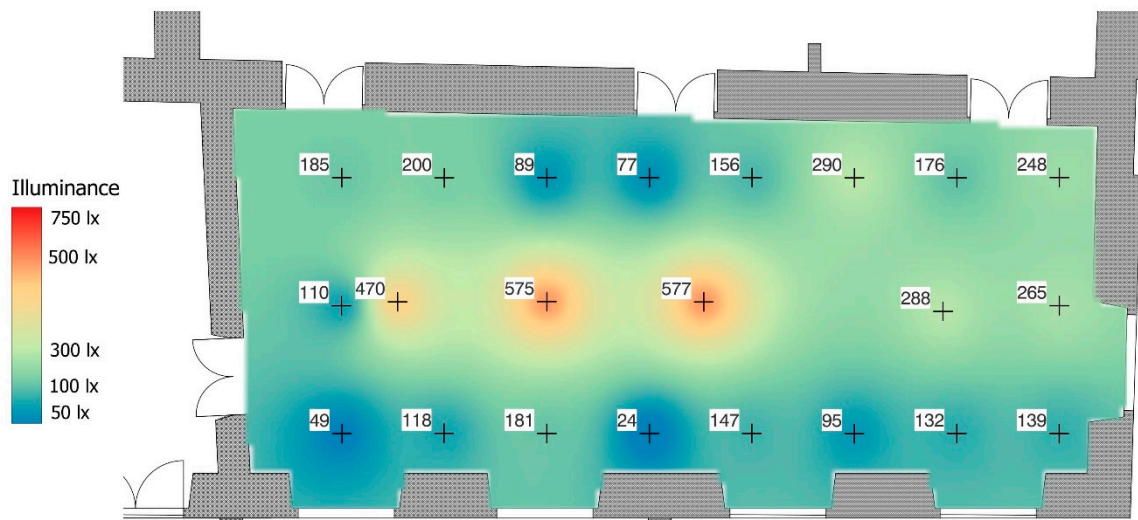


Figure 12. Horizontal illuminance (height = 80 cm) gradient map built from discrete measurement points (the “+” symbols with numbers are discrete measurement points) – PoAC room.

3.2. Deposit

The trend is similar to that seen for the PoAC Room. The room is only frequented sporadically by museum staff. Therefore, only the environmental parameters for the preventive conservation of the artworks are checked. The Global Performance Index is respected for some measurements during the spring monitoring campaign, but never during the summer and the winter (Figures 13–15). IAQ parameters, like CO₂ emissions and PM, always respect the threshold values.

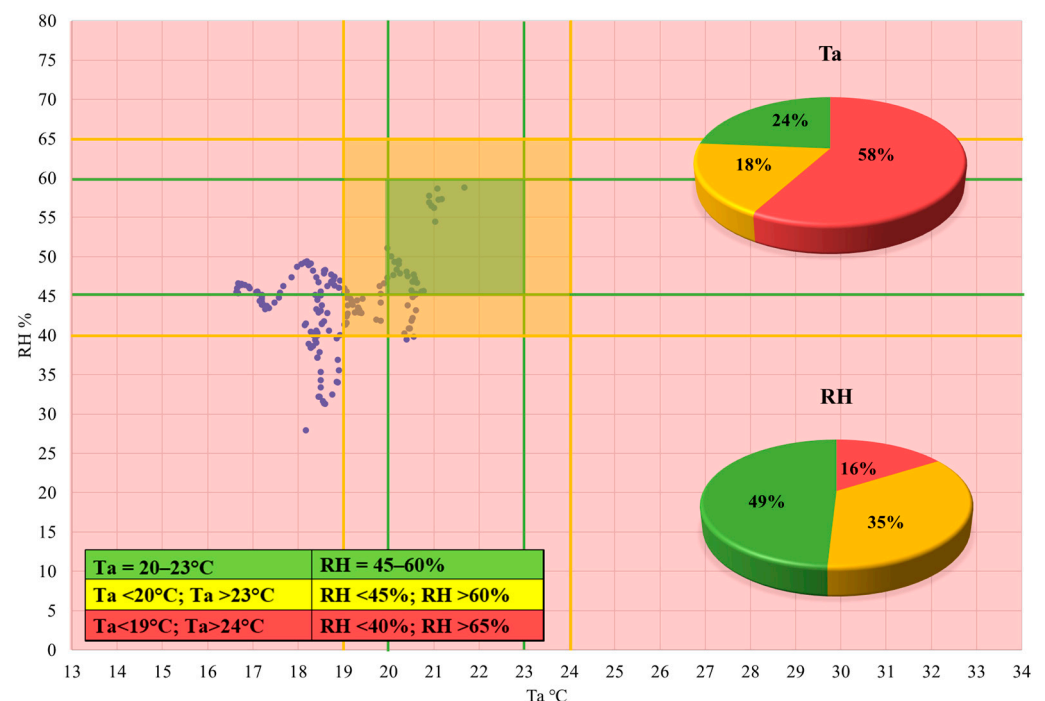


Figure 13. Deposit—deviation index, spring (16–23 of April). The colored areas indicate different compliance levels: green for conditions within the required range, yellow for the alert zone, and red for critical values outside the recommended limits.

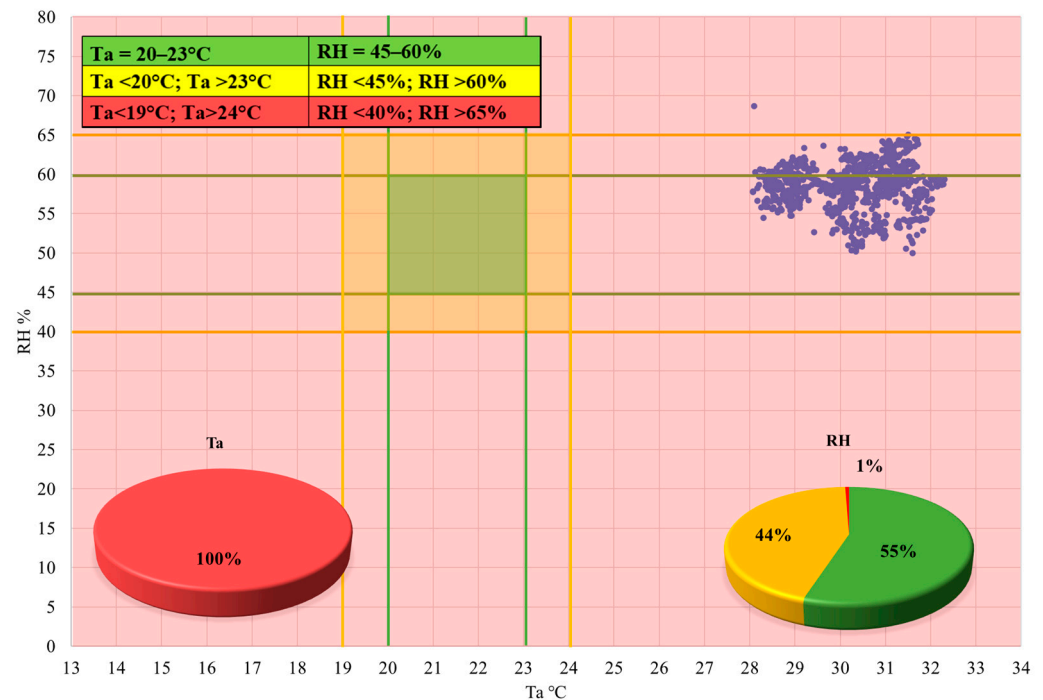


Figure 14. Deposit—deviation index, summer 23–27 of July. The colored areas indicate different compliance levels: green for conditions within the required range, yellow for the alert zone, and red for critical values outside the recommended limits.

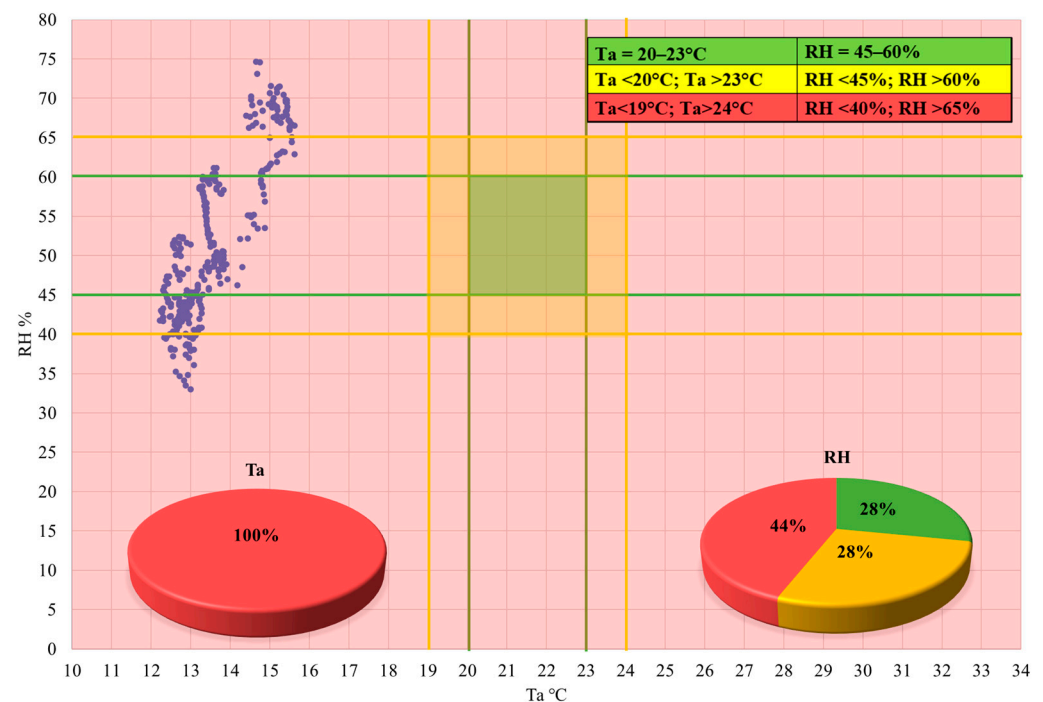


Figure 15. Deposit—deviation index, winter 8–22 of January. The colored areas indicate different compliance levels: green for conditions within the required range, yellow for the alert zone, and red for critical values outside the recommended limits.

As in the PoAC room, temperature shows limited fluctuations, exceeding the daily limit of 1.5 °C only on two days during the summer period and on one day during the spring. RH is more critical, exceeding the limit for almost all days during spring and winter and on 28 of 36 days during summer, with a standard deviation of 10.17% during winter (Table 9).

Table 9. Daily temperature and relative humidity gradients—deposit.

Period	T _{mean} (°C)	T _{max} (°C)	T _{min} (°C)	∂Ta _{24h,max} (°C)	N° Days Δ > 1.5 °C	St.dev.T (°C)	RH _{mean} (%)	RH _{max} (%)	RH _{min} (%)	∂UR _{24h,max} (%)	N° Days Δ > 4%	St.dev. (%)
Spring	18.9	22.5	20.0	2.5	1/8	1.20	44.9	59.5	26.5	24.4	7/8	5.27
Summer	30.2	32.40	28.00	2.20	2/36	1.05	58.5	68.70	49.40	14.70	28/36	2.84
Winter	13.6	15.70	12.20	1.00	0/15	0.93	52.9	75.60	32.70	14.60	13/15	10.17

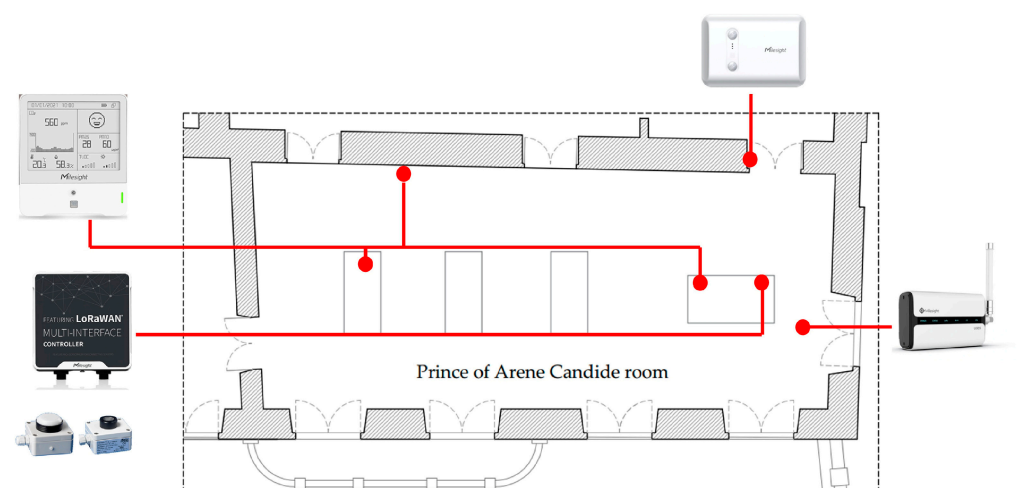
3.3. Design of the Long-Term Monitoring Campaign

All the information collected during the previous steps permitted the design of the long-term monitoring campaign, balancing performances, showcase size and visual impact, power and connectivity, maintenance, and cost.

The monitoring system is structured as a LoRaWAN-based wireless sensor network (Table 10, Figure 16), in which distributed environmental sensors transmit data to a central gateway. The gateway forwards the collected data to a cloud platform, where measurements can be accessed, visualized, and analyzed in real time.

Table 10. Sensors' specifications.

	Parameter	Range	Accuracy	Resolution
Microclimatic station	Air temperature	−20 °C ÷ 60 °C	Typ. ±0.3 °C (−20 °C ÷ 0 °C), ±0.2 °C (0 °C ÷ 60 °C)	0.1 °C
	Relative Humidity	0% ÷ 100%	Typ. ±2%RH (25 °C)	0.5%
	Illuminance	0–6000 lux, 6-level range		
	CO ₂ concentration	400 ÷ 5000 ppm	±(30 ppm + 3% of reading)	
	PM _{2.5} , PM ₁₀	0~1000 µg/m ³	0 ÷ 100 (±10 µg/m ³)	1 µg/m ³
E-sensor	Illuminance	0.02 ÷ 2 klux	<8%	
UV-A sensor	UV-A radiation	0 ÷ 20 W/m ²		

**Figure 16.** Design of the continuous monitoring asset – Prince of Arene Candide room.

In PoAC, a microclimatic station is placed in an open environment to monitor main environmental parameters for human comfort, but also inside two showcases to monitor the main artifact parameters. Since it provides only a qualitative result for illuminance and does not detect the UV-A component, an additional illuminance and UV-A sensor

is included, connected to a controller to communicate with the LoRaWan technology. A bi-directional people counter is installed to count people inside the room and correlate the output with this data. Technically, it was difficult to find appropriate sensors to measure NO_x and SO₂. It was decided to program spot measurements during different periods of the year.

Showcases have no power points, so the sensors will have to be battery-powered, although this poses a problem as the showcase can only be opened in the presence of the supervisory authority. The acquisition is set to 15 min to be representative, but at the same time, not require the case to be opened too often.

4. Discussion

The method described in this paper provides all the necessary information to optimally design a long-term monitoring campaign, essential to understanding the historical climate of the environment where an artifact is exposed and preserved, especially in the absence of HVAC systems. Short-term monitoring represents a crucial preliminary step in this process that can be challenging.

The three short-term monitoring campaigns carried out in the Ligurian Archaeological Museum in Genoa, in the exhibit room and deposit, represented an important step toward deepening the understanding of these environments and identifying critical issues as well as the constraints that will influence the selection of sensors for the long-term monitoring campaign. Both rooms show seasonal discrepancies between indoor conditions and target ranges defined both for human comfort and artifacts' preventive conservation. Temperature tends to be too high in summer and too low in winter, while daily temperature fluctuations remain relatively limited (few days exceed the 1.5 °C daily gradient). RH behaves differently, falling within the target ranges more frequently than temperature but showing large daily fluctuations and frequent exceedances of the allowable daily gradient. The combination of moderate temperature variability and large RH variability is critical because damage mechanisms (mechanical stress, salt migration, biological growth) are driven by RH excursions as much as by absolute temperature [13,51]. The combined analysis of Ta and RH shows that the joint target is rarely met, especially in summer and winter. This raises concern about hygroscopic organic materials and composite objects in the PoAC room and the deposit.

IAQ parameters (CO₂, PM) generally remained within the selected thresholds during the campaigns, but CO₂ trends clearly correlate with opening hours and visitor presence, confirming that occupancy is a relevant driver of indoor conditions. The absence of an installed people counter does not allow for accurate correlation between occupancy, CO₂ peaks, short-term RH increases, and transient temperature rises; the data therefore support the recommendation to install a people counter to enable correlation analysis and to evaluate ventilation effectiveness.

Illuminance measurements show a conflict between visitor comfort and object safety: illuminance values on the top of showcases exceed recommended limits for sensitive materials, producing a LO above thresholds for skeletal and ivory materials. UV levels are low, indicating appropriate lamp spectra, but the management of luminous flux (intensity, distribution, and operating hours) is the main issue. The current lighting strategy appears to prioritize visitor visibility over cumulative light exposure to objects. The long-term monitoring campaign will permit us to quantify exactly the operating hours of lighting systems and the foreseen control strategy to mitigate long-term photochemical risk to artifacts.

The deposit on the third floor shows high mean temperatures in summer, large RH excursions, and evidence of water infiltration and mold. These findings underline the need for targeted interventions in storage areas that are structurally exposed to weather and

moisture ingress. The deposit has the advantage of being accessed only by museum staff, and the installation of sensors has fewer constraints. After analyzing the annual monitoring data and comparing it with any potential damage observed on the preserved objects, it will be possible to evaluate the possibility of relocating the more sensitive materials in case it is not possible to improve the control of the environmental parameters.

The holistic approach adopted within this research permitted the analysis of air temperature, relative humidity, main IAQ parameters, and illuminance and UV, and to correlate them to human comfort and artifacts preservation needs. The three short campaigns proved effective as a diagnostic and design tool: they identified the most relevant parameters, informed sensor selection and placement, and highlighted practical constraints (size, visibility, power supply) for permanent installations. Short-term data allowed prioritization of monitoring needs: adding case sensors, a people counter, and, if possible, VOC, SO₂, and NO_x instruments. Continuous monitoring for at least one year is necessary to define the historical climate in accordance with EN 15757 [13], to adjust the environmental range, and to apply appropriate improvement strategies.

5. Conclusions

This study presents a replicable approach based on short-term environmental monitoring as a preliminary step toward the design of a long-term monitoring strategy. Short-term campaigns were essential for identifying priority parameters, detecting potential risks, validating sensor types, and spatial distribution. These investigations lay the foundation for the design and subsequent implementation of long-term monitoring over at least one year.

The short-term monitoring campaigns provided a comprehensive overview of micro-climatic conditions, highlighting fluctuations in temperature and relative humidity and confirming the absence of HVAC systems as a critical factor. These results enabled the optimization of sensor placement for long-term monitoring. While IoT-based sensors will play a central role in the next phase, portable instruments remain necessary for parameters requiring higher accuracy, such as illuminance and UV radiation, or for pollutants that demand quantitative VOC analysis.

The analysis of the one-year data collected through the long-term monitoring system will permit the reconstruction of the historical climate of environments and showcases, allowing ‘to correct’ the ranges to be respected by correlating the values with the state of conservation of artifacts. Future research should also explore predictive models and adaptive conservation strategies while considering the constraints of historic buildings and the need to balance artifact preservation, visitor comfort, and energy efficiency. Achieving this balance will require a multidisciplinary approach and may include passive solutions and localized interventions. Engaging visitors to assess their perception of comfort could further enhance the design of sustainable museum environments.

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Abbreviations

The following abbreviations are used in this manuscript:

Ta	Air Temperature (°C)
DI	Deviation Index
PI	Global Performance Index
E	Illuminance (lux)
UV _{max}	Maximum amount of ultraviolet radiation (mW/lm)
LO _{max}	Maximum annual light dose (Mlx/h yr)
ΔT _{a,max}	Maximum daily Air Temperature Range (°C)
ΔRH _{max}	Maximum daily Relative Humidity range (%)
NO _x	Nitrogen Oxides (ppb)
O ₃	Ozone (ppb)
PM _{10,24h}	Particulate Matter with a diameter of 10 μm or less, 24 h mean (μg/m ³)
PM _{2.5,24h}	Particulate Matter with a diameter of 2.5 μm or less, 24 h mean (μg/m ³)
PoAC room	Prince of Arene Candide's room
RH	Relative Humidity (%)
SO ₂	Sulfur Dioxide (ppb)

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