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Indoor Microclimate Monitoring in Heritage Buildings: The Bologna University Library Case Study

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Abstract

The indoor microclimate conditions of historical libraries play a pivotal role in ensuring the long-term preservation of their valuable collections, while also influencing the comfort and well-being of staff and visitors. These two objectives may be in contrast, as proved in extensive literature. Microclimate monitoring is essential to evaluate which factors could expose the content of the library to a risk of damage and to design prevention measures. This paper presents the monitoring project, the systems and methodology, and the initial results of an experimental study on the indoor microclimate conditions of the University Library of Bologna (BUL), a very relevant cultural heritage building in the historic city center. The overall objective of the monitoring project is to gain knowledge of the specific microclimate conditions and the historical climate of the three main rooms of the BUL to define the right balance between the needs of conservation and the thermal comfort of staff, users, and visitors. The paper focuses on the short-term indoor monitoring assessment, carried out in the initial phase of the monitoring campaign. This phase, rarely addressed in the literature, is crucial because it enables the collection of results that can guide and orient the entire long-term monitoring campaign. The research results produced so far demonstrate the validity of the methodological approach and the monitoring framework, as well as the reliability of the related data. Moreover, they offer insights that can support the forthcoming inclusion of the BUL in a broader museum system.

Keywords: historic library; indoor microclimate monitoring; heritage buildings; conservation and preservation practices; historical climate; energy optimization

Academic Editors: Shi-Jie Cao and Alireza Afshari

Received: 30 April 2025
Revised: 26 August 2025
Accepted: 3 September 2025
Published: 8 September 2025

Citation: Boeri, A.; Fabbri, K.; Longo, D.; Roversi, R. Indoor Microclimate Monitoring in Heritage Buildings: The Bologna University Library Case Study. *Buildings* **2025**, *15*, 3235. https://doi.org/10.3390/buildings15173235

1. Introduction

The indoor microclimate conditions of historical libraries play a pivotal role in ensuring the long-term preservation of valuable collections, while also influencing the comfort and well-being of staff and visitors [1,2]. In recent years, a growing emphasis on balancing conservation needs with evolving patterns of use and energy efficiency within cultural heritage buildings has been manifested [3–7]. In contemporary conservation practice, the regulation of indoor microclimate variables within libraries is predominantly managed through the deployment of Heating, Ventilation, and Air Conditioning (HVAC) systems [4,8]. These systems are widely recognized as critical for ensuring the environmental stability necessary for the long-term preservation of cultural heritage materials [9,10]. Nevertheless, notable exceptions remain, particularly among historical libraries, where such systems are absent and indoor environmental control depends exclusively on passive mechanisms [3,11,12].

These mechanisms are closely tied to architectural features such as building mass, material properties, spatial orientation, and overall structural design. Prominent examples of libraries operating without HVAC systems include the Biblioteca Malatestiana in Cesena, Italy, and the historical library of the University of Salamanca, Spain [1,2]. In these institutions, internal environmental stability is primarily achieved through traditional construction methods that inherently buffer external climatic variations [3,13].

Conversely, the retrofitting of HVAC systems into historical libraries often introduces conservation challenges. As these installations occur centuries after the buildings were constructed, they frequently disturb the pre-existing equilibrium, producing abrupt variations in temperature and relative humidity [6,14]. These fluctuations may accelerate the degradation of both the buildings and their collections [2,3,13,15]. For example, the Bibliothèque Nationale de France has encountered complications in reconciling its historical infrastructure with the requirements of modern environmental control, resulting in inconsistent humidity levels and ventilation issues [16]. Several historic libraries, for instance the Vatican Apostolic Library, have also experienced difficulties in maintaining constant microclimate variables, despite possessing HVAC infrastructure [10,17]. These examples underscore the limitations of conventional mechanical systems when applied in heritage contexts. Back in 1998, Camuffo argued for a conservation-driven approach to climate control, advocating for adaptive methodologies that are sensitive to the historical and physical attributes of the structure [18]. His findings reinforce the broader shift in heritage conservation towards flexible, minimally invasive environmental management strategies.

Ultimately, while HVAC systems are indispensable tools in many modern libraries, their application in historical contexts must be critically assessed. As emphasized by Staniforth, a successful conservation strategy should balance the benefits of technological intervention with the enduring resilience offered by passive climate regulation techniques [18]. Knowledge of microclimatic conditions is the essential starting point for assessing the suitability of HVAC systems or for evaluating the best solutions to guarantee proper well-being for humans and the precious assets contained in heritage buildings.

This paper presents the methodology and initial findings of an updated microclimate monitoring campaign conducted at the University Library of Bologna (Biblioteca Universitaria di Bologna—BUL), one of Italy's most historically significant library buildings. The objective of this applied research is to prove that a first short-term indoor monitoring assessment, carried out in the initial phase of the monitoring campaign, is crucial to collect data to drive and orient the whole monitoring campaign, in order to guarantee the validity and reliability of the long-term collected data. Despite the availability of literature on short-term monitoring period case studies [19], this topic is not specifically addressed and related to the validation of the monitoring system in terms of design, reliability, and efficiency.

In the heritage sector, the placement of sensors must be carefully adapted to the specific context. In most cases, the installation of the probes requires compromises—their ideal number or optimal installation placement are often not feasible. In this context, a correct set up of the monitoring system refers to a system architecture and validation that meets the following criteria:

(a) It ensures continuous data acquisition and transmission;
(b) The probes are installed in positions that do not interfere with the visitor experience and with the protection of the cultural heritage asset (i.e., probes are hidden) and in positions that are secured against tampering or removal;
(c) The system enables the collection of data from at least one representative point per room, and at least two in the largest spaces, without introducing measurement disturbances.

Accordingly, the empirical assessment of the BUB sensor placement is based on these three criteria.

The importance of this first phase of the monitoring project in relation to the entire monitoring period relies on the reliability of the data collection activities, which enables us to understand whether the data is usable or whether the system needs to be adjusted. This qualitative assessment avoids the disadvantage of only realizing at the end of the campaign that the results are unreliable, discontinuous, or distorted. This type of problem is particularly relevant in the case of historic and monumental buildings. Their technical and structural characteristics, such as the thickness of walls or their construction materials, may prevent data transmission, or the impossibility of positioning the probes in the most suitable detection points due to the presence of decorations, could affect the efficiency of the system.

The monitoring activities started on 5 September 2024. This research considers data produced in the first 6 months, during Autumn and Winter 2024–2025. The monitoring campaign is still running, and further data and results will be collected in Spring and Summer 2025. The stages of the monitoring campaign covered in this contribution include the installation, setting, and validation of the monitoring system and the verification of data transmission.

The study builds upon a previous monitoring campaign carried out during the H2020 ROCK project (Regeneration and Optimisation of Cultural Heritage in Creative and Knowledge Cities_GA730280) between 2018 and 2020. The earlier results—focused on the performance of the library's indoor environment with and without the heating system—were published in Boeri et al. [20], highlighting the tensions between conservation strategies and energy use. The previous study demonstrated the importance of the aforementioned initial phase of the monitoring procedure and the relevance of the related data.

Furthermore, this paper focuses on the way the current boundary conditions of the library, which include both daily and seasonal meteorological variations, influence the indoor microclimate conditions. Climate change is causing the boundary conditions to change over time [21]. This dynamic puts the preservation of historic buildings at risk, as was reported in several studies, including Fabbri et al. [3,13], and in other studies focusing specifically on historical libraries [2,9,11,15–17,22,23], such as Lankester et al. [24,25] and Sandrolini et al. [26]. The damage produced by outdoor pollution, particularly that deriving from particulates, represents an additional thread, as pointed out in De la Fuente et al. [27].

The thermal conditions, which must aim for the protection of goods as well as visitor and staff thermal comfort, may be in contrast to those proven in the literature [28–31]. Very often, the focus lies primarily on human comfort, which leads to the introduction of building services and systems. However, mechanical systems introduce "microclimate stress conditions" for buildings and their contents, radically changing the originally planned microclimate logics.

Several studies investigated similar issues in heritage libraries and archival buildings [17]. Camuffo et al. (2010), for instance, documented the risks posed by inconsistent microclimate conditions in historical buildings, emphasizing the long-term degradation effects on manuscripts and rare books [32]. Leissner et al. (2015), within the European Climate for Culture project (https://www.heritageresearch-hub.eu/project/climate-for-culture/, accessed on 20 April 2025), explored how human-induced variations affect indoor environments in heritage sites, including libraries, pointing out that increased visitor presence can significantly alter local microclimates, sometimes leading to unacceptable fluctuations in temperature and humidity [33]. Similarly, Michalski [34], discussed the conflict between conservation standards, such as those recommended by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [35] or EN 15757 [36], and human comfort needs, especially in multifunctional heritage spaces.

Since the first 2018–2020 monitoring campaign, the functional use of BUL's spaces has progressively shifted from traditional library activities toward broader cultural and community engagement, necessitating a reassessment of the environmental conditions [37]. The functional use of the library spaces—particularly the iconic Great Hall—has evolved considerably over recent years. While previously limited to research and archival consultation, the premises are now increasingly used for lectures, exhibitions, and public events. These activities generate greater internal loads (e.g., from lighting, body heat, and ventilation requirements), which can result in destabilized environmental conditions that threaten the long-term stability of stored materials.

In response to these changes, and recognizing the limitations of the original monitoring system, a new campaign was launched in September 2024 under the ECOSYSTER project, part of Italy's National Recovery and Resilience Plan (NRRP) in the framework of NextGenerationEU (https://ecosister.it/, accessed on 5 August 2025). This updated initiative employs a newly installed monitoring system to investigate the microclimate dynamics of BUL's three principal rooms. The main overall objectives of the campaign are to establish risk thresholds for climate-sensitive assets; enable the management of the BUL to activate strategies for the different spaces, in order to reconcile conservation requirements with occupant comfort; and explore the relationship between indoor climate conditions and energy consumption patterns.

By presenting the methodological framework and initial results of the 2024 monitoring project, this paper contributes to the broader discourse on sustainable heritage management, offering insights that can support the resilience and adaptive reuse of historic library environments.

2. Materials and Methods

2.1. The Bologna University Library Case Study

The Bologna University Library (BUL) was founded in 1712 by Luigi Ferdinando Marsili, a Bolognese aristocrat who decided to donate to the Alma Mater Studiorum University his personal library. In 1742, the library increased its collections of scientific books, manuscripts, xylographies, etc., thanks to Ulisse Altrovandi, one of a most important Naturalist of XVIII Century. In 1755, Pope Benedict XIV Prospero Lambertini, a Bolognese, further expanded the librarian collections. In 1869, the BUL became an Italian library. Since 2000, it has been managed and administered by the University of Bologna.

The BUL consists of three main rooms (Figures 1–3):

(a) The Great Hall, a large room where the original solid walnut shelving on two orders is present and where about 30,000 ancient volumes are stored; it is part of the museal path and it is occasionally used as a conference room;
(b) The Special Collections Room, where the library people and consultation/study are located;
(c) The Mezzofanti Room, accessible by a security door, where the archives are located.

The Great Hall floor surface is around 340 m^2 with a volume around 6000 m^3; the Special Collection floor surface is around 135 m^2 with a volume around 2100 m^3; finally, the Mezzofanti Room floor surface is around 104 m^2 with a volume around 1560 m^3. Currently, Great Hall and Special Collection rooms have a centralized heating system, composed by radiators. The Great Hall balcony and the Mezzofanti Room have no air conditioning at all.

The design of the monitoring project involves three rooms equipped with four temperature and relative humidity sensors, as these are the physical variables that can most likely cause damage to the precious books and furniture, which are present in all three rooms.

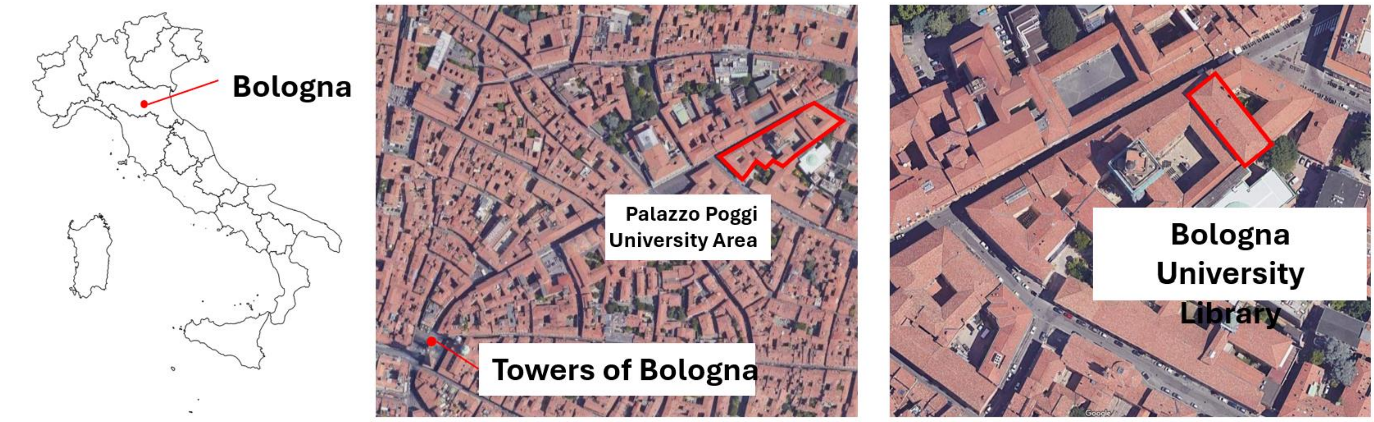

Figure 1. City of Bologna and the Bologna University Library localization. Source: the authors.

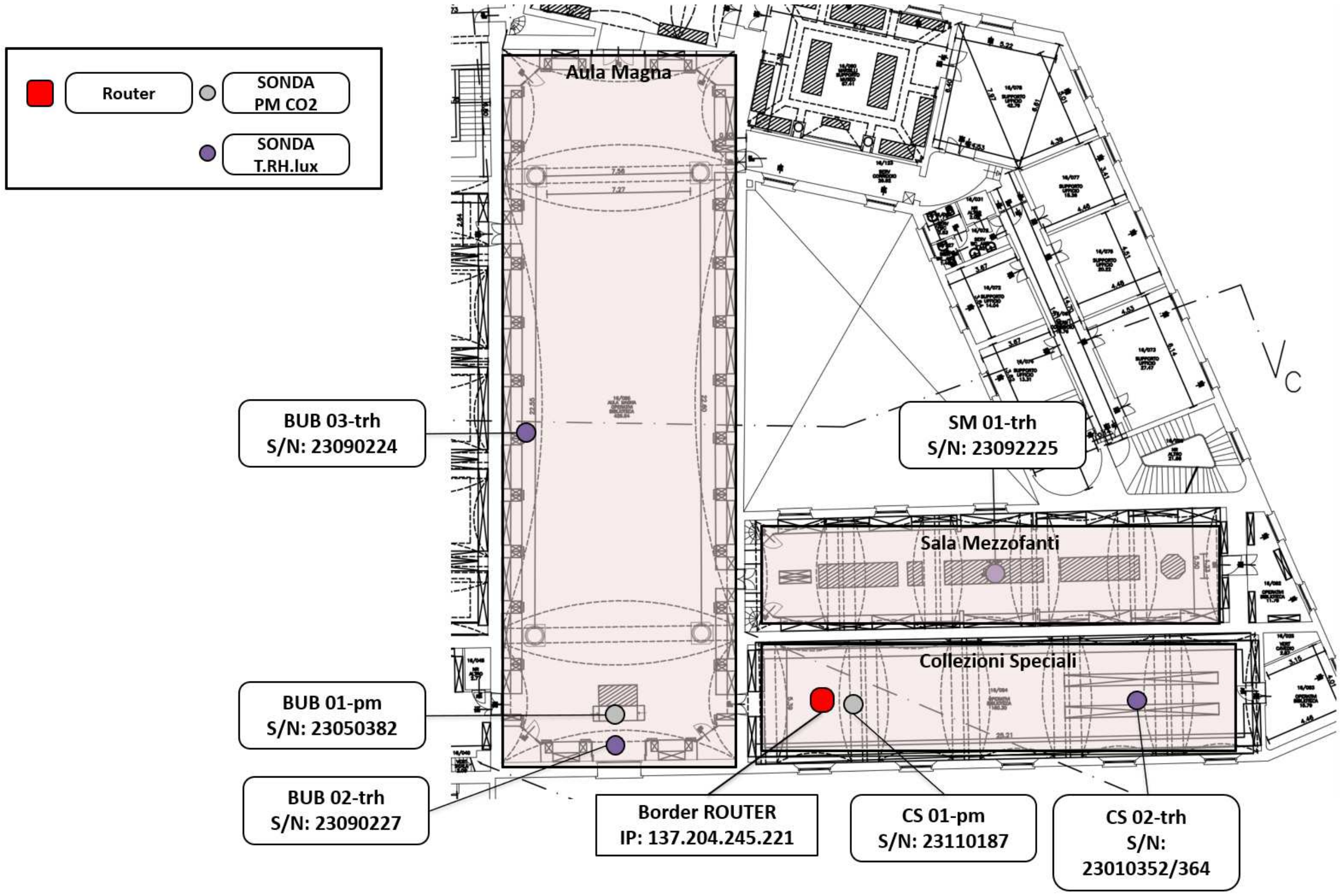

Figure 2. Floor plan of the BUL premises showing the positioning of the monitoring system. Source: the authors (“Sonda” is sensor; “-pm” is sensors with carbon dioxide (CO_2) probes; “-trh” is sensors with temperature and relative humidity probes; BUB is the Great Hall; CS is the Special Collection Room; SM is the Mezzofanti Room).

The objective of the long-term 2024 monitoring project of the premises of the Bologna University Library is to know, for each room, the specific microclimate conditions and historical climate, to define the following:

(a) The alert ranges in case of microclimate risk;
(b) The choices and methods of management and use of the different environments;
(c) The right balance between conservation needs and the comfort of staff, users, and visitors (attendance and access management).

Figure 3. Interior views of the premises being monitored in the current campaign. Aula magna is the Great Hall, Sala Mezzofanti is the Mezzofanti Room, and Collezioni Speciali is the Special Collections Room. Photos by Kristian Fabbri.

The library building itself presents unique challenges due to its architecture: large brick masonry, wooden and brick flooring, and substantial wooden furniture, which interfere with the transmission of radio signals, particularly at the 2.4 GHz frequency used by many wireless devices. To address this, a series of transmission tests were conducted, and the final configuration of the monitoring system was agreed upon and confirmed by the technical expert of the University Library staff, responsible for managing the library's computer networks and facilities.

The air temperature and relative humidity in these rooms are influenced by several factors: external climate variations, the presence of heating systems (except for the archive in the Mezzofanti Hall), and crowd density, particularly in the Great Hall and Special Collections Room. These variables require constant monitoring to ensure the integrity of the library's holdings.

2.2. Methodology

The ongoing monitoring project is designed to provide data and tools that will facilitate the management of the current use of the library premises and in view of the future envisioned changes. By doing so, the project seeks to strike an effective balance between the library's new public-facing role and its fundamental mission of preserving historical materials.

To address these challenges, the monitoring project has selected the three aforementioned rooms for microclimate monitoring, to be equipped with four temperature and relative humidity sensors. These two physical variables are the most critical in terms of potential damage to the library's collections and furniture, which are sensitive to their fluctuations. The damage from uncontrolled microclimates can include condensation and mold growth on paper, books, and wooden furniture, as well as physical-chemical degradation that may foster the development of biological pests such as insects, woodworms, and moths [38].

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The location of the probes was decided in relation to the geometric characteristics of the rooms, the number of the available probes (funded by the Ecosister project), and the configuration of the electrical and computer (wi-fi) wiring. The first step was to decide where to put the border router, based on the use of the rooms and the electrical wiring; after that, one probe per room was placed, as described below. The precise positioning of the probes considers three elements: (i) at least one measurement point per room; (ii) a location where the probes cannot be "stolen/picked up" by visitors; and (iii) a location where the probes can transmit via radio to the border router. Of course, the placement of the probes was also conditioned by the presence of the relentless decorative apparatus that characterizes the rooms and the need for monitoring equipment not to interfere with the adequate perception of the quality of the spaces and the artistic works contained therein (e.g., ornate ceilings, moldings, bookcases, and wooden artifacts). This aspect represents a critical element that needs to be evaluated and tested before initiating the monitoring campaign, as a placement of the probes that is driven not only by the choice of the most effective location but also by the need to safeguard the cultural heritage asset, may lead to invalid or biased results that undermine the entire monitoring campaign.

As shown in Figure 2 (purple dots), the disposition of the probes is as follows:

- Great Hall: Two temperature and relative humidity probes positioned on the mezzanine;
- Special Collections room: One temperature and relative humidity probe, positioned on a shelf in the center of the room;
- Mezzofanti Hall archive: One temperature and humidity probe placed in the center of a shelf cabinet.

The two temperature and humidity probes in the Great Hall were installed above the balcony because this is about half of the total height of the room, so as to have a representative point, not only in plan but also in section.

After a trial-and-error phase and the verification of data transmission, the interpretation of the first results was carried out. The results show that the choice of probe positioning is correct, and the collected data is significant.

In addition to temperature and humidity sensors, two probes were installed to measure CO_2 levels, volatile organic compounds (VOCs)—chemical pollutants commonly found in detergents, solvents, and other substances—and particulate matter (PM). The CO_2 and pollutant measurements are particularly important in rooms frequently used for public events, where human activity can contribute to indoor air quality issues [39]. These probes are strategically placed: one near the speaker's chair in the Great Hall, where an electrical outlet is available, and the other in the Special Collections Room, near the border router (Sphensor Gateway, by LSI-Lastem, Milan, Italy) connected to the university's Ethernet LAN (Figure 2, gray dots).

2.3. Features of the Sphensor Monitoring System

The monitoring system installed at the BUL provides continuous measurements of the relevant environmental variables. This is achieved through a network of indoor multi-parameter sensors that track temperature, relative humidity, and CO_2 levels, reported in this research, and other variables such as pressure, volatile organic compounds (VOC), particulate matter (PM), and illuminance (lux), not reported in this research. Data is transmitted via radio protocols and visualized on a Cloud-based software Indoor Cube V.1 platform for analysis and decision-making. The probes and associated materials were supplied by LSI-LASTEM (Milan, Italy, https://lsi-lastem.com/, accessed on 18 April 2025).

2.3.1. System Architecture and Monitoring Equipment

The system's architecture for data acquisition and transmission consists of the following components:

- Multi-parameter sensors: They are distributed throughout the monitored rooms. Some sensors are battery-powered, while others draw power through USB connections, ensuring low energy consumption and long-term sustainability;
- Radio transmission: Sensor probes transmit the collected data wirelessly to the Sphensor Gateway (border router, https://lsi-lastem.com/products/sphensor/, accessed on 18 April 2025), which, in turn, communicates with the Cloud platform through a local area network (LAN) via an Ethernet connection.

The monitoring system deployed on-site consists of the following:

- Four T-RH probes: These probes measure temperature, relative humidity, air pressure, illuminance (lux), and UV-A radiation, providing critical data for both the preservation of collections and the management of room conditions (see Table 1 for technical specifications).

Table 1. Probes data.

Measure	**Range**	**Accuracy**	**Calibration**
Temperature	−30...60 °C	• ±0.1 °C; Max ±0.3 °C (@20...60 °C) • ±0.2 °C; Max ±0.3 °C (@−40...20 °C; 60...80 °C)	0.015 °C
Relative Humidity	0...100%	• ±1.5%; Max ±2% (@25 °C; 0...80%) • ±2%; Max ±3% (@25 °C; 80...100%)	0.01%
Air Pressure	600...1100 hPa	0.18 hPa (@25 °C); ±0.6 hPa (@−40...85 °C)	0.1 hPa
CO_2	0...5000 ppm	<±(50 ppm + 3% of the measured value)	-
VOC	0...1000 ppb	Ethanol: 15% of the measured valueH_2: 10% of the measured value	0.2% of the measured value
Lux	0.1...90 klx	• 0°, 90°, 180°, 270°, 45° elevation from the sensor plan • 1 measurement on the plane normal	±5% MV ± 5 lx
PM (1, 2.5, 4, 10)	0...1000 µg/m^3	PM_1 e $PM_{2.5}$: • 0...100 µg/m^3, ±10 µg/m^3 • 100...1000 µg/m^3, ±10% of the measured value PM_4 e PM_{10}: • 0...100 µg/m^3, ±25 µg/m^3 • 100...1000 µg/m^3, ±25% of the measured value	• 0...100 µg/m^3 ±1.25 µg/m^3/year • 100...1000 µg/m^3 ±1.25% of the measured value

- Two PM-CO_2 probes: They measure particulate matter (PM_1, $PM_{2.5}$, PM_4, PM_{10}), volatile organic compounds (such as benzene, tetrachloroethene, and other VOCs), and carbon dioxide (CO_2) (Table 1). This is essential for assessing indoor air quality, particularly in spaces frequently used by the public.
- Sphensor Gateway: This serves as the border router for the Thread network and is connected to the University of Bologna's LAN (Ethernet) network (https://lsi-lastem.com/it/prodotti/sphensor/, accessed on 18 April 2025). It acts as the central hub for collecting and transmitting data from the sensor probes.

- Cloud platform (LSI LASTEM Cloud Service ENVIRO CUBE; https://lsi-lastem.com/products/enviro-cube/, accessed on 18 April 2025): It enables the configuration of individual sensors, the management of the monitoring plan, and the retrieval of data. Data can be accessed through standard reports generated by the platform, or they can be exported in Excel (*.xls) or text (*.csv) formats for further analysis, processing, or archiving.

2.3.2. Data Transmission and Processing

The data collected by the sensors are transmitted wirelessly via a radio signal to the Sphensor Gateway. The Gateway's primary role is to decode the incoming messages sent from the probes via the Thread protocol and relay them to an MQTT broker, accessible via the Ethernet connection within the University of Bologna's LAN. Once transmitted to the MQTT broker, the data is forwarded to the Cloud platform, where it is stored and made available for real-time monitoring and historical analysis (Figure 4). This advanced infrastructure provides a robust and reliable tool for continuous tracking of environmental conditions, ensuring both the optimal preservation of the library's assets and the safety of people using the space. The system's flexibility allows for the creation of customized reports and data management, making it a valuable tool for long-term conservation and operational decision-making.

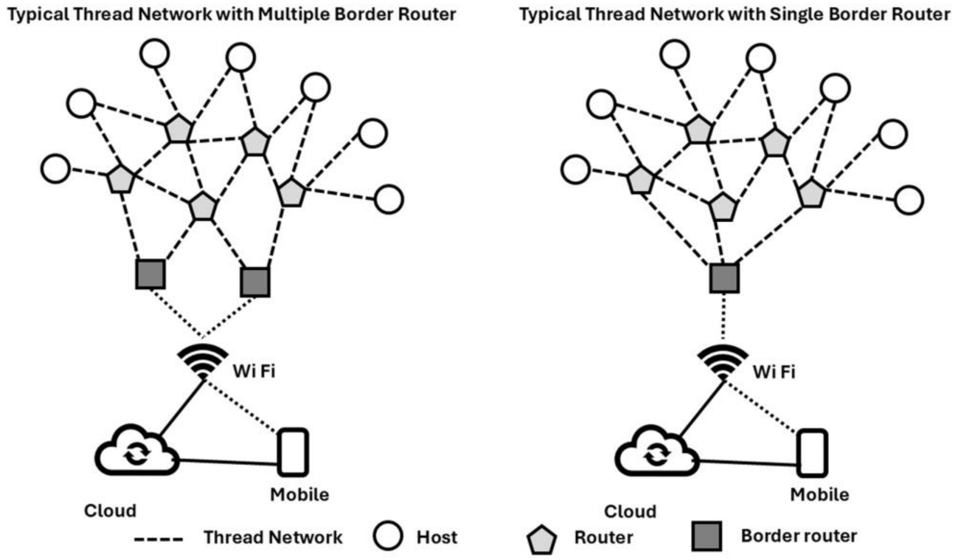

Figure 4. Thread Protocol configuration. Source: LSI—Lastem (https://lsi-lastem.com/, accessed on 18 April 2025).

2.3.3. Key Steps of the Monitoring Activities

The process of designing, setting up, and launching the monitoring system for the University of Bologna Library is divided into two key phases: the initial phase involves the installation and calibration of the system, while the second phase focuses on the consolidation of the configuration and the full-scale launch of the monitoring campaign.

During the first phase, the following activities were carried out:

- Delivery, inspection, and testing of equipment: The probes and associated materials supplied by LSI-LASTEM were thoroughly inspected and tested to ensure they were in optimal working condition.
- Site survey and installation: A detailed site survey was conducted to determine the optimal locations for the probes, followed by their installation. The technical integrity

of the internal radio network and the connection to the local LAN was also tested to ensure seamless data transmission.
- Activation and data transmission: The system was activated, and data transmission was successfully established with the INDOOR CUBE cloud platform, ensuring that all components were functioning properly and transmitting real-time data.
- Initiation of the monitoring campaign: After system activation, the monitoring campaign officially began, and initial results started to be generated and analyzed.

The calibration and quality check of the Sphensor multiparametric radio sensors for indoor measurement is performed by LSI-LASTEM, Milan, Italy, according to the ISO 17025 recommendations [40], ensuring that measurements are traceable to national and international standards. LSI-LASTEM is a calibration laboratory accredited by Accredia, the association designated by the Italian Government to certify the competence and impartiality of bodies and laboratories that verify the conformity of products and services to standards (https://www.accredia.it/en/, accessed on 5 August 2025). The sensors are configured via the Sphensor Manager software, accessing the sensor via Sphensor Gateway (other technical data can be found on the website https://lsi-lastem.com/products/sphensor/, accessed on 5 August 2025). Through rapid field checks, it is possible to detect any drifts or malfunctions without removing the in-place sensors.

Following the completion of the on-site installation and setup, the microclimate monitoring of the BUL became fully operational, continuously transmitting data as of 5 September 2024. Currently, the system provides valuable insights into the environmental conditions of the library's interiors, with data being continuously recorded and processed.

3. Results

The results from the first 6-month-long monitoring campaign allow for an initial assessment of the system's performance and the accuracy of the data collected. These initial findings provide the following:

- Trends for individual variables: Detailed analysis of each probe's readings, including comparisons between different environments within the library;
- Graphical representation of measurements on a psychrometric diagram: Visualization of the relationship between temperature, humidity, and air conditioning, helping to identify any deviations from optimal microclimate conditions;
- Carbon Dioxide concentration and occupancy patterns: The system monitors carbon dioxide levels to assess crowding and indoor air quality, especially in spaces with a high presence of people.

3.1. Indoor Microclimate: Air Temperature Trend and Relative Humidity

The graphs from the probes installed in the loft areas of the Great Hall (see Figure 5) indicate air temperature values ranging between 24 °C and 29 °C, with a gradual decrease over time. This trend is particularly evident on 21 September, when a notable temperature drop occurred, likely due to the shift in external weather conditions signaling the end of the long, hot summer of 2024 and the transition to cooler autumnal conditions.

The relative humidity (RH) values recorded by the probes are between 55% and 65%, which is consistent with the environmental characteristics of the library and its usage. Both graphs display a sinusoidal pattern, which reflects the daily fluctuations in temperature and humidity due to various factors such as the presence of people and the operation of equipment (e.g., lighting, computers, and HVAC systems). These fluctuations are closely aligned with the library's access hours and usage intensity. Relative humidity (RH) is referred to as a variable providing direct information about dryness and indicates the degree of water vapor saturation in the air, not the absolute moisture content or degree of dryness of materials or environments.

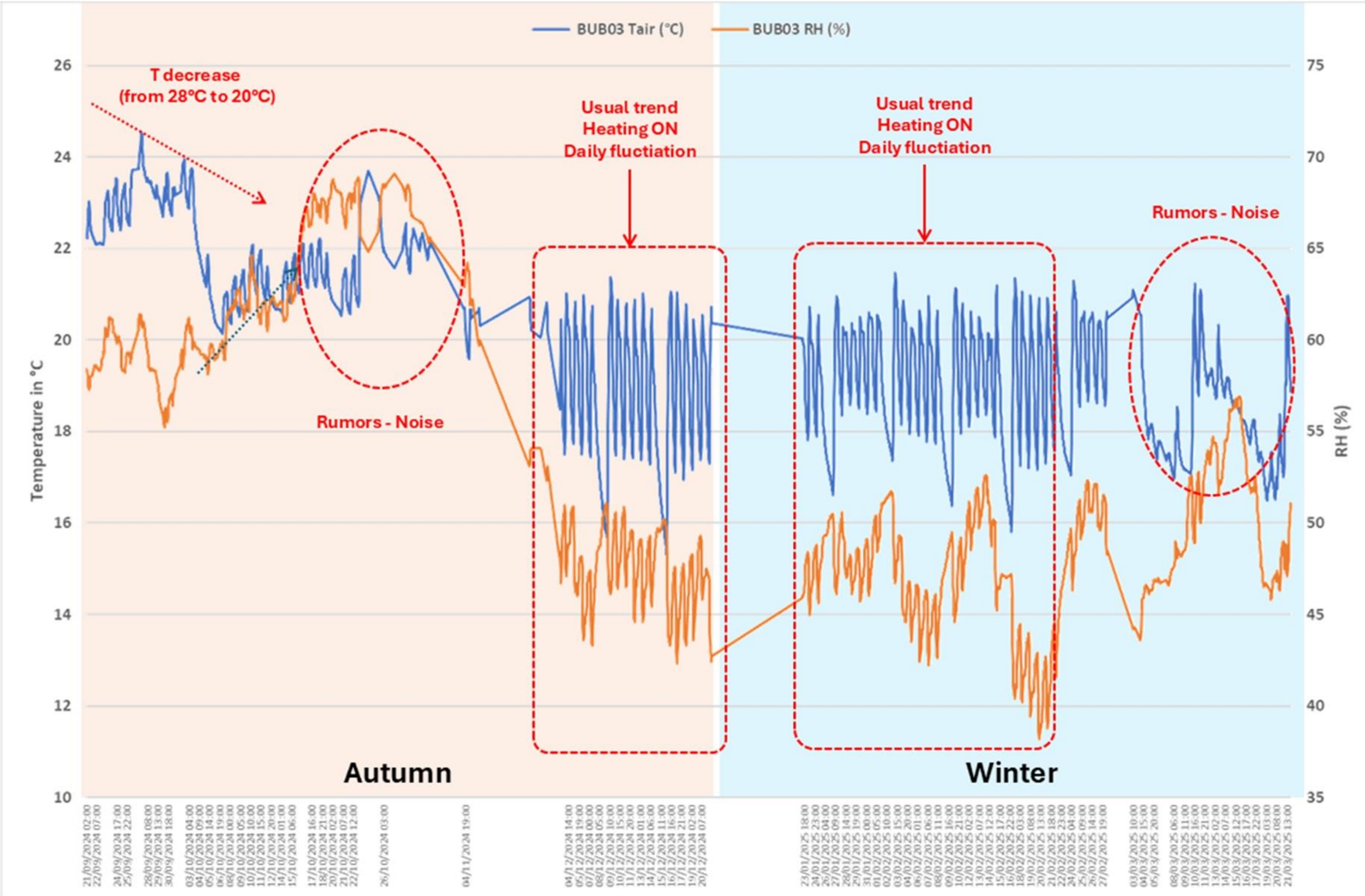

Figure 5. Great Hall Trend air temperature (blue) and Relative Humidity (orange). Source: Kristian Fabbri.

In Figure 5, a decrease in temperature in September can be observed, after the long, hot summer of 2024 that lasted until mid-October and beyond. After that period, with the activation of the heating systems, we can see an oscillatory trend, characteristic of the indoor microclimate during the period of activation of the heating systems.

The graph derived from data collected by the probe installed in the Special Collections Room (see Figure 6) indicates temperature values ranging from 23 °C to 30 °C, with a noticeable downward trend. A significant temperature drop began on 13 September, marking a clear shift in environmental conditions. This decrease in temperature aligns with the broader climatic transition occurring during this period. Once again, it can be noted that the indoor microclimate changes when the heating system is activated: the air temperature trend undergoes daily fluctuations due to the heating system being turned on/off and suspended during the weekend. The fluctuation of relative humidity values shows some days when the value is below 40% (dry environment). This is probably related to the crowding of people or the set-point temperatures of the heating system; this will also be investigated at the end of the annual campaign.

The relative humidity (RH) levels in the room fluctuate between 55% and 70%, which is typical given the nature of the space and its usage. However, it is important to highlight the sharp decline in relative humidity just before and after 21 September, where the RH values drop by nearly 15%. This sudden shift may be attributed to a combination of external weather changes and the internal environmental control systems, such as HVAC adjustments or variations in the number of occupants in the room. The abrupt decrease in humidity during this period is particularly significant, as it can impact both the preservation of the delicate materials housed in the Special Collections Room and the overall indoor air quality. These fluctuations in microclimate conditions require careful monitoring, as they could pose potential risks both to the stored materials and to the comfort of those accessing the room. Further investigation may be necessary to identify the precise cause of this rapid change and to implement preventive measures to maintain stable conditions.

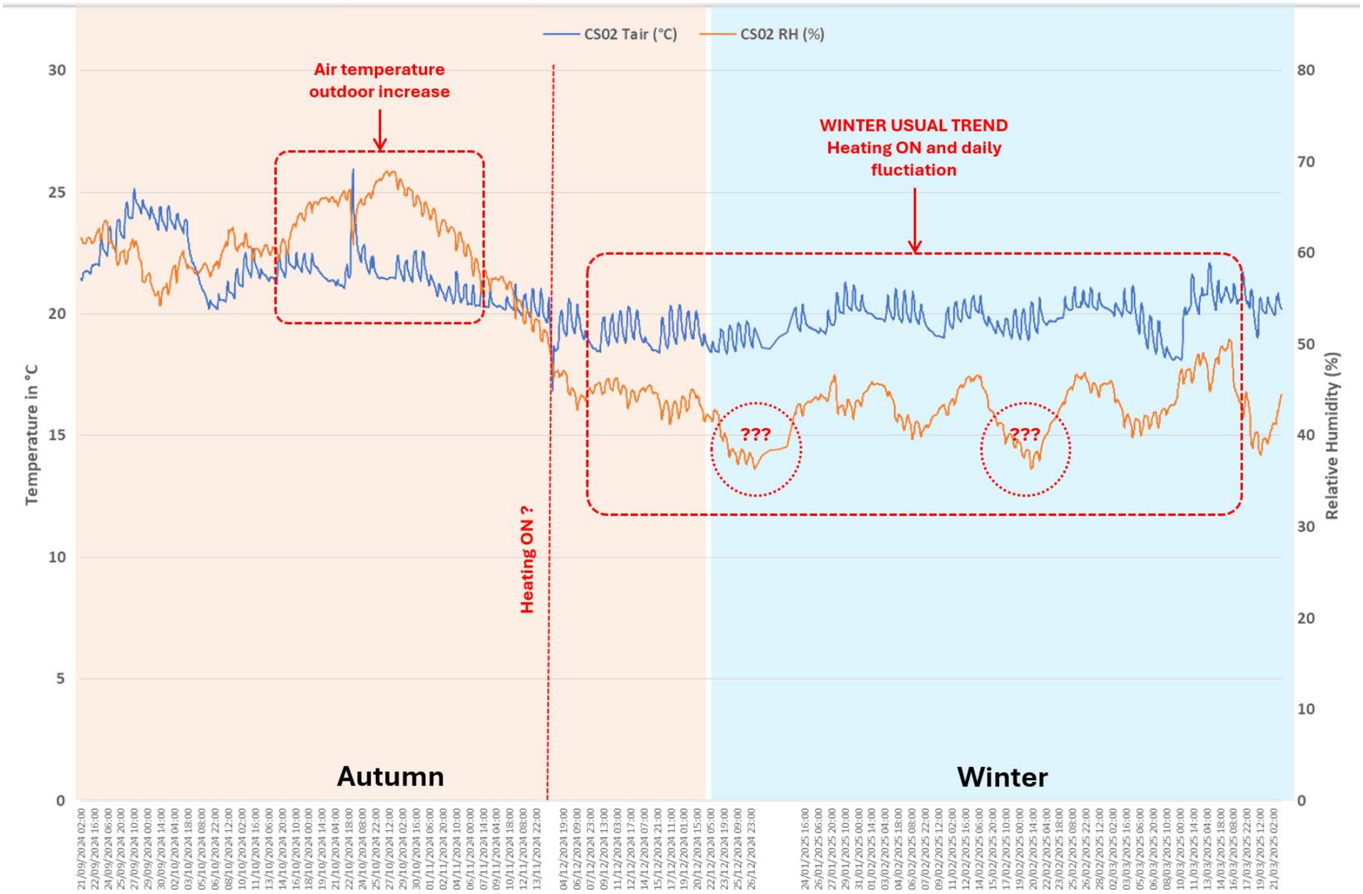

Figure 6. Special Collection Room, trend of the air temperature (blue) and relative humidity (orange). Source: Kristian Fabbri. The question mark indicates a data value that deviates from the overall trend.

The graph from the probe installed in the Mezzofanti Hall (see Figure 7) shows temperature values ranging from 23 °C to 28 °C and relative humidity levels between 52% and 58%. Unlike other monitored spaces, the reduction in both temperature and humidity after 21 September occurs slowly and gradually, reflecting the unique conditions of this room.

One notable difference from the previous graphs is the stability of the values recorded in the Mezzofanti Hall, with no significant daily fluctuations. This consistency can be attributed to two main factors: the absence of active HVAC systems, which eliminate artificial influences on the room's microclimate, and the limited foot traffic in the hall, resulting in fewer disturbances to the environmental conditions.

In other words, the microclimate conditions in the Mezzofanti Hall closely follow the natural variations in external weather, leading to more stable and uniform measurements. This indicates that the hall, unlike spaces with higher occupancy and active climate control systems, maintains a relatively passive and consistent environment, which could be advantageous for the preservation of sensitive materials stored within.

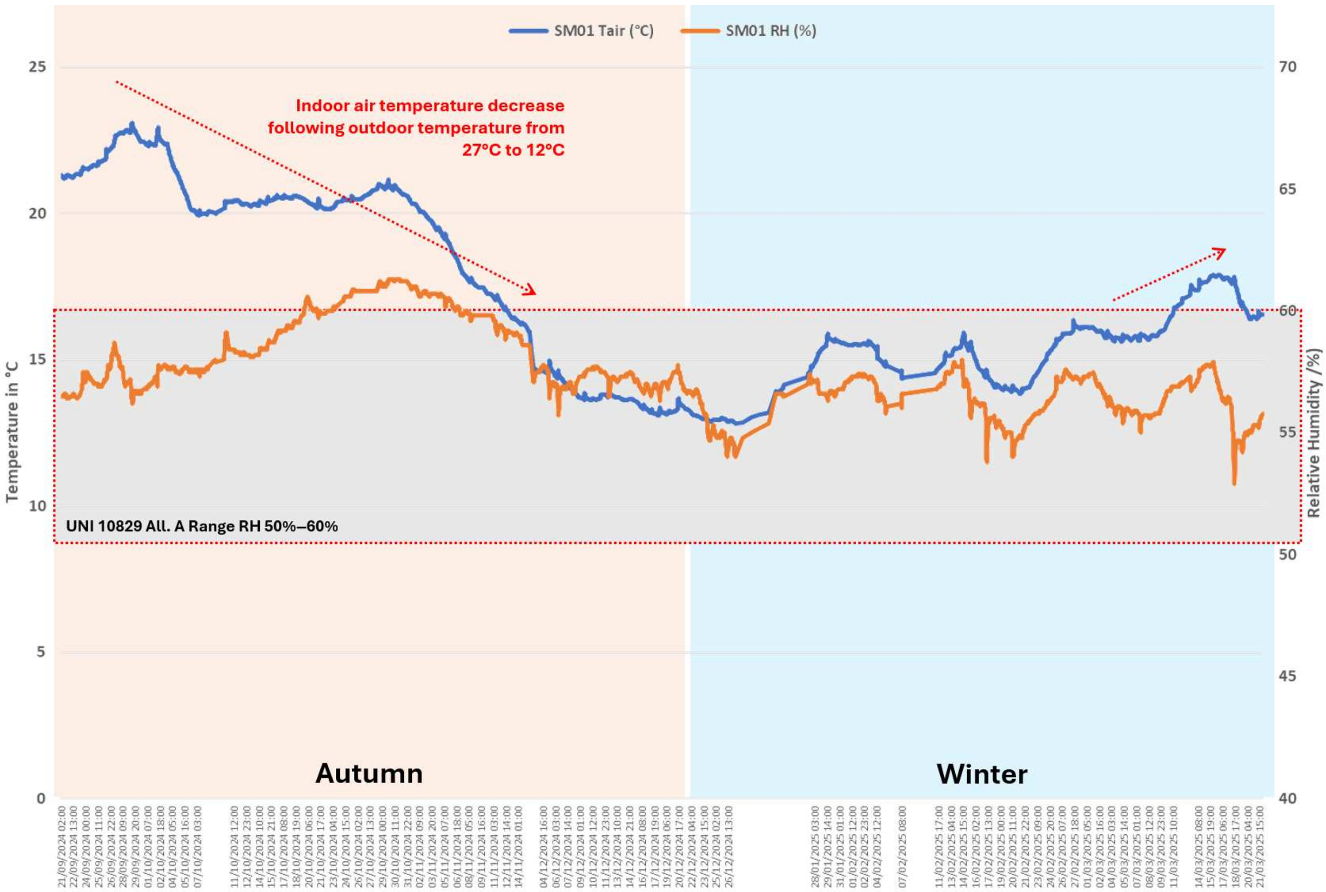

Figure 7. Sala Mezzofanti, trend of the air temperature (blue) and relative humidity (orange). The figure reports the threshold that follows the standard UNI 10829. Source: Kristian Fabbri.

A comparative analysis of the air temperature trends in the three rooms (Figure 8) reveals a noticeable difference of approximately 3 °C to 4 °C between the Special Collections Room and the Great Hall, with the highest temperatures recorded in the latter. This is likely due to temperature stratification near the loft area in the Great Hall—an aspect that recommends further investigation. In both rooms, the sinusoidal patterns in temperature reflect the natural daily cycles and fluctuations, with distinct peaks corresponding to periods of higher occupancy or system activation.

The Mezzofanti Hall results show a temperature of 1 °C to 1.5 °C lower than that of the Great Hall, and around 1.5 °C to 2 °C lower than the Special Collections Room.

When comparing relative humidity values (Figure 9), greater variability is evident, especially in the Great Hall and Special Collections Room, where fluctuations of up to +3% to +5% are recorded throughout the days. A more pronounced shift is observed around September 13, with humidity levels in these two rooms exhibiting a sharp ±15% change before and after this date. This sudden fluctuation likely correlates with external weather changes or adjustments to environmental control systems within these spaces.

In contrast, the Mezzofanti Hall, which serves as an archive, maintains a notably stable microclimate. The relative humidity in this room shows minimal fluctuations, both throughout the day and over the entire monitoring period, highlighting the controlled and consistent environmental conditions that are crucial for the preservation of sensitive archival materials. The difference between the dynamic microclimate conditions in the

Great Hall and Special Collections Room and the steady, regulated environment in the archive is particularly evident, emphasizing the varied microclimate demands across different areas of the library.

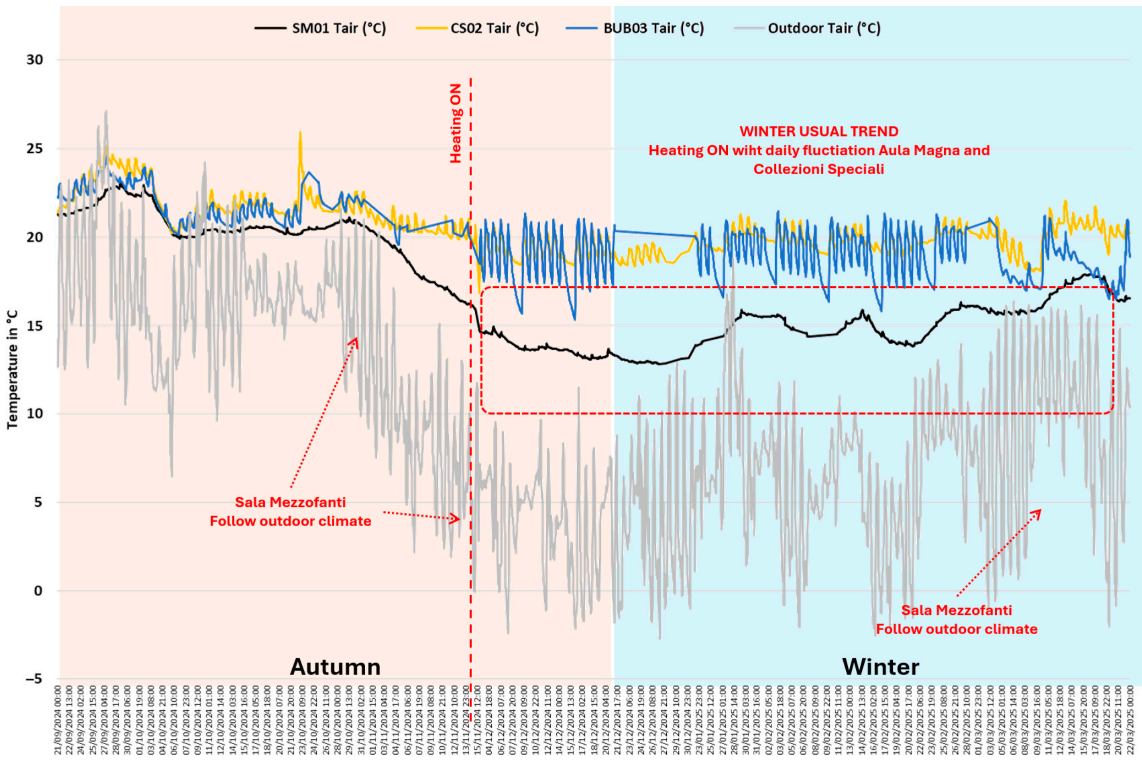

Figure 8. A comparative analysis of the air temperature trends in the three rooms and outdoor temperature (Regional Meteorological data Dexter ARPA). Source: Kristian Fabbri.

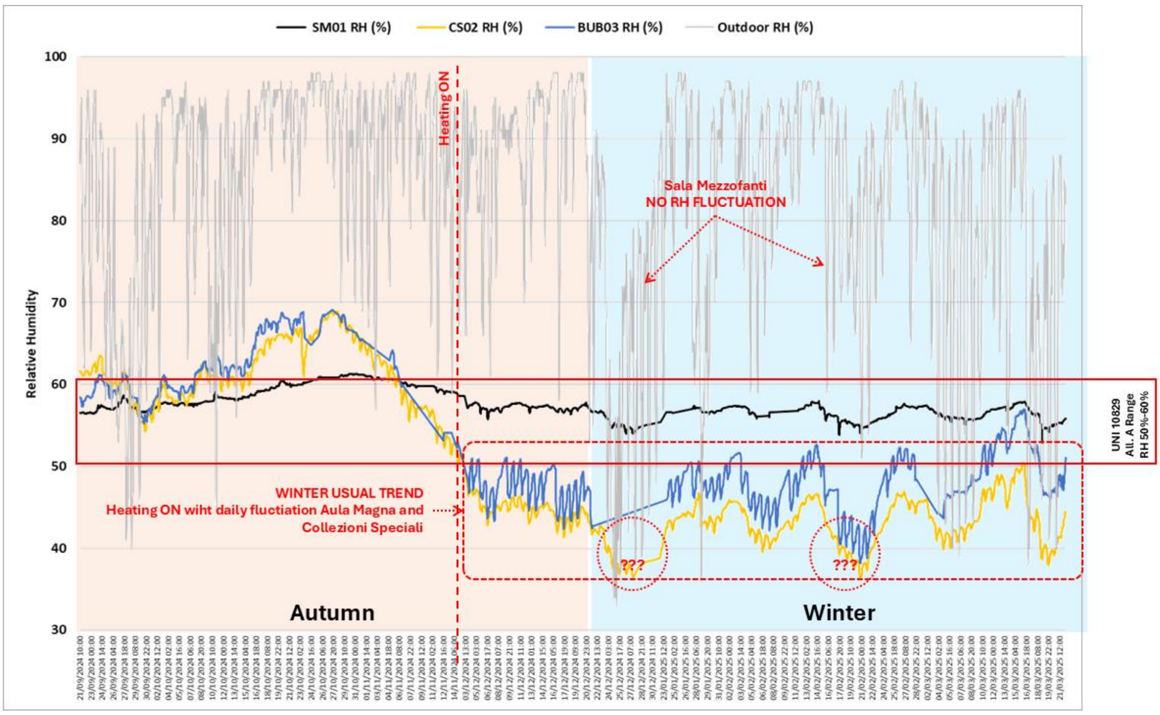

Figure 9. A comparative analysis of the relative humidity trends in the three rooms and the outdoor relative humidity (Regional Meteorological data Dexter ARPA). Question marks indicate data values that deviate from the overall trends. Source: Kristian Fabbri.

3.2. Indoor Microclimate on Psychrometric Chart

The psychrometric diagram is a valuable tool used across various disciplines, particularly in the study of indoor microclimates, assessing human thermal comfort, and designing air treatment systems. By plotting the distribution of measured data points on a psychrometric chart, it is possible to characterize the microclimate of indoor environments.

In the specific context of the BUL, even though the monitoring period has been 6 months, we can already derive some significant insights. Figure 10 illustrates the data recorded by the four probes plotted on the complete ASHRAE Psychrometric Chart, while Figure 11 provides a detailed elaboration created for further analysis.

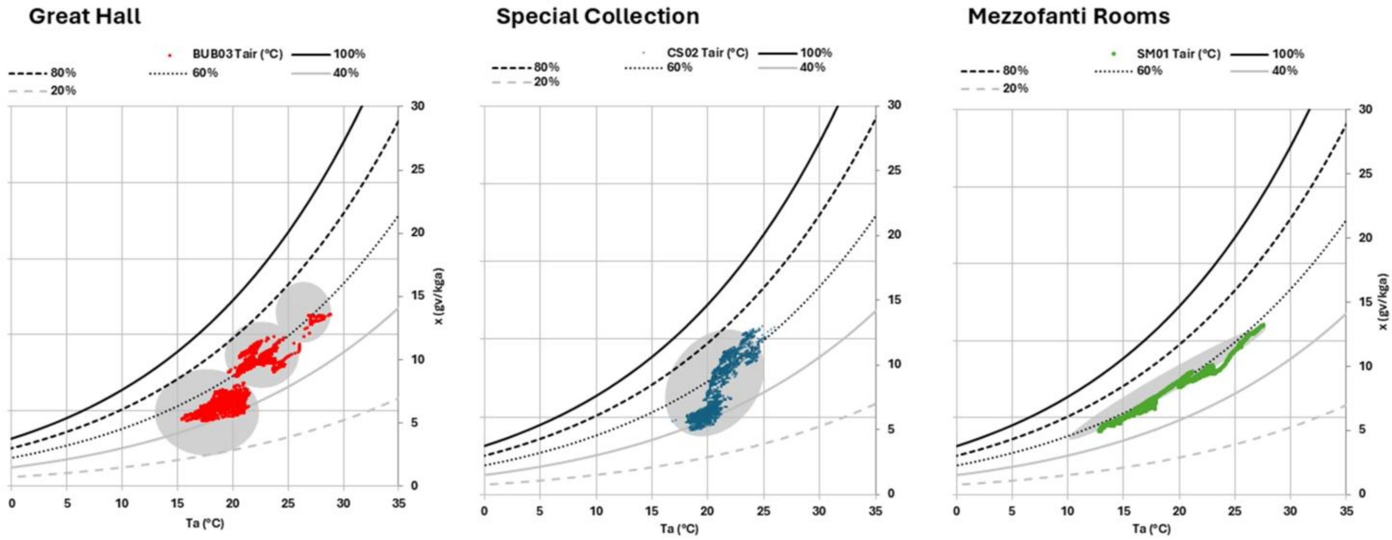

Figure 10. Psychrometric Chart for each environment. It is possible to note the data distribution (grey area). Source: Kristian Fabbri.

The data collected by the BUL probes (represented in red and blue) exhibit a distinctive pattern of disaggregated and distributed values, which seem to cluster around two distinct poles. This configuration is indicative of air-conditioned environments, where the distribution of points often forms a double elliptical pattern, reflecting the cyclical nature of the air treatment system's operation.

In contrast, the Special Collections Room (represented in orange) shows a more compact, circular point cloud, which is characteristic of air-conditioned spaces with constant occupancy and controlled microclimate conditions. The elliptical-to-circular shape of the point cloud is typically observed in environments where both temperature and humidity are actively regulated and the presence of people introduces regular heat and vapor loads, further stabilizing the environmental conditions.

Finally, the data from the Mezzofanti Room (represented in green) displays a markedly different distribution. The points form an elongated, almost linear ellipse, following a line of constant relative humidity (RH = 60%). This distribution is typical of non-air-conditioned environments, where there are no significant internal heat or vapor sources, such as human occupancy or mechanical systems. In this case, changes in the indoor microclimate are driven primarily by outdoor temperature variations, while relative humidity remains stable, showing minimal fluctuation. This type of linear pattern reflects the natural response of an environment to external climatic changes, with little internal disruption to the microclimate.

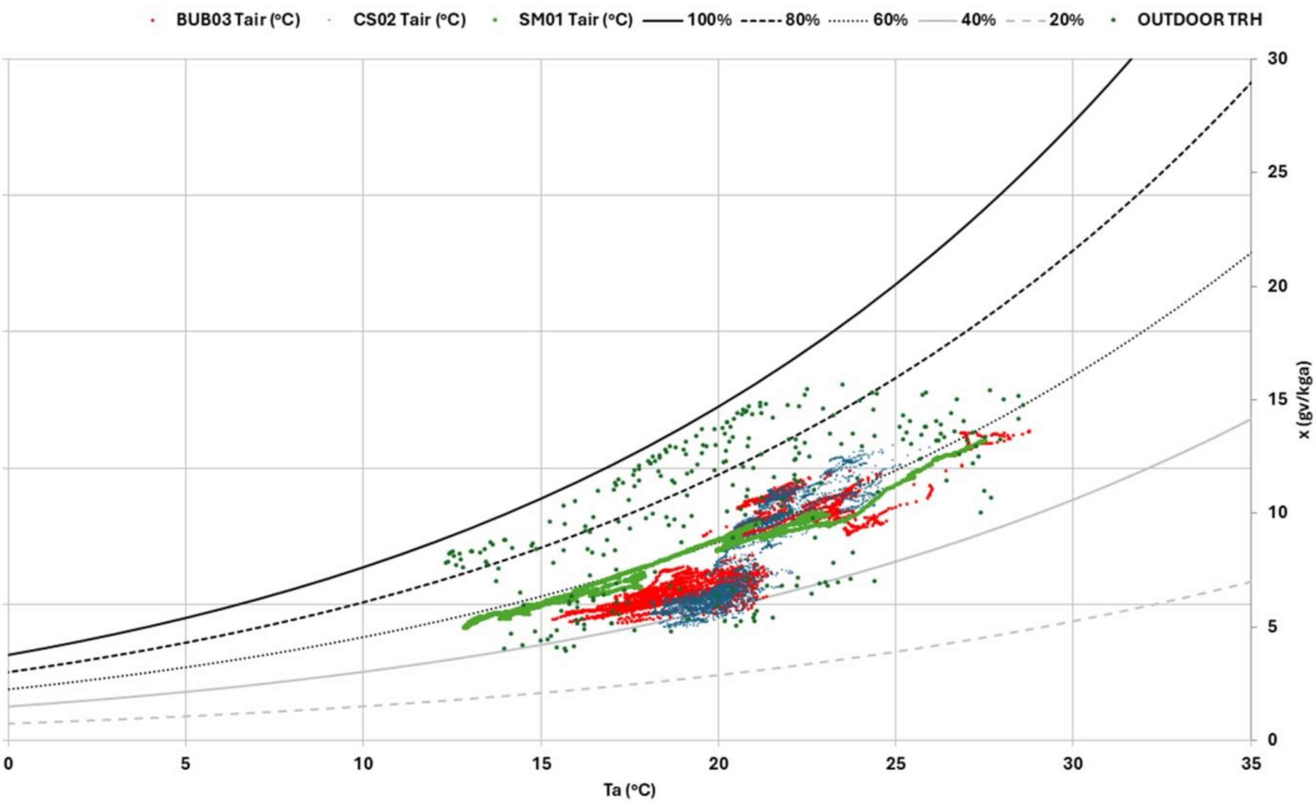

Figure 11. Psychrometric Chart. Source: Kristian Fabbri.

In summary, the psychrometric diagram provides a clear visual representation of how different environments within the library—whether air-conditioned or not—behave in terms of temperature and humidity. The BUL probes show a typical air-conditioned behavior, the Special Collections Room demonstrates controlled conditions suited for preservation and occupancy, while the Mezzofanti Room exhibits a stable, naturally regulated environment, ideal for archival storage.

3.3. Carbon Dioxide Values and Human Presence

At the moment, the BUL has no occupancy data or visitors' logs about human presence. The Special Collection room is solely occupied by employees and, occasionally, researchers for no more than 10 people; the Mezzofanti room is an archive, and nobody enters it except for a few employees. Finally, in the Great Hall, more than 10 individuals are registered only during events such as conferences or seminars, as shown in the graphs.

The graphs depicting the trend of Carbon Dioxide (CO_2) values (see Figures 12 and 13) show readings between 400 ppm and 500 ppm (represented by the gray area), which correspond to the baseline CO_2 concentrations typically found in indoor environments. It is common to observe CO_2 levels indoors that are approximately 400 ppm higher than those recorded outdoors, as indoor air is influenced by human activity. These results align with standard CO_2 concentration values reported in the literature for indoor spaces.

CO_2 is widely regarded as a reliable indicator of human presence in enclosed environments, as it is directly emitted through respiration. Both graphs exhibit a sinusoidal pattern, reflecting daily occupancy patterns: CO_2 levels rise sharply during the working day as people enter the rooms, reaching a peak, and then gradually decline (diluting) during the evening and night hours when the rooms are unoccupied.

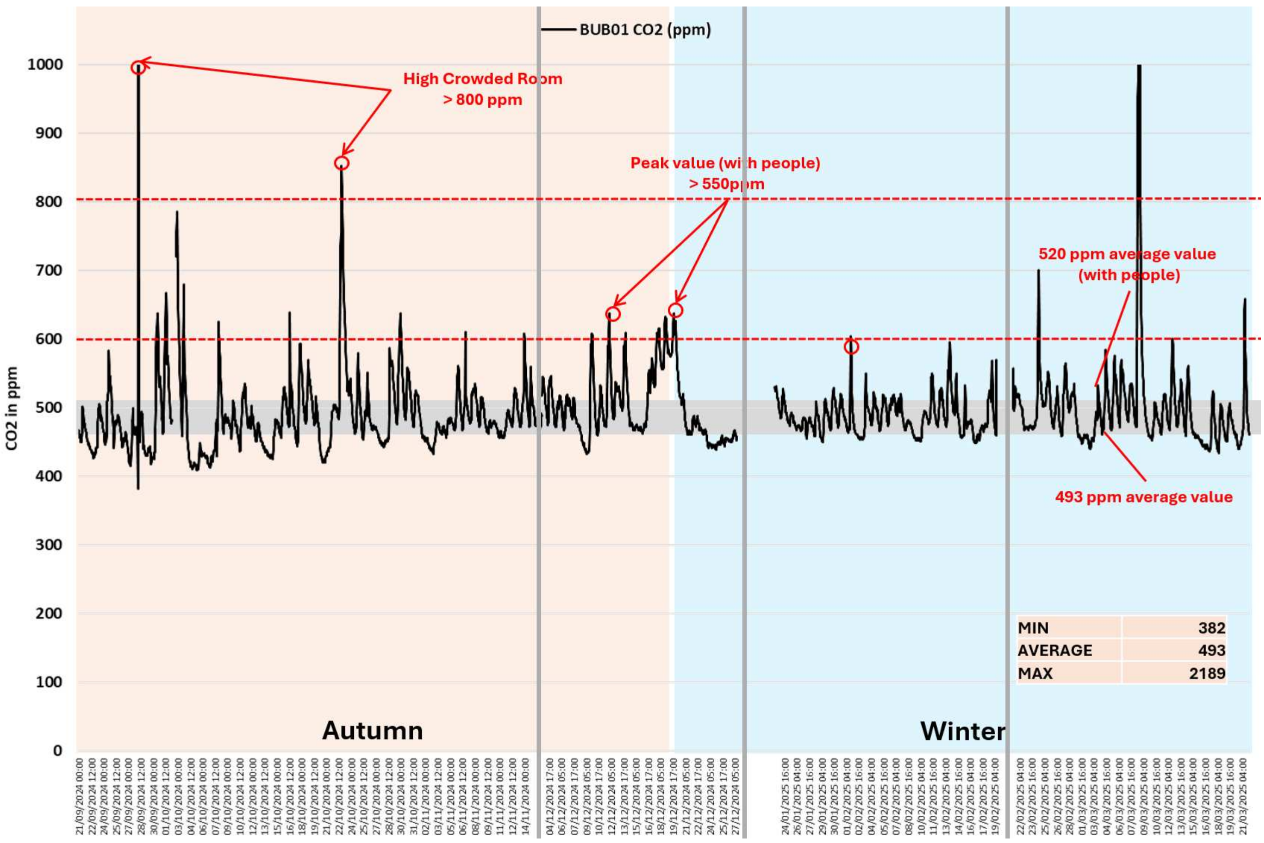

Figure 12. Great Hall, CO_2 emission trends. Source: Kristian Fabbri.

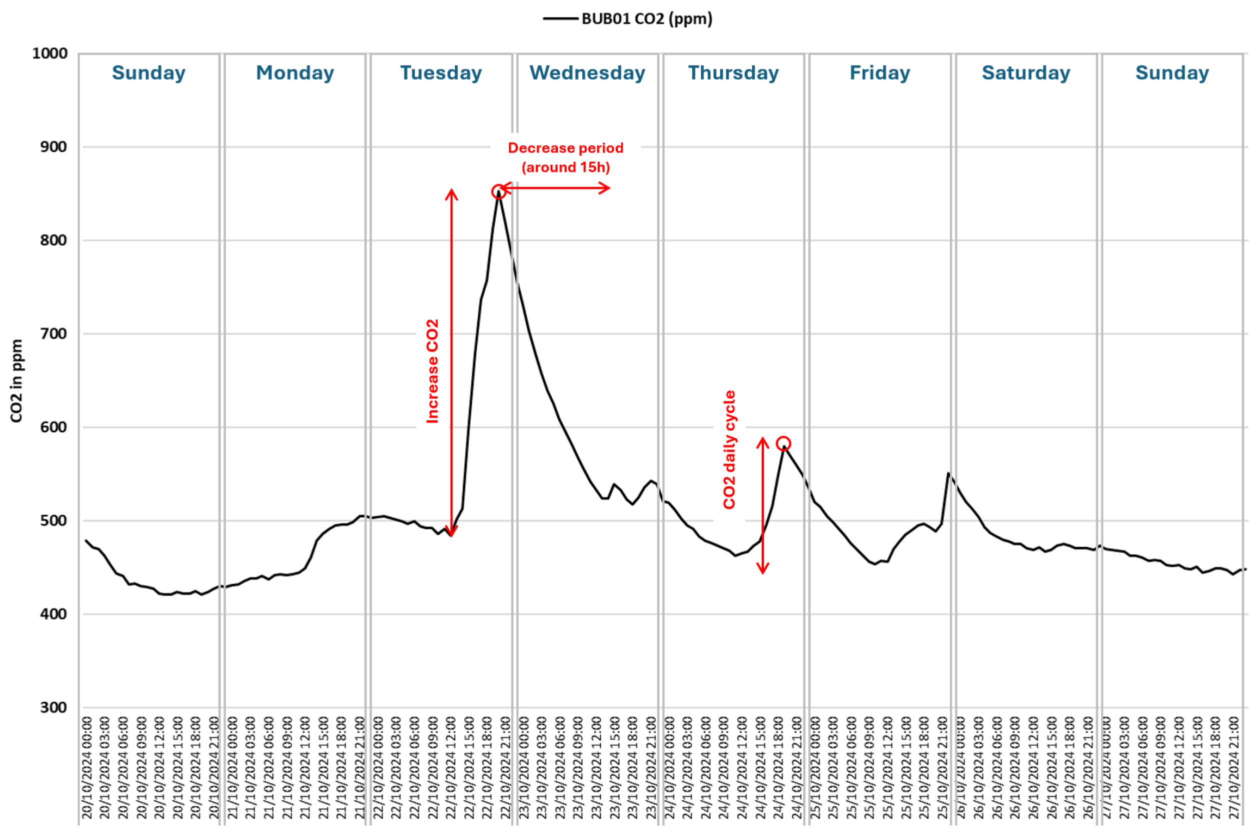

Figure 13. Great Hall, CO_2 emission trends in a week. Source: Kristian Fabbri.

In the Special Collections Room (Figure 14), the CO_2 peaks closely follow the working hours, clearly demarcating periods of activity. It is important to note that the probe in this room is positioned near the staff workstations, making the CO_2 levels highly sensitive to staff presence and daily routines.

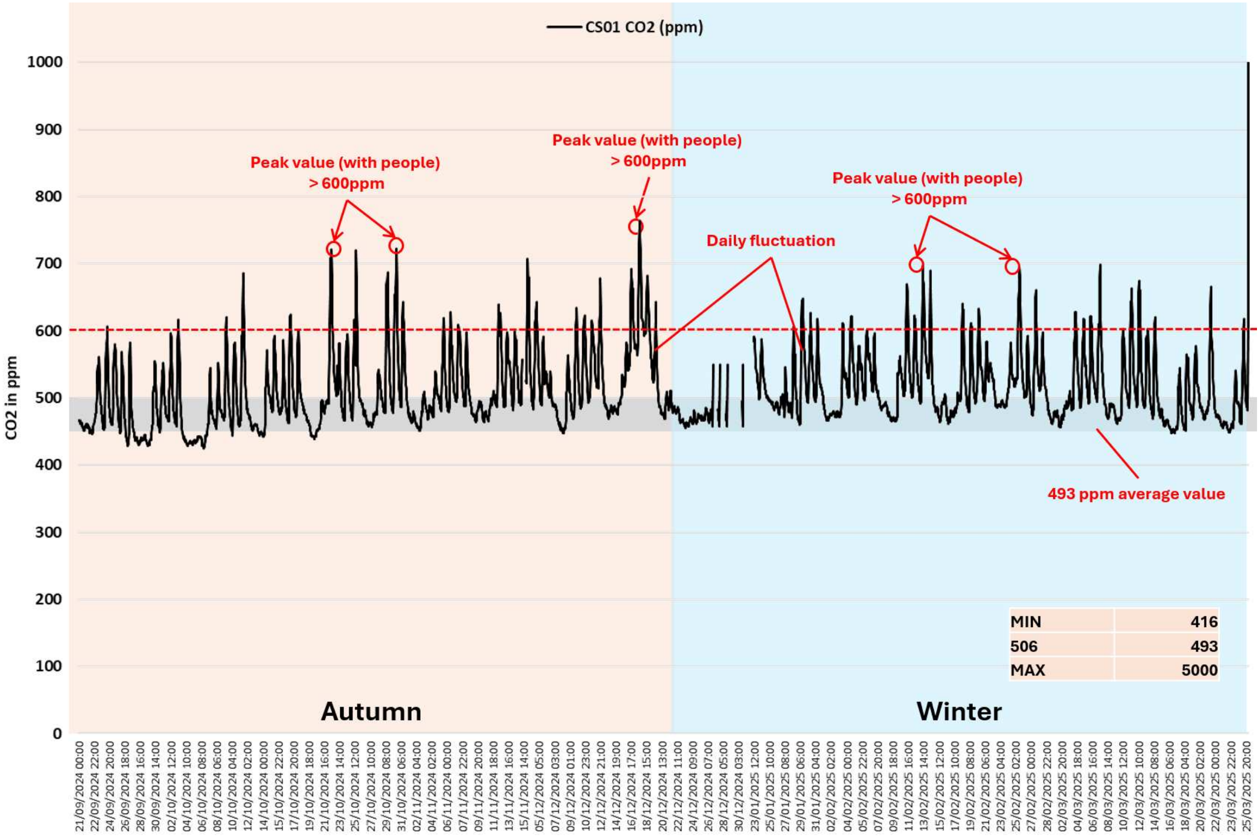

Figure 14. Great Hall, CO_2 emission trends in short monitoring period. Source: Kristian Fabbri.

In the Great Hall, by contrast, there is a noticeable spike in CO_2 levels up to 900 ppm at noon on 27 September, which is likely caused by a momentary increase in the number of people present in the room or near the probe. This could be due to a small event, meeting, or gathering that temporarily heightened CO_2 levels. Such spikes are significant as they highlight variations in occupancy and the need for ventilation adjustments to maintain optimal air quality in large, periodically crowded spaces.

Overall, the data indicates that CO_2 levels are closely tied to human occupancy in both rooms, with predictable daily cycles. However, localized spikes, such as the one observed in the Great Hall, underscore the importance of real-time monitoring to effectively manage indoor air quality, particularly during events or periods of increased foot traffic.

4. Discussion

4.1. Short-Term Indoor Monitoring

The EN 15757 [36] requires at least one year of monitoring for a complete understanding of the historical climate ("*Historical climate: 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 one year) and to which it has become acclimatize*", point 3.5) [4–6,8,13,19]. As already pointed out, this paper is not intended to address the topic of "historic climate" following EN 15757, but the validity and calibration of the monitoring system itself. Thus, one year of monitoring is not the appropriate timeframe. This research and the related case study show that a "short-term indoor monitoring" allows one to obtain the necessary data to drive the monitoring campaign to guarantee the validity and reliability of the collected data. The scientific literature reports several research experiences referring to heritage building indoor monitoring with durations of less than one year [41–57]. These contributions lead to highlight the autonomous characteristics and potentialities of the short-term indoor monitoring in heritage buildings and museums, reporting useful results. This topic was also addressed in Fabbri et al. [19] where, in the "1.1 Observations about the Monitoring Period: Several Kinds of Approach" paragraph, a list of articles with monitoring periods of less than one year is provided.

The following paragraphs delve into the discussion of the results of the BUL case study, adding a contribution to the aforementioned literature and to the state of the art of experimental studies on microclimate monitoring in heritage buildings, in particular historic libraries.

4.2. Effectiveness of Indoor Microclimate Monitoring Systems in Heritage Buildings

The results of this research are significant in demonstrating how extremely useful an indoor microclimate monitoring system can be. Its presence, in fact, allows hypotheses and strategies to be formulated as early as the initial data acquisition phase. This is advantageous for two reasons: on the one hand, it allows us to assess whether the sensor layout, the radio data transmission system, communication via Wi-Fi, and cloud interrogation are suitable for the specific case without having to wait a year of monitoring; on the other hand, the first data allows us to make hypotheses on how the rooms are used in relation to various activities, such as the lending of artifacts, books or manuscripts, and/or on the possibility of extending the monitoring system, for example, to the Marsili Museum, which, in our case, is located in a neighboring room.

Regarding the first aspect mentioned above, thanks to the flexibility of the LSI Sphensor system and the radio data transmission system, homogeneous data was obtained even when the reposition of one of the two probes on the balcony was necessary after the first three weeks of monitoring. The implementation of a monitoring system inside heritage buildings requires a longer settling-in period than in other building typologies. The main reasons are: (a) the geometric configuration of the rooms, which are often large, such as the Great Hall, and have thick walls, affecting the radio transmission of the probes; (b) the need to keep the probes/sensors out of sight of visitors because they would alter the architectural quality of the places and, in some cases, could be stolen or tampered by visitors; and (c) the fact that the technological infrastructure is constrained and cannot be modified, particularly the electrical and computer networks. In the case of the BUL, the last aspect implied the involvement of the library technicians and of the CESIA, the Information Systems and Services Area computer scientists of Bologna University.

The results of the short-term monitoring period make it possible to "adjust the monitoring campaign on the run," using the "trial and error" method (sometimes just "error and fix it") and to evaluate its usefulness, both for the technical and strategic aspects of library management. The results about the evaluation of the concentration and trend of CO_2 as well as its dilution time provide useful information regarding the use of the rooms for activities not planned or not yet established, such as the use of the Great Hall for conferences, which is used sporadically, or such as the inclusion of the BUL in the museum itinerary of Palazzo Poggi, which will result in a significant increase in the presence of people.

Processing data using psychrometric diagrams remains cumbersome. Nevertheless, the identification of the role of thermal systems in the winter season and of the difference in the archive microclimate compared to other environments is already possible.

Compared with the previous research conducted on BUL in the ROCK project during the 2018–2020 period, the flexible, catalog-based system used in the current monitoring campaign provides greater assurance of continuity in data collection. In fact, due to the COVID pandemic and other problems in the system setting, the ROCK monitoring was discontinued. In designing the new monitoring system, a different sensor architecture was chosen in order to ensure continuity over time. In the previous ROCK research, the first phase took about 3 months before useful data could be obtained. During the three months, although data production was underway, action had to be taken by changing the position of the probes, replacing the batteries, and rechecking the data connection and the power grid. This resulted in wasting time and uncertainty about the validity of the data produced. On the contrary, the research described in this paper aims to return the results of the first phase of settling on data monitoring, the importance of which has been understood through previous experience.

4.3. Improvements and Extension of the Monitoring System

Regarding the second aspect, the BUL is incorporated in Palazzo Poggi which is part of the University Museum Network of the University of Bologna (www.sma.unibo.it/en, accessed on 22 May 2025). The catalogue of the Palazzo Poggi Museum is a journey through naturalistic collections, xylographic matrices, maps and naval models, and anatomical preparations in wax and terracotta, all of which tell the story of the Ulisse Aldrovandi Museum and the Institute of Arts and Sciences. The University Museum Network includes four other museums and collections on Via Zamboni, within a hundred meters from the BUL: Specola Museum of Astronomy, European Museum of Students (MEUS), Geological Collection “Giovanni Capellini Museum” and Mineral Collection “Luigi Bombicci Museum”, to which are added the more distant university museums on Via Irnerio (Botanic Garden and Herbarium, “Luigi Cattaneo” Anatomical Wax Collection, Collection of Physics Instrument) e on Via Selmi (Zoological Collection, Giacomo Ciamician Chemistry Collection, Comparative Anatomy Collection).

The extension of the monitoring system to the entire Poggi Museum or the entire museum network, given its relevance, could be a very interesting development of the current experimentation. It may facilitate the choice of strategies for the preservation, display, and enjoyment of museum assets, not only for the benefit of scholars but also for the large university population that frequents the area, visitors, and citizens (Figure 15).

The first phase of the monitoring system required a series of trials and errors, particularly for both radio data transmission and communication by the Wi-Fi network. We optimized indoor monitoring systems thanks to BUL’s electrical engineers and the support of CESIA. During September–November 2024, a signal settling was necessary to change the position of one probe because the radio signal could not pass through the thick walls at the frequency of 2.7 GHz. Moreover, in the first phase, the electrical system was turned off at the end of the day by the janitors, resulting in the loss of data in the early morning hours and at weekends. Again, thanks to the support of the BUL staff, the problem was solved by leaving the system on all the time.

The coordination among those involved made it possible to ensure the continuity of the monitoring system. In spite of this, it is recommended to adopt LoRa (Long Range) radio transmission in the future, which allows thick walls to be traversed. Another aspect concerns the wiring of electrical networks, which the administration plans to upgrade in the future; the ideal solution is to equip the BUL with its own electrical system with the possibility of continuous power supply.

Figure 15. The Bologna University Museum Network around Palazzo Poggi (in the red circle). Source: map elaboration by the authors.

The results of the current monitoring campaign, as reported in Section 3, show the role of thermal systems, which, at present, are not optimized with respect to the needs of the place, as they cause several thermal fluctuations. At this stage, it is not possible to intervene in the air conditioning systems, since it is centralized for the whole building. It is desirable that the results of at least one year of monitoring will support the demand for a different and dedicated management system.

4.4. Indoor Microclimate as Benchmarking

The results of this study proved useful in defining and verifying the reliability of the monitoring system and of the initial measured results. Monitoring the indoor microclimate in these heritage buildings, representative of historic libraries, allows us to know and predict possible conditions of degradation or risk that may also affect the precious stored materials. The ongoing monitoring enabled the definition of the benchmarking for future planned changes in the use of the Great Hall and the adjacent rooms. As mentioned, in fact, the BUL will be included in the Ateneo museum itinerary, a condition that will result in an increased pollutant load, particularly water vapor and dust, due to the presence of visitors. The determination of the monitoring baseline allows us to assess how the indoor microclimate will change in the future. Most importantly, we verified that the measurements were within the thresholds defined by the standard, in particular UNI 10829, and there were no abnormal values for book conservation. Moreover, the presentation of the data collection and analysis implemented in this first phase provided the opportunity to discuss with the Library Director the relevance of such a monitoring campaign and highlight the future possibilities for its continuation and improvement. Establishing this kind of data-based and evidence-generated dialogue with those in charge of the management and planning of cultural heritage protection and enhancement is very important because it makes it possible to benefit from the different competencies and to chart a shared course of action for interventions and activities.

4.5. Methodology Characteristics and Transferability

The methodology of the study is designed as a mixed-methods approach with a strong emphasis on quantitative data collection and analysis, supported by qualitative assessments to validate and contextualize the technical setup. Table 2 summarizes and lists its key features in order to allow transferability and application in other heritage contexts.

Table 2. BUL case study key features: quantitative and qualitative methodological aspects. Acronyms: DA: Bologna University Department of Architecture; BUL: Bologna University Library; CESIA: Information Systems and Services Area of the Bologna University.

Methodology	Phase	Details	People Involved
Qualitative	Sensor positioning	limited by heritage décor visitor visibility; avoid damaging historical interiors; balance between ideal sensor placement and heritage preservation	BUL director DA researchers
	Trial-and-Error Approach	probes repositioned due to radio signal loss; electricity network limitations (e.g., power cuts); collaboration with library and CESIA IT staff to ensure functionality	DA researcher BUL technicians CESIA IT
Quantitative (measured data)	Instrumentation (type, numbers, etc.)	multi-parameter sensors: Temperature, RH, CO_2, VOC, PM. Placement considers room geometry and signal transmission	DA researchers
	Data Collection	short-term monitoring period, 6 months (September 2024–February 2025)	DA researchers
	Data Analysis	variables trends; data gaps or bugs; CO_2 trends and occupancy patterns	DA researchers

In synthesis, the methodology is primarily quantitative in terms of data acquisition, sensor-based monitoring, and environmental parameter analysis. However, it integrates qualitative, contextual, and adaptive elements crucial for research in complex, historically sensitive environments. This dual focus allows the researchers to ensure both scientific rigor and practical applicability in heritage conservation contexts.

The methodology developed for the BUL offers several features that make it transferable and adaptable to other heritage buildings, particularly those with similar constraints and conservation needs. These transferable aspects include the following:

- Preliminary short-term assessment: The focus on validating sensor positioning and data reliability before launching a long-term campaign ensures robust data collection from the outset. This staged approach is especially useful in contexts where system access, building usage, or technical limitations may change over time.
- Non-invasive installation criteria: the study demonstrates how sensor placement can be harmonized with heritage preservation requirements, including minimizing visual and structural intrusiveness. This is critical for listed buildings and spaces with decorative and artistic elements.
- Scalable sensor architecture: The modular setup using Sphensor multi-parameter probes and a cloud-based data infrastructure allows easy adaptation to sites of varying size and complexity. This is particularly valuable for institutions with multiple rooms or different functional uses (e.g., storage, exhibition, public access).
- Collaborative governance: The methodology highlights the importance of institutional collaboration (between researchers, facility managers, IT staff). Such a model can be replicated in multi-actor governance contexts typical of complex heritage sites.

5. Conclusions and Next Steps of Monitoring Activities

The research described in this paper is based on the results of the first phase of the Ecosister monitoring activities carried out in three monumental rooms in the BUL. This phase lasted 6 months (from September 2024) and will be followed by at least another 6 months. During this phase, the settling and verification of the monitoring system and the analysis of the related data were performed in three main rooms of the BUL. They are characterized by different morphological, climate, and usage conditions.

The autonomous importance of this first phase of the monitoring project with respect to the complete monitoring period emerged during the previous experience carried out within the ROCK project, and it is confirmed by the current Ecosister campaign. The specific assessment of the efficiency of the monitoring system and the reliability of the data at the initial stage of the activities enables understanding whether the data are usable or need to be adjusted. This allows us to avoid the risk of realizing only at the end of the campaign that unreliable, discontinuous, or biased results have been produced. This type of risk is particularly high in the case of historic and monumental buildings because of their morphological characteristics, such as the thickness of the masonry that might prevent data transmission, or the impossibility of positioning the probes in the most suitable detection points due to the presence of decorations. These constraints may affect the efficiency of the system and the quality of results.

The first phase of the project, which involved the complete installation and activation of the on-site monitoring system and the Cloud INDOOR CUBE platform, was successfully concluded: the results of the present study proved the monitoring activities to be stable and reliable. The approach proposed in this case study can be generalized and adapted to other heritage contexts.

This approach enables us to face strategic aspects related to library management. During this first phase, we discussed with employees and the Director, particularly regarding two aspects: the definition of alert ranges, to avoid too many alerts being sent via e-mail, and attendance management. The CO_2 graphs, as we described above, provide information about the days with the maximum peaks of CO_2 concentration corresponding to the conferences/events and the dilution time. Such information has been provided to the Director, and it will be considered by the museum network management to decide whether to increase or decrease the number of events and lectures. In addition, the 6-month data provide the basis for the discussion with the BUL management of BUL regarding the feasibility of extending the monitoring network to other premises and prolonging its duration. The compatibility of the inclusion of the BUB in the University Museum System itinerary is also verified through the monitoring results, as confirmed by the BUL director. For these reasons, the research conducted so far can be useful to the scientific community target, especially from a methodological point of view, but also to the cultural heritage asset management target.

Being the monitoring system fully operational, the next steps of the research will focus on continuing the collection and analysis of data to accurately characterize the indoor microclimate of the Bologna University Library.

The primary objective of the second phase of the Ecosister monitoring project will allow the definition of the Historic Climate of the library in accordance with the UNI EN 15757 standard [14,19].

In addition to this, the next phase will include the following:

- Improving and extending the indoor monitoring systems with new sensors and probes to study air stratification in the Great Hall: A monitoring network extension to Marsili Museum and/or other rooms, and, when the BUL is included in the University

Museum Network, causing an increase in the visitors' flux, the purchase of a visitor counting sensor.

- Defining risk alerts and microclimate risk indices: This includes the development of Heritage Microclimate Risk (HMR) and Percentage Damage Risk (PDR) indices [5–7], which will provide early warnings for environmental conditions that may pose a risk to the preservation of heritage materials. These indices will preferably be defined towards the end of the year-long monitoring period, once sufficient data has been collected.
- Establishing the historical climate of the archive: This step is crucial for preparing condition reports for the lending of archival materials, ensuring that the environmental conditions of the library are suitable for both storage and transport.
- Defining criteria for the use of spaces: When the library is integrated into a new museum itinerary, criteria will be established to guide the appropriate use of its premises, particularly regarding visitor access. The impact of increased foot traffic and new uses of the spaces on the microclimate will be carefully evaluated. In addition, consideration will be given to extending the microclimate monitoring system to adjacent spaces, such as those housing the Marsili Museum, in order to ensure the continued preservation of both the library and the museum collections.

These next research steps will ensure a detailed and scientifically grounded understanding of the indoor environmental conditions in the library, enabling effective conservation strategies and enhancing its role as both a research institution and a cultural site.

Author Contributions: Conceptualization, A.B., D.L., K.F. and R.R.; methodology, D.L. and K.F.; software, K.F.; validation, K.F.; formal analysis, K.F.; resources, A.B. and D.L.; data curation, K.F. and R.R.; writing—original draft preparation, R.R.; writing—review and editing, R.R., K.F., D.L. and A.B.; funding acquisition, D.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the ECOSYSTER_Ecosystem for Sustainable Transition in Emilia-Romagna project (CF: 91449190379; Code: ECS_00000033; CUP: B33D21019790006), part of the Italian National Recovery and Resilience Plan (NRRP, in the context of NextGenerationEU) Mission 4, Component 2 Investment 1.5. https://ecosister.it/.

Data Availability Statement: Restrictions apply to the availability of these data. Data can be available only after the University of Bologna's permission. Please contact: danila.longo@unibo.it.

Acknowledgments: The authors thank Maria Pia Torricelli, BUL Director, and Francesco Citti for their valuable help; moreover, the authors thank the BUL and CESIA employees for their kind availability. The authors thank the LSI Lastem company (https://lsi-lastem.com/), especially Pietro Amendola, for his help in data collection.

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

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