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Impacts of Heatwaves on the Indoor Microclimate of Heritage Buildings Under Climate Change: A Case Study of the Malatestiana Library

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Abstract

The IPCC has emphasised the increasing impacts of climate change across multiple sectors, including cultural heritage. In response, UNESCO launched the Policy Document on Climate Action for World Heritage in 2023, offering guidance on mitigation strategies for historic sites. Cultural heritage faces risks not only from sudden catastrophic events—such as floods, droughts, and wildfires—but also from the gradual deterioration of buildings and artefacts due to shifting environmental conditions. Climate change further affects the indoor microclimate of heritage sites, including museums, archives, and libraries, which are critical to the long-term preservation of cultural assets. Heritage, including heritage buildings and both tangible and intangible heritages, are subject to changes; therefore, their conservation should be assessed to identify sustainable approaches. This study investigates how climate change and microclimate alterations impact the conservation of historic buildings without modern climate control, using the Malatestiana Library—a UNESCO Memory of the World site—as a case study. The library has preserved a remarkably stable indoor environment for centuries, without the introduction of heating, cooling, or major restorations. A monitoring campaign during the summer of 2024 assessed the effects of extreme heat events on the library's microclimate, comparing two internal spaces to examine the attic's role in mitigating thermal stress. Data from the 2024 heatwave are also compared with similar data collected in 2013. Results show a marked shift toward a more tropical indoor climate over the past decade, signalling new threats to the preservation of historic materials. These findings highlight the urgent need for adaptive conservation strategies to address the evolving challenges posed by climate change.

Keywords: climate change; heat wave; Malatestiana library; heritage building; indoor microclimate; historic libraries; heritage microclimate risk; historic indoor microclimate; indoor microclimate risk

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1. Introduction

The IPCC reports underscore the causes and consequences of climate change on human activities, spanning sectors such as agriculture, industrial production, the economy, and tourism, as well as its profound impact on urban environments and buildings [1–6].

1.1. From Environmental Risk to Climate Change

The literature addressing climate change effects on the microclimate of historic libraries is limited, with only a few case studies available. For instance, Turhan, C. et al. [7] examine its impact on historic Mediterranean libraries, particularly focusing on the Necip Paşa Library, built in 1827 in Tire-Izmir, Turkey. Another study by Cadelano G. et al. [8] investigates the thermal behaviour of libraries across past and future climate scenarios. Additional studies assess risk evaluation in historic libraries in Rome, Italy [9,10], while climate change also affects the presence of insects and fungi in monastic libraries [11]. The impact of climate change on cultural heritage extends to museums as well [12,13], with studies by Brimblecombe P. [14,15] further exploring these effects.

1.2. From Climate Change to Heatwaves and Overheating

While much of the scientific literature on climate change and the urban heat island effect focuses on the impact of energy consumption and the social and health effects of heatwaves on populations [16], only a few studies address their implications for cultural heritage. Some research examines the effects on historic city centres, such as in the Bilbao case study [17], or evaluates thermal comfort for occupants of historic buildings, as in the case study of the Basilica of Santa Maria in Trastevere in Rome by Figliola et al. [18]. However, to date, there appears to be a lack of research specifically investigating the direct effects of heatwaves on cultural heritage itself.

In a broader climate context, rising global temperatures are having a profound effect on the cultural heritage sector, with heatwaves emerging as a particular source of thermal stress for historical and artistic artefacts. Although there is no universal definition for heatwaves, they tend to be defined as "*A period of abnormally hot weather, often defined with reference to a relative temperature threshold, lasting from two days to months. Heatwaves and warm spells have various and, in some cases, overlapping definitions.*" [19]. Heatwaves alter the indoor microclimate, primarily by raising temperatures and causing overheating in indoor spaces. During heatwaves, thermal comfort deteriorates both outdoors [20,21] and indoors, especially in spaces lacking air conditioning [22,23]. In indoor environments, air-conditioning systems are typically relied upon to ensure human comfort.

Similarly, heatwaves induce thermal stress on historical and artistic artefacts, particularly fragile items such as manuscripts and books. However, maintaining "thermal comfort" for these artefacts by altering the indoor microclimate through air-conditioning systems is not always feasible or advisable.

A crucial aspect of this long-term degradation is the alteration of microclimates, especially due to changes in relative humidity. Climate change—through rising global temperatures, increased precipitation variability, and intensified tropical weather patterns—is disrupting the delicate balance of humidity that many heritage materials depend on for preservation. In temperate regions, the "tropicalisation" of weather—marked by the encroachment of tropical species and climatic conditions—is leading to heightened humidity levels and altered ecosystems [24]. Conversely, tropical and subtropical regions are experiencing an intensification of their inherent climatic traits, with exacerbated humidity and more extreme weather patterns. These changes pose significant risks to cultural heritage, as increased moisture and temperature fluctuations can accelerate the deterioration of materials and structures. Elevated relative humidity promotes mould growth, accelerates material decay (especially of organic materials like paper, textiles, and wood) [25–27], and causes swelling, warping, or corrosion of historical objects. These effects are further compounded in indoor environments where traditional climate control systems may struggle to cope with the increased moisture loads, thus threatening collections in archives, libraries, and historic interiors.

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1.3. Cultural Heritage and Built Heritage: UNESCO Framing

The impacts of climate change on cultural heritage are becoming increasingly evident, with flooding, in particular, causing extensive damage to historic buildings, artefacts, and archaeological sites [28]. In the Mediterranean region, Kapsomenakis et al. [29] have demonstrated a growing vulnerability of UNESCO World Heritage sites to the effects of anthropogenic global warming and extreme weather events. Central Europe has experienced similar challenges over recent decades, with major fluvial floods in 2002, 2009, 2014, and more recently in 2023 and 2024 severely affecting cultural landmarks, especially in Italy's Romagna and Tuscany regions [30]. At the same time, the rise in wildfire frequency, driven by increasingly dry climatic conditions, has further endangered heritage structures, as evidenced by recent devastating events in Greece [31,32] and Portugal [33–35]. These impacts also affect the cultural heritage sector, including historical sites, archaeological remains, landscapes, and historic architecture. Cultural institutions such as museums and libraries, along with individual artefacts—such as paintings, books, manuscripts, frescoes, and statues—are increasingly vulnerable to environmental stresses.

In response to the challenges posed by climate change, UNESCO has launched several initiatives to enhance knowledge, education, and communication in this field (https://www.unesco.org/en/climate-change, accessed on 6 November 2025), and actively participates in the COP Climate Conferences. In 2023, UNESCO introduced the Policy Document on Climate Action for World Heritage [36–38], which, in Annex II, focuses specifically on the built environment. Drawing on the IPCC's 2018 Special Report on Global Warming of 1.5 °C [2], it proposes measures such as retrofitting historic buildings for greater energy efficiency, applying traditional passive strategies to reduce energy use, and promoting the integration of new technologies into historic structures.

However, the document primarily addresses ways to mitigate cultural heritage's contribution to climate change, rather than focusing on the vulnerability of heritage buildings to the changing climate itself. Moreover, when the impact of climate change on cultural heritage is discussed, the emphasis falls largely on natural and landscape heritage sites—such as the Great Barrier Reef, Komodo National Park, the Greater Blue Mountains, and historic cities like Venice, London, Prague, and Timbuktu [39,40].

While current international policy efforts, such as those by UNESCO, have rightly emphasised the need to address catastrophic events and reduce cultural heritage's carbon footprint, they tend to overlook the slower, cumulative impacts of climate change on historic structures. To better understand these threats, the risks posed by climate change to cultural heritage can be broadly divided into two categories. On the one hand (a), there are acute, high-impact risks associated with extreme events such as floods, wildfires, or storms that can devastate large areas within a short period—days or weeks. On the other hand (b), there are more insidious risks related to long-term climate shifts that lead to gradual but persistent degradation. These include impacts on single buildings, historic city centres, archaeological sites, and particularly indoor environments within heritage spaces such as historic buildings, museums, archives, and libraries. This second category of risk, though less dramatic and often overlooked by media, affects a vast number of artefacts and heritage structures, slowly deteriorating them over time.

In the scientific literature, the relationship between cultural heritage, historic buildings, and climate change has primarily focused on mitigating the relatively minor environmental footprint of heritage structures. Much of this research addresses strategies for reducing the impact of historic buildings on climate change, often through case studies on energy retrofitting, minimising energy consumption, and applying green architecture solutions [41–44]. In contrast, the effects of climate change on cultural heritage itself have received comparatively less systematic attention, although several important strands of research have emerged. Studies have examined the vulnerability of historic city centres and individual buildings to climate-related risks (Pinheiro et al. [45]), as well as the impact of changing climates on the indoor environments of heritage structures, particularly in warmer regions (Bievenido-Huertas et al. [46]). Other work has focused on the processes of building deterioration (Prieto et al. [47]) and material degradation under evolving climatic conditions (Janssens et al. [48]). Additionally, scholars have developed methodologies for assessing climate change impacts on cultural heritage (Rajčić et al. [49]), while efforts to implement preventive conservation measures in museums and similar institutions have been documented (Lucchi [50]).

The study by Lharti et al. [51] on the thermal behaviour of the Lascaux Cave demonstrates that "the cave's internal temperature is closely linked to external temperature variations; we could show that the climate change observed in the external temperature is also observed inside the cave." Similarly, the indoor temperature of cultural heritage sites and historic buildings is influenced by outdoor climate conditions, both over long-term trends and during short-term events such as heatwaves.

1.4. Heatwave Effect in Indoor Environments of Historic Building Without Air Conditioning

There remains, therefore, a significant gap in understanding how gradual, climate-induced alterations to the microclimate—rather than immediate catastrophic events—affect the long-term conservation of historic buildings, a library, particularly those without modern climate control systems.

This study addresses this overlooked aspect by examining the Malatestiana Library, a UNESCO Memory of the World site. Through microclimate monitoring during recent extreme heat events, this research provides new evidence on how subtle, progressive shifts in environmental conditions are beginning to challenge traditional conservation practices, highlighting the need for adaptation strategies specifically tailored to historically passive, non-air-conditioned heritage sites.

Historically, the destruction of libraries and books has often resulted from deliberate acts such as arson, war, or ideological purges—as seen in the Nazi book burnings in Munich in 1934, as described in Bàez F.'s book [52]. However, today, many collections are at risk from more passive but equally destructive forces, such as flooding or long-term neglect. In the context of climate change, even well-maintained heritage collections are vulnerable unless proactive strategies are implemented to monitor and adapt indoor environmental conditions. The safeguarding of our cultural memory requires urgent attention—not only in response to dramatic events but also in anticipation of the slow, silent damage caused by a changing climate.

In recent years, climate change and the increasing frequency of heatwaves have significantly altered the indoor microclimate of historic buildings, museums, and libraries, introducing new risk factors for the preservation of cultural heritage. Scientific literature and relevant standards [53–61] have developed the concept of the "historical microclimate," referring to the stable environmental conditions to which artefacts have gradually acclimatised over their lifespan. Prestigious sites such as the Scrovegni Chapel [62,63], Leonardo da Vinci's *The Last Supper*, and the Sistine Chapel exemplify heritage spaces that maintain preservation without the use of modern air-conditioning systems—an approach still common among churches, archaeological sites, and many historic buildings.

Standard EN 15757 [55] is the main reference regarding "Conservation of cultural property"; it is a "guide specifying temperature and relative humidity levels to limit climate-induced physical damage of hygroscopic, organic materials, kept in long-term storage or exhibition (more than one per year) in indoor environments of museums, galleries, storage areas, archives, libraries, churches and modern or historical building."

Standard EN 15757 underscores the importance of maintaining historical microclimates, particularly in buildings where the installation of mechanical climate control would compromise their artistic or historical integrity. In such cases, the indoor environment naturally adapts to external climatic shifts, a process that can be beneficial, as artefacts often acclimatise over long periods to their original ambient conditions. However, recent studies, such as that by Kumar et al. [64], highlight the emerging risks of overheating in historic structures, noting its detrimental effects on both building performance and the thermal comfort of occupants, particularly in the UK context.

Meanwhile, museums, libraries, and historic sites that introduced air-conditioning systems during the 20th century to improve human comfort created entirely new microclimates, often forcing artefacts to undergo accelerated and sometimes stressful acclimatisation processes. Overall, evidence suggests that cultural artefacts preserved within stable, long-standing historical microclimates tend to suffer less damage over time, whereas abrupt or unmanaged shifts in environmental conditions pose greater threats to their conservation.

Despite growing recognition of the vulnerability of cultural heritage to climate change, significant gaps remain in both policy frameworks and scientific research. Current international efforts, such as those led by UNESCO, primarily emphasise mitigation strategies and the protection of natural and landscape heritage, with less attention given to the gradual degradation of built heritage due to slow environmental shifts. Similarly, while the scientific literature acknowledges the importance of preserving historical microclimates, most studies focus either on reducing the carbon footprint of heritage buildings through retrofitting or on the impacts of extreme weather events, rather than on the subtle yet critical effects of long-term climate alteration on indoor environments.

This study seeks to address these gaps by exploring a key research question:

- How and to what extent do climate change and microclimate alterations affect the preservation of historic buildings and cultural heritage sites without air conditioning, both currently and in future projections?

Through a detailed case study of the Malatestiana Library, this research aims to provide empirical evidence of how historic indoor environments are evolving under contemporary climate pressures, and to assess the implications for future conservation strategies.

The layout of the paper is as follows: Section 2 elaborates on the research context to explain specific issues; Section 3 describes the case study of the Malatestiana Library; Section 4 presents the research methodology and monitoring campaign; Section 5 shows the results of the 2024 monitoring campaign with a comparison of Sala Piana and Malatestiana Library to explain the role of the attic and a comparison of the effect of the 2013 and 2024 heatwaves on Malatestiana Library's indoor microclimate. The latter is the main point of discussion in Section 6, where we highlight the risk of Microclimate Tropicalisation; finally, in Section 7, "Conclusions", we discuss future conservation strategies.

2. Research Context

This study examines the impact of climate change on a prestigious UNESCO heritage site: the Malatestiana Library in Cesena, Italy. Built in the 15th century, the library has maintained an exceptionally stable indoor microclimate for centuries, without the introduction of any thermal systems—an ideal condition that has ensured the perfect conservation of its manuscripts, furnishings, and architectural elements. However, in recent years, prolonged and intense summers, particularly in 2022, 2023, and 2024, have raised concerns about possible alterations to this historically stable environment. Observations from the library's Scientific Director, Paolo Zanfini, along with reports from custodians and tour guides, suggest that noticeable changes may be occurring.

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To investigate these concerns, this research presents the results of a microclimatic monitoring campaign conducted during the summer of 2024, building on comparable data collected a decade earlier, in 2013. Through this case study, the project aims to assess how climate change and recurrent heatwaves are affecting the preservation conditions of heritage buildings and their conserved artefacts, with a particular focus on the manuscripts housed in the Malatestiana Library—the world's oldest surviving humanist library.

The analysis concentrates on two main aspects:

- first, the role of the library's architectural form, including the attic space, in mitigating thermal stress during extreme heat events; and
- second, the broader impact of climate change on the indoor microclimate over the past decade.

The Malatestiana Library offers an especially valuable case study due to the diversity of its internal environments, which allows for a detailed examination of how different architectural features respond to external climatic pressures.

Concerning the research, we would like to clarify that the aim of article is not to demonstrate climate change itself but just to highlight a heritage case study where the effect of climate change is evident, even just from a comparison of two results spaced 10 years apart. As we reported below, the results show a ongoing change; we called it "Microclimate Tropicalization". "Tropicalization" means "the quality or state of being tropicalized"; in other words, "to tropicalize" is to become like the tropics, with increases in water vapour, specific humidity, temperature, and relative humidity, as in a tropical climate. The indoor "Microclimate Tropicalization" refers to an increase in both indoor temperature and relative humidity. The monitoring results and ongoing monitoring campaign should be used to decide possible future adaptation strategies or management decisions.

3. Case Study: The Malatestiana Library

The Malatestiana Library in Cesena, Italy (Figure 1) is a complex of buildings (Figure 2) constructed on the site of the former Convent of San Francesco. It includes:

- The Ancient Library (Sala del Nuti);
- The Piana Library (Sala Piana);
- The Wooden Hall (Sala Lignea, 18th century);
- The Modern Malatestiana Library (20th century).

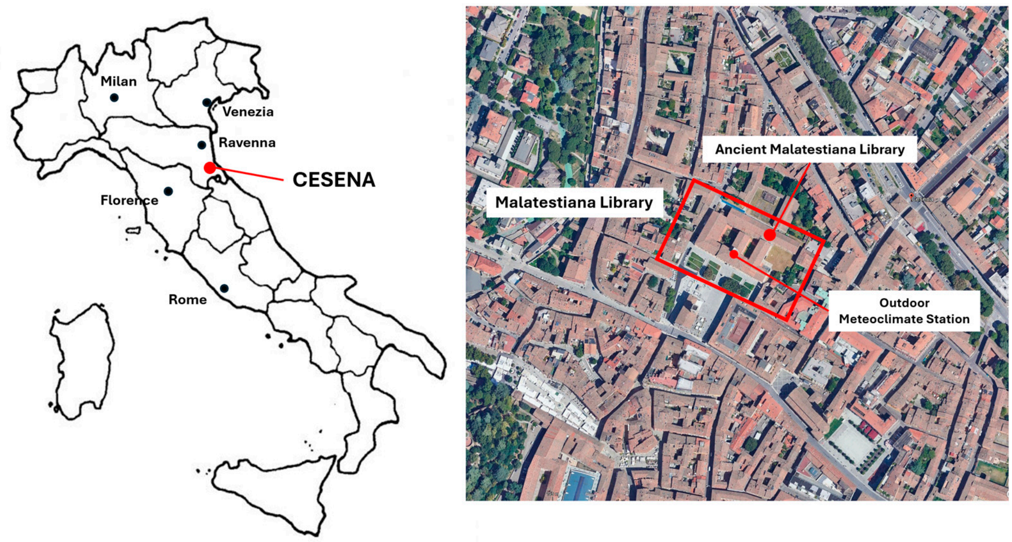

Figure 1. Case study location on a map of Italy and Cesena city.

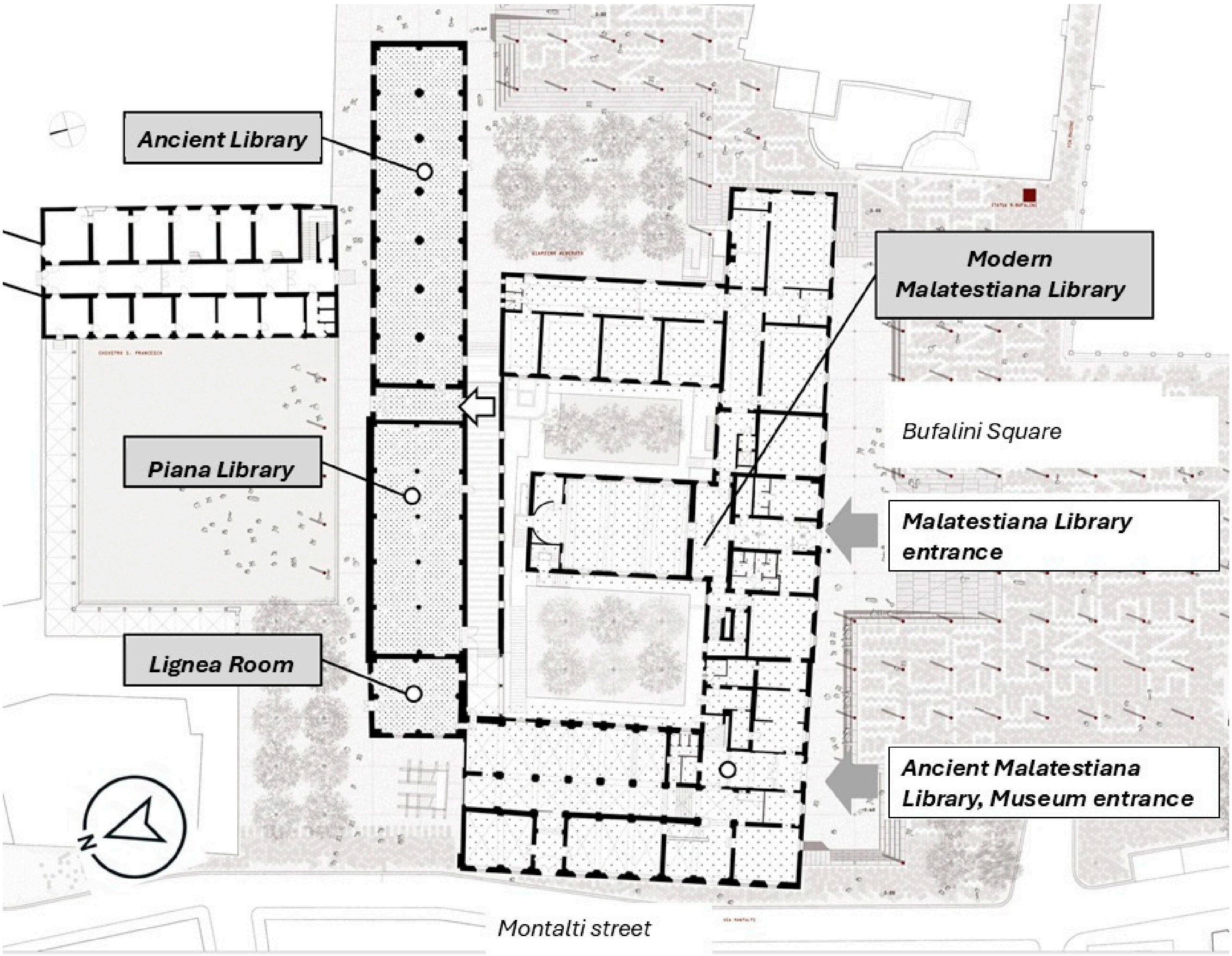

Figure 2. The planimetry of Malatestiana Library.

3.1. The Ancient Malatestiana Library

The *Ancient Malatestiana Library* was commissioned by Malatesta Novello, Lord of Cesena, and designed by Matteo Nuti. Construction began in 1447, and the library was inaugurated on 15 August 1454. It is the only surviving humanist monastic library that remains perfectly preserved, including its structure, furnishings, and book collection.

The *Sala del Nuti* appears today exactly as it did in the 15th century, with the same architectural features, materials, wooden reading benches (*plutei*), and manuscripts. The *plutei* are wooden structures that integrate seating, storage for manuscripts, chain supports, and reading stands. In 2005, the library was inscribed on UNESCO's *Memory of the World* Register (www.unesco.org/en/memory-world/malatesta-novello-library, accessed on 6 November 2025).

The *Sala del Nuti* (Figures 3 and 4) is a single basilica-style hall measuring 40.87 m × 10.47 m, divided into three naves. The central nave has a height of 6.30 m, while the side naves are 4.10 m high. The hall is illuminated by 44 windows (22 on each side) and features a large rose window on one short side. Access is possible through a vestibule shared with the *Sala Piana*, which connects to the rest of the library via a corridor. Beneath the hall, there is a spacious two-nave vaulted area now used as a storage room (*Sala Comandini*). Above it, an attic space measures 4.52 m at the ridge and 1.87 m at the eaves.

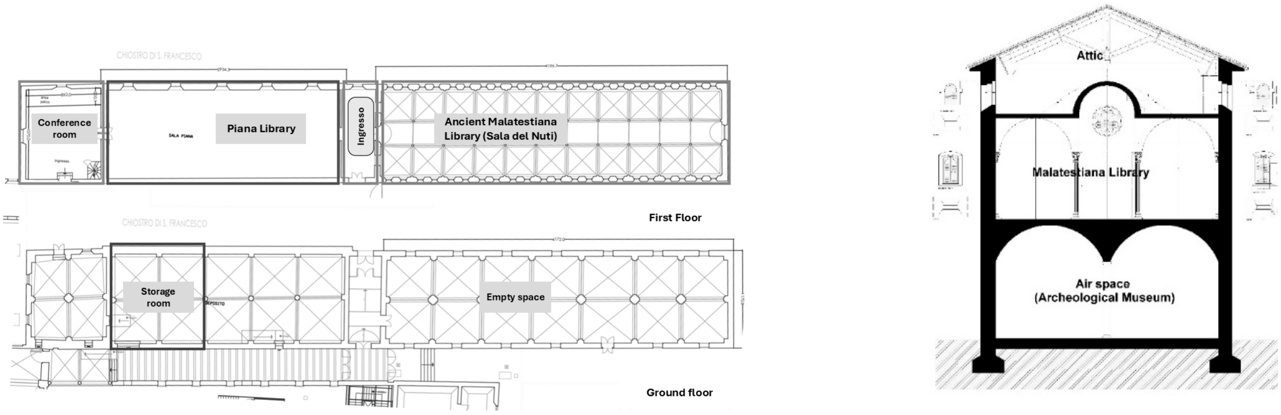

Figure 3. Museum itinerary (with the ground floor at the bottom and first floor above) and architectural section.

Figure 4. Malatestiana Library, Sala del Nuti (or Ancient Malatestiana). Photo taken opposite the entrance (credit: K. Fabbri).

The rooms have no air conditioning, artificial lighting, or other mechanical systems, except for an anti-intrusion security system. The original furnishings are still in place, with 150 manuscripts commissioned by Malatesta Novello and an additional collection of ancient codices, totalling 343 manuscripts made of parchment and goatskin [64].

The microclimatic conditions of the *Sala del Nuti* are considered optimal, as evidenced by the exceptional preservation of its manuscripts, which show no signs of damage or alterations due to microclimatic conditions.

A microclimatic monitoring campaign was conducted in 2013, and its results were published in previous studies [65–68]. This study constitutes a further step in the ongoing research on the indoor microclimate of the Malatestiana Library.

3.2. The Piana Library (Sala Piana)

The *Sala Piana* (Figure 5) is a single hall measuring 27.60 m × 10.47 m. It houses approximately 5500 printed volumes from the 15th–19th centuries, stored in wooden bookcases. The centre of the room features glass display cases for permanent exhibitions.

Figure 5. Malatestiana Library, Sala Piana (credit: G. Tresoldi).

This study investigates how recent climate trends, particularly prolonged heatwaves, have affected the library's unique microclimate and what implications this may have for future conservation efforts.

4. Methodology

The research methodology is based on data collected through two indoor monitoring campaigns: the ongoing monitoring campaign (2024) and the monitoring campaign carried out in 2013 in the same environments. Analysis of the Malatestiana Library visitor archive indicates that the annual number of visitors—approximately 20,000—and the daily attendance during the summer season—around 60–80 visitors per day—remained largely unchanged between 2013 and 2024.

4.1. The Monitoring Campaign

The ongoing campaign, covering multiple rooms of the library, allows for the evaluation of the effects of architectural configuration and the attic. In particular, the comparison focuses on the 'Sala del Nuti' (Ancient Library), built in the 15th century and equipped with a large attic where 15th-century manuscripts are preserved, and the 'Sala Piana', built later in the 18th century with a smaller attic where primarily printed books are stored.

In 2022, the management of the Malatestiana Library initiated a plan to address emerging microclimatic risks and enhance conservation measures by implementing a continuous indoor environmental monitoring system across its museum rooms. The monitoring system, designed and provided by LSI LASTEM, features an integrated network of sensors and probes configured through the Sphensor architecture [69,70]. The indoor monitoring systems were installed to define and set an alert state, for indoor microclimate risk, for visitors, management, and for maintenance operation. This system includes battery-powered temperature and humidity probes (Table 1), strategically positioned within the Sala del Nuti (six probes) and the Sala Piana (two probes). Data from these probes are transmitted using the Thread protocol to a central Sphensor Gateway located in the Sala Piana, which is connected to the library's Wi-Fi network and uploads real-time data to an online cloud platform (Figure 6). To complement indoor monitoring, a meteorological station was installed on the roof of the modern Malatestiana Library building, enabling correlation with external climatic conditions.

Table 1. Sphensor sensor technical data.

Units	Measuring Range	Accuracy	Resolution
Temperature	−30 + 60 °C	• ±0.1 °C; Max ± 0.3 °C (@20–60 °C) • ±0.2 °C; Max ± 0.3 °C (@20–40 °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

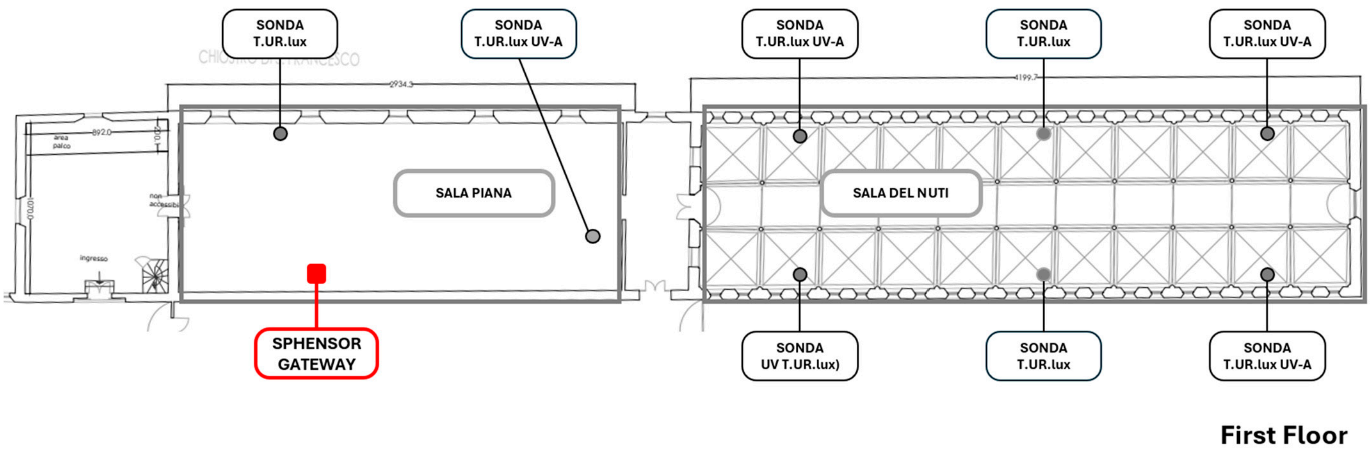

Figure 6. Indoor monitoring design: "Sala Piana" (Piana Library) and "Sala del Nuti" (Ancient Malatestiana Library). "Sonda" indicates a probe. "Sonda T.UR.lux" refers to a temperature, relative humidity, and illuminance probe, while "Sonda T.UR.lux UV-A" refers to a temperature, relative humidity, illuminance, and UV-A probe.

4.2. The 2024 Heatwaves and the Monitoring Campaign

The summer of 2024 proved to be one of the hottest in Cesena over the past five years, with daily temperatures frequently exceeding 35 °C and peaks reaching 38 °C. The summer heatwave in 2024 is not an isolated event, as heatwaves occurred in Cesena in 2022, 2023, 2024 and 2025, but not in 2013, and they appear to be part of a long-term trends. We compared the 2013 and 2024 indoor monitoring campaigns because we have these data and believe ten years is enough to show the difference, as this depends only on the outdoor microclimate.

Meteorological data were obtained from the ARPAER weather station [71] and our own station on top of the Malatestiana buildings over the past five years. Against this backdrop, the monitoring campaign recorded microclimatic data between 17 June and 23 September 2024. This study specifically compares the 2024 indoor environmental data with results from a similar monitoring campaign conducted in 2013, in order to evaluate the evolving impact of heatwaves on the library's historically stable indoor environment.

(a) The indoor microclimate, including air temperature and relative humidity, of the Sala del Nuti and the Sala Piana, to assess the effects of their different geometric configurations and attic structures.
(b) The indoor microclimate of the Sala del Nuti in the summer of 2024 with that recorded in the 2013 monitoring campaign, as described in previous research focused exclusively on the Sala del Nuti.

5. Results

The results of the 2024 monitoring campaign provide clear evidence of the impact of climate change on the indoor microclimate of the Malatestiana Library. This section presents a comparative analysis of the microclimatic conditions recorded in two key areas—the Sala Piana and the Sala del Nuti—during the summer of 2024. Additionally, for the Sala del Nuti, the 2024 data are compared with those collected during a similar monitoring campaign in 2013, allowing for an assessment of long-term environmental shifts. The analysis focuses on trends in air temperature and relative humidity, as well as the interpretation of these data through the ASHRAE adaptive comfort diagram.

5.1. The Difference in the Indoor Microclimate Between the Sala Piana and the Sala del Nuti in the 2024 Monitoring Campaign

Figure 7 illustrates the air temperature trends for the Sala Piana, the Sala del Nuti, and the outdoor environment. The outdoor temperature fluctuates between 20 °C and 30 °C, with peaks exceeding 35 °C and a daily variation of approximately ±10 °C.

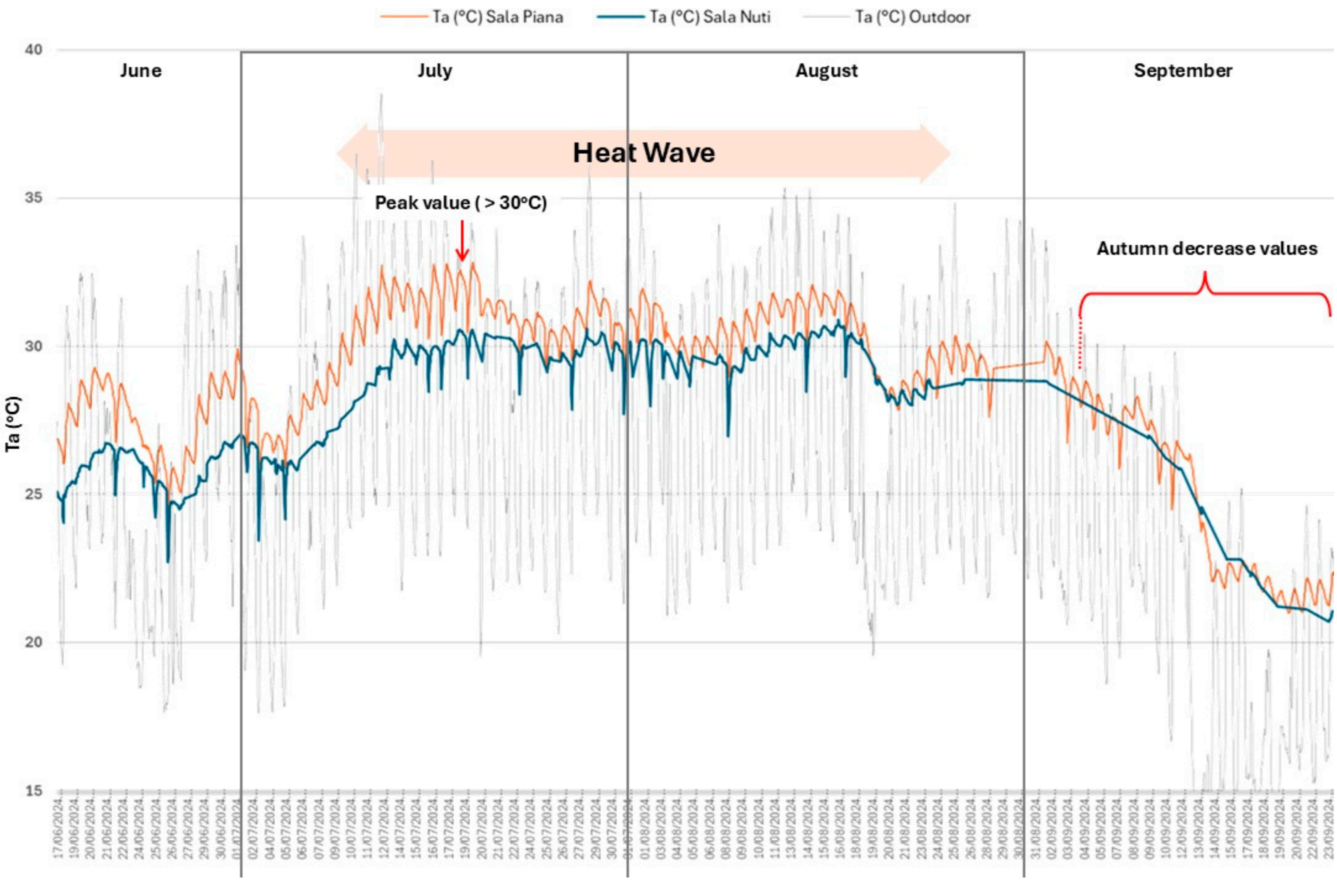

Figure 7. Monitoring results for summer 2024: Indoor air temperature trends in Sala Piana, Sala del Nuti and outdoor air temperature.

In general, there is a temperature difference of at least ±10 °C to 12 °C between indoor and outdoor environments. The Sala Piana shows temperature values ranging between 25 °C and 32 °C, with daily fluctuations of about ±5 °C.

The Sala del Nuti, on the other hand, exhibits smaller daily fluctuations, and only on the hottest days does the temperature exceed 30 °C, which represents the maximum recorded temperature. Figure 8 illustrates the relative humidity trends for the Sala Piana, the Sala del Nuti, and the outdoor environment. Outdoor values range between 30% and 90%, depending on local meteorological conditions.

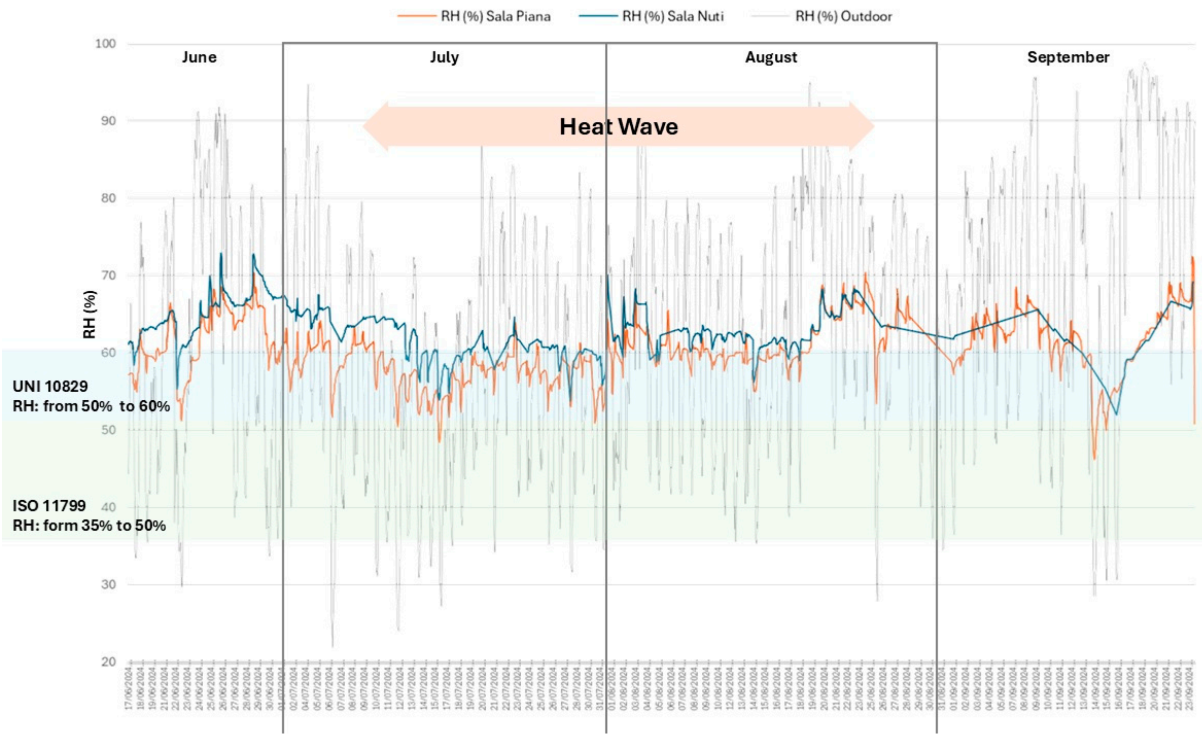

Figure 8. Monitoring results for summer 2024: Indoor relative humidity trends in Sala Piana, Sala del Nuti and outdoor relative humidity.

In the Sala Piana, relative humidity varies between 50% and 65%, while in the Sala del Nuti, it ranges between 55% and 65%. Despite the summer season, the indoor microclimate is not "dry." Additionally, in both rooms, the values fall outside the range specified by standard 11799 [72] but are within the limits set by UNI 10829 [57]. The historic climate of the Biblioteca Malatestiana exhibits slightly higher relative humidity values compared to the regulatory standards.

The comparison between the two rooms (Table 2) shows that the air temperature in the Sala del Nuti is, on average, 0.5 °C lower than in the Sala Piana, with a peak difference of almost −2 °C. Relative humidity levels show a +2.3% higher value in the Sala del Nuti compared to the Sala Piana.

Table 2. Monitoring results for summer 2024 and comparison between Sala del Nuti and Sala Piana. Minimum, maximum, and average values.

	Ta (°C)		Diff. Ta	RH (%)		Diff. RH	UNI 10829	
	Sala Piana	Sala Nuti	(SP-SN)	Sala Piana	Sala Nuti	(SP-SN)	Ta (°C)	RH (%)
MIN	20.99	20.71	−0.28	46.20	51.90	+5.70	13	50
AVERAGE	28.58	28.04	−0.54	60.37	62.71	+2.34		
MAX	32.82	30.88	−1.94	72.40	72.90	+0.50	18	60

Another noteworthy aspect is highlighted in Table 3: the Sala Piana recorded 36.2% of hours with temperatures above 30 °C (with 11.6% exceeding 32 °C), compared to only 11.6% of hours in the Sala del Nuti. This difference can be attributed solely to the differing geometry and architectural section of the two spaces.

Table 3. Monitoring results for summer 2024 and comparison between Sala del Nuti and Sala Piana. Percentages of hours refer to air temperature thresholds.

Ta (°C)			RH (%)		
	Sala Piana	**Sala Nuti**		**Sala Piana**	**Sala Nuti**
less than 25 °C	250 (10.6%) *	96 (4.08%)	less than 50%	12 (0.5%) *	0 (0.0%)
more than 30 °C	852 (36.2%)	266 (11.3%)	more than 60%	1064 (45.2%)	978 (41.5%)
more than 32 °C	88 (3.7%)	0 (0.0%)	more than 65%	320 (13.6%)	271 (11.5%)
			more than 70%	8 (0.3%)	20 (0.8%)

* Sum of hours where values are above/below thresholds. Parentheses indicate a percentage of hours in relation to the total hours of the monitoring campaign.

Regarding relative humidity, the Sala Piana had 45.2% of values outside the UNI 10829 standard range (RH = 60%), whereas in the Sala del Nuti, only 41.5% of values were out of range. This suggests that humidity levels are fairly similar in both rooms. However, the Sala del Nuti is slightly "drier" than the Sala Piana.

Finally, analysing the ASHRAE diagram (Figure 9), it is evident that the values recorded in the Sala Piana exhibit a wider and more dispersed distribution compared to those in the Sala del Nuti, where the values are concentrated within a more compact cluster. In other words, the Sala del Nuti demonstrates a more stable indoor microclimate compared to the Sala Piana.

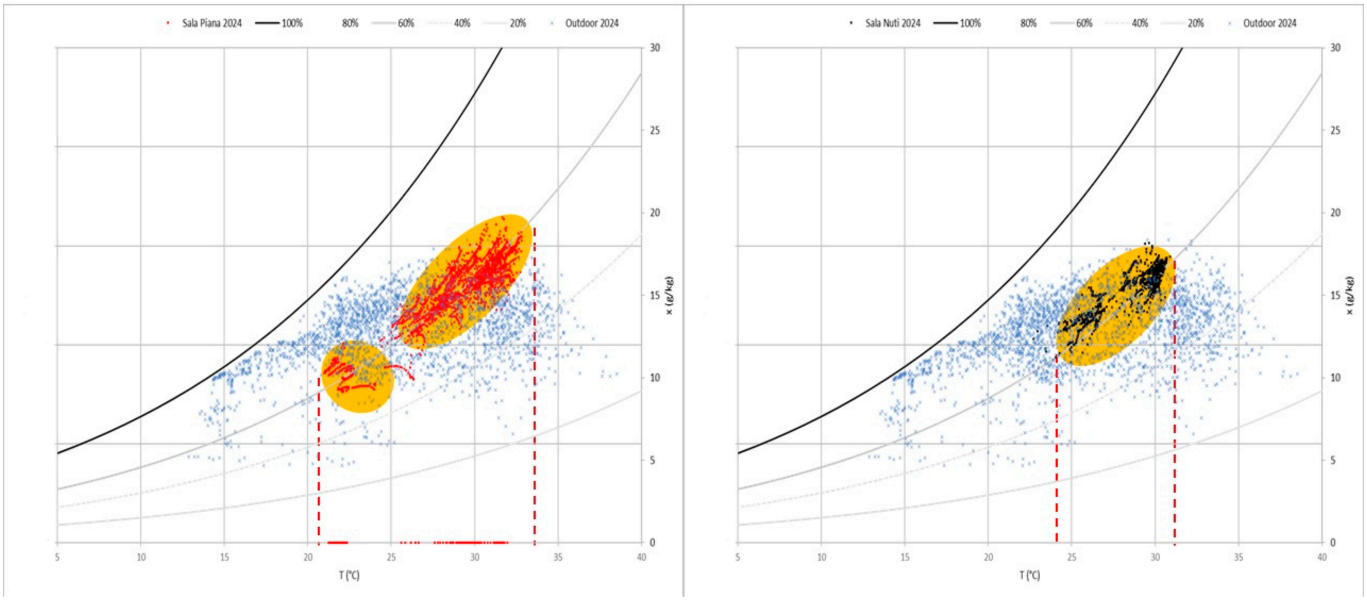

Figure 9. Monitoring results for summer 2024 for Sala Piana (**left**) and Sala del Nuti (**right**) using the ASHRAE Psychrometric Chart.

5.2. Sala del Nuti: Comparison Between the Monitoring Campaigns of 2013 and 2024

Figure 10 shows the trend of outdoor air temperature in 2013 and 2024. The comparison reveals that during 2024, the air temperature remained above 30 °C from the last week of June until the first week of September, with peak values exceeding 35–38 °C. In contrast, during the summer of 2013, days with temperatures above 30 °C were limited to around 10 days between the end of July and the beginning of August. The summer of 2024 in Cesena aligns with the values recorded in the previous two years and represents the new climatic context, the effects of which also influence the indoor microclimate of the Biblioteca Malatestiana, as described below.

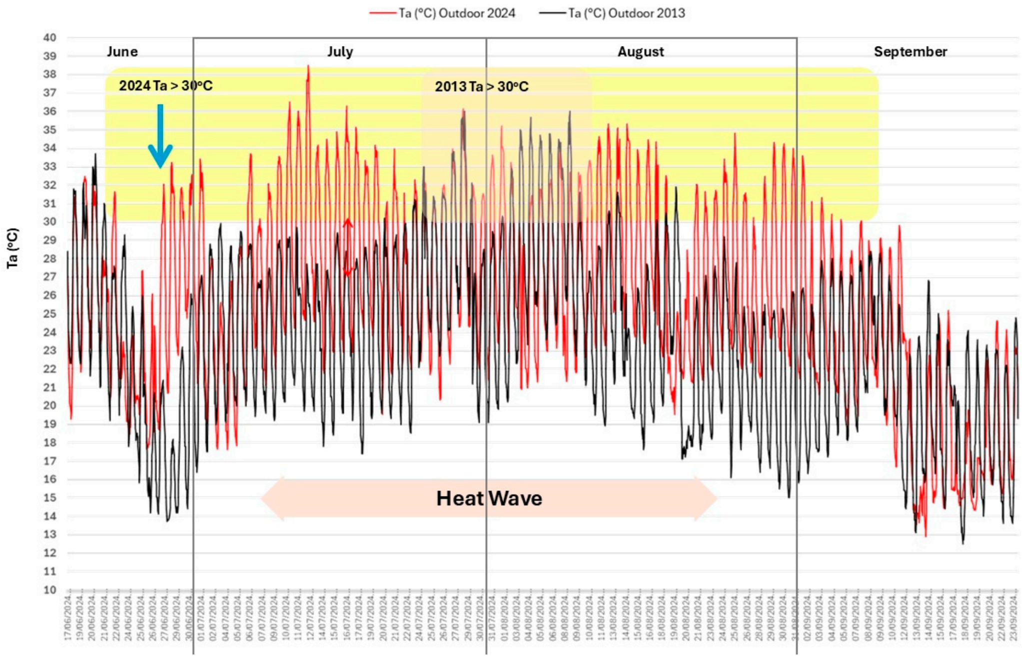

Figure 10. Comparison between outdoor air temperature in summer 2013 and 2024. In 2024, an increase in indoor air temperature is observed from 26 June (blue arrow).

Figure 11 shows the trend of the air temperature in the Sala del Nuti in 2013 and 2024. The difference between the two trends is evident. During the 2024 heatwave, the air temperature rapidly reaches values above 28–30 °C in the first week of July. The heatwave is preceded by a temperature increase starting from the last week of June 2024, rising from about 24 °C to 26 °C. During the heatwave, the values continue to fluctuate around 28–30 °C until August 20, after which they return to lower values, following the seasonal trend.

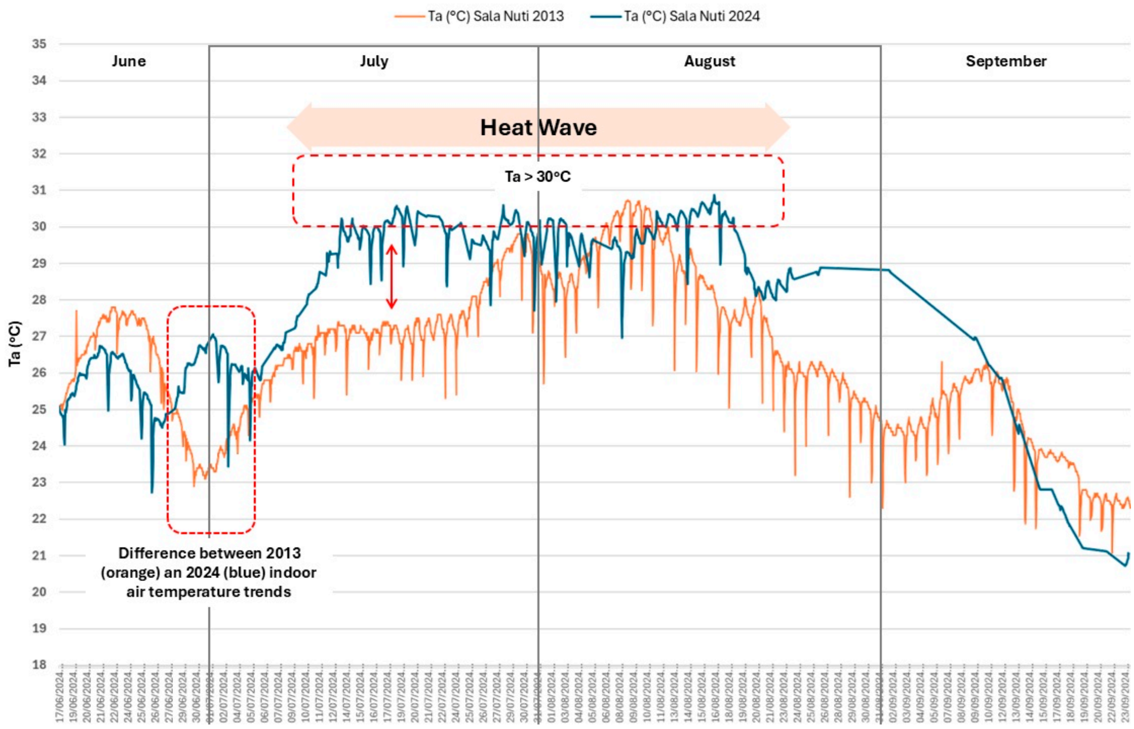

Figure 11. Sala del Nuti: comparison between indoor air temperature while monitoring in summer 2013 and 2024. In June, an increase is observed in 2024 compared to 2013.

Figure 12 shows the trend of the relative humidity in the Sala del Nuti in 2013 and 2024. The differences are huge and evident. During 2013, heatwave relative humidity values fluctuated between 40% and 50%, while during 2024, heatwave relative humidity values fluctuated between 60 and 65%, a very considerable difference that changed the indoor microclimate of the Malatestiana Library.

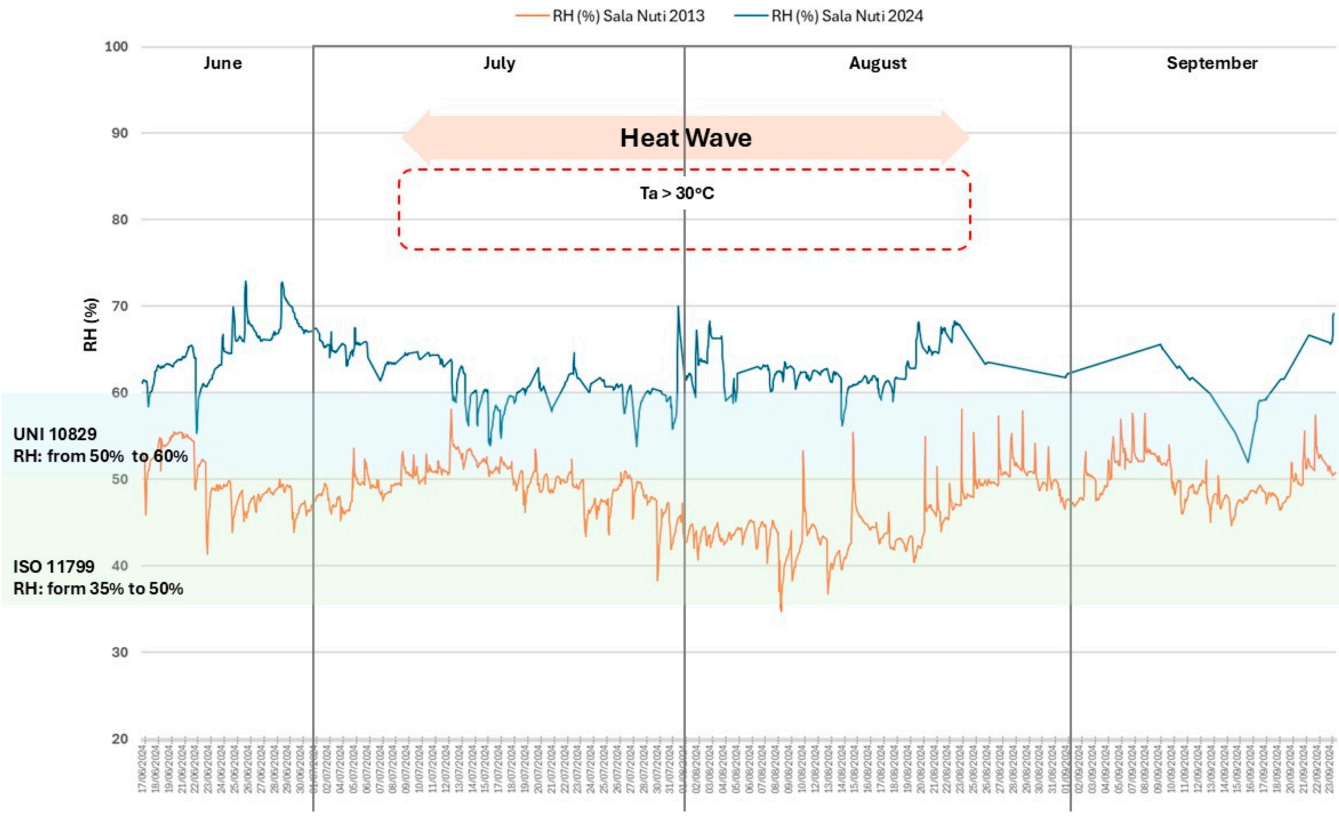

Figure 12. Sala del Nuti: comparison between indoor relative humidity during monitoring in summer 2013 and 2024.

The comparison between the two periods (Table 4) shows that the indoor air temperature in the Sala del Nuti during 2024 is, on average, +1.6 °C higher compared to 2013, a significant value, while the minimum and maximum values for the period are essentially similar. The change that occurred during the decade 2013–2024 is characterised by an increase in the number of days with higher air temperature values. The outdoor temperature shows an average increase of +2.3 °C, with a rise in peak temperature values (+2.52 °C). The Sala del Nuti continues to provide attenuation of peak air temperature values even during heatwaves. Table 5 presents the relative humidity values, both indoor and outdoor, for 2013 and 2024. There is an increase of +14% in the indoor relative humidity values, both as an average value and as a maximum value. This increase is consistent with the rise in outdoor relative humidity values (+11%), indicating that the indoor microclimate seems to persist with relative humidity values higher than those of the previous decade.

Table 4. Sala del Nuti: results for monitoring campaign in summer 2013 and 2024 for Sala del Nuti and. Air temperature minimum, maximum, and average values.

	MIN (°C)	AVE (°C)	MAX (°C)
INDOOR Air Temperature			
2013	21.07	26.45	30.73
2024	20.71	28.04	30.88
Difference 2013–2024	−0.36	1.59	0.15
INDOOR Air Temperature			
2013	12.50	23.50	36.00
2024	12.87	25.79	38.52
Difference 2013–2024	−0.36	1.59	0.15
Difference INDOOR–OUTDOOR			
2013	8.57	2.95	−5.27
2024	7.84	2.25	−7.64
Difference indoor–outdoor 2013–2024	−0.36	1.59	0.15

Table 5. Sala del Nuti: results for monitoring campaign in summer 2013 and 2024 for Sala del Nuti and. Relative humidity minimum, maximum, and average values.

	MIN (%)	AVE (%)	MAX (%)
INDOOR Relative Humidity			
2013	34.77	48.22	58.10
2024	51.90	62.71	72.90
Difference 2013–2024	17.13	14.48	14.80
OUTDOOR Relative Humidity			
2013	13.00	50.98	98.00
2024	21.90	62.77	97.60
Difference 2013–2024	8.90	11.79	−0.40
Difference INDOOR–OUTDOOR			
2013	21.77	−2.76	−39.90
2024	30.00	−0.06	−24.70
Difference indoor–outdoor 2013–2024	8.23	2.69	15.20

The detailed data reading (Table 6) shows an increase in the number of hours with indoor temperatures greater than 30 °C, which rises from 88 h in 2013 (3.7% of the total) to 266 h (11.3%), tripling the number of hours with temperatures between 30 °C and 31 °C. This phenomenon is consistent with climate change and the increase in the number of hours during which the outdoor temperature exceeds 30 °C, which triples from 202 h in 2013 to 606 h in 2024. Furthermore, in 2024, there were 303 h with temperatures exceeding 32 °C and 31 h with temperatures exceeding 35 °C, numbers that confirm the ongoing climate change.

Another relevant aspect concerns the reversal of indoor microclimatic conditions regarding relative humidity values. While in 2013, about 70% of the hours recorded relative humidity below 50%, in 2024, 50% of the relative humidity values were above 55%, and 41% were above 60%. These values are partly consistent with the increase in outdoor relative humidity values.

Table 6. Sala del Nuti: results for monitoring campaign in summer 2013 and 2024. Percentages of hours refer to air temperature thresholds. Sum of hours where values are above/below thresholds. Parentheses indicate a percentage of hours in relation to the total hours of the monitoring campaign.

Number of Hours Where Temperature Is:			**Less Than 25 °C**	**More Than 30 °C**	**More Than 32 °C**	**More Than 35 °C**
INDOOR Air Temperature						
2013			578 (24.5%) *	88 (3.7%) *	0	0
2024			96 (4.9%) *	266 (11.3%) *	0	0
Difference 2013–2024			−482	+178	-	-
OUTDOOR Air Temperature						
2013			1423 (60.5%) *	202 (8.6%) *	94 (4.0%) *	11 (0.5%) *
2024			1096 (46.6%) *	606 (25.7%) *	303 (12.9%) *	31 (1.3%) *
Difference 2013–2024			−327	+404	+209	+20
Number of Hours Where Relative Humidity Is:	**Less Than 40%**	**Less Than 50%**	**More Than 55%**	**More Than 60%**	**More Than 65%**	**More Than 70%**
INDOOR Relative Humidity						
2013	34	1622	41	0	0	0
2024	0	0	1194	978	271	20
Difference 2013–2024	−34	−1622	+1153	+978	+271	+20
OUTDOOR Relative Humidity						
2013	705	1170	908	710	518	348
2024	188	618	1477	1264	1091	875
Difference 2013–2024	−517	−552	+569	+554	+573	+527

* percentage of hours relative to the total hours.

5.3. *The Significant Change Marks the Establishment of a New Indoor Microclimate in the Sala del Nuti*

Finally, the comparison analysis of the indoor microclimate in 2013 with 2024 (Figures 13–16) confirms the modification of the indoor microclimate of the Sala del Nuti during the summer period.

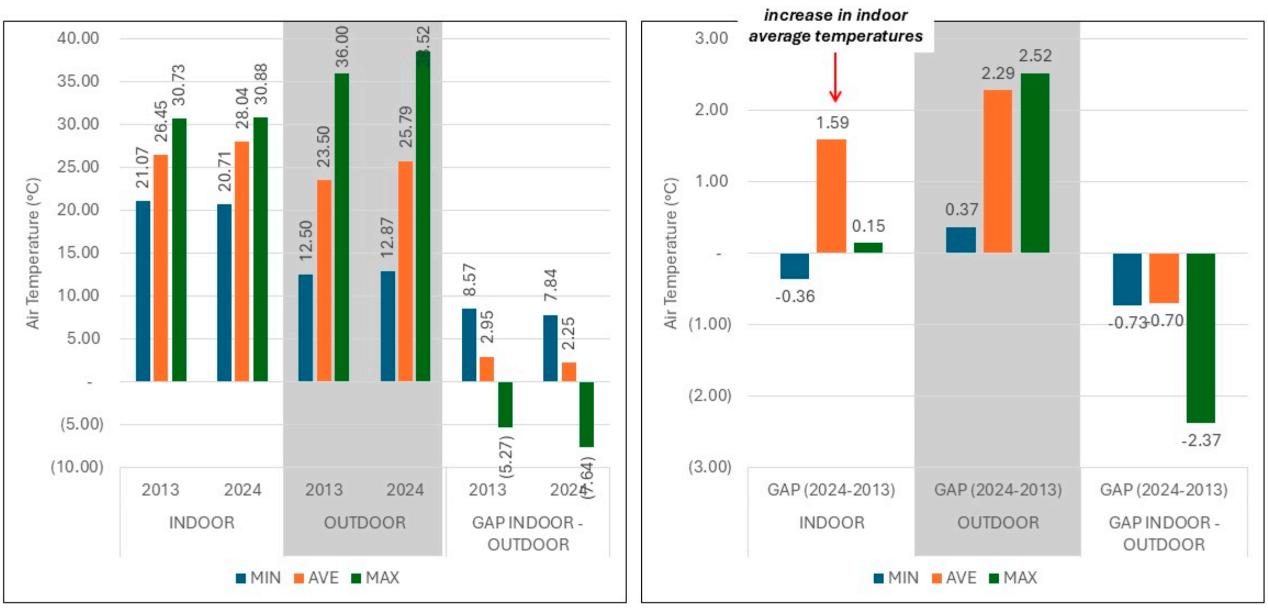

Figure 13. Air temperature graphics: (**left**) graphic with minimum, average, and maximum values divide by indoor, outdoor, and gap; (**right**) graphic with the difference between indoor–outdoor temperature, with minimum, average, and maximum values and gap between indoor–outdoor gaps (Gray is used to highlight outdoor results versus indoor results).

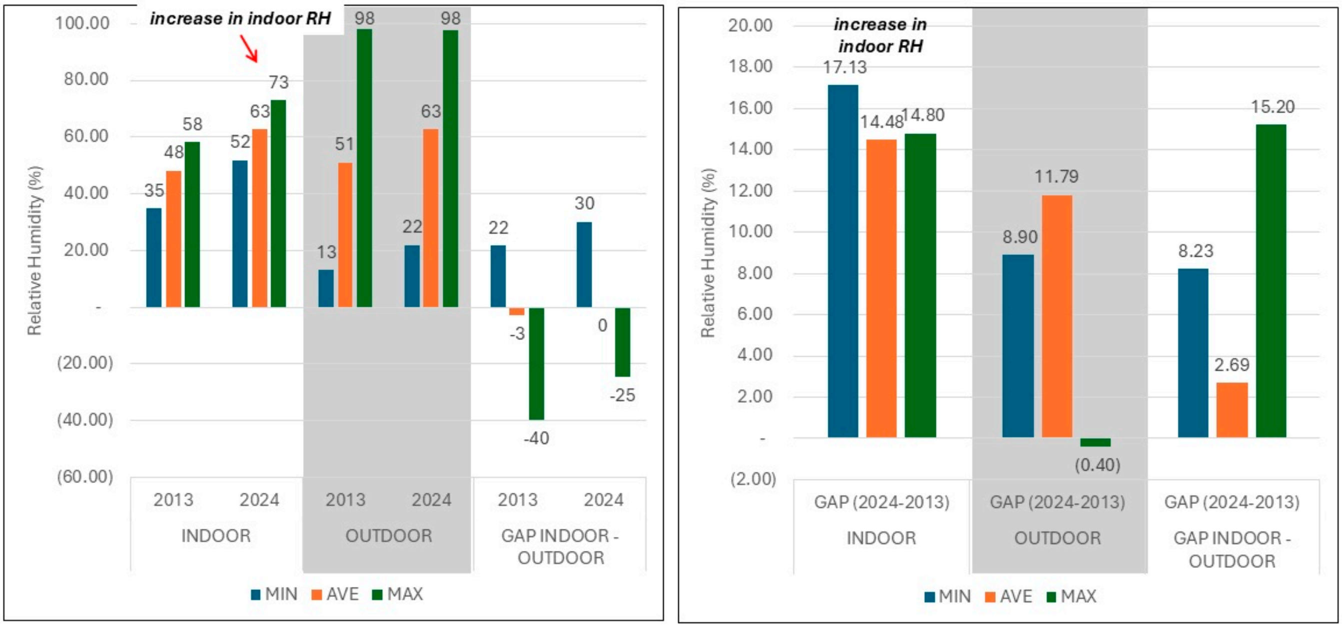

Figure 14. Relative humidity graphics: (**left**) graphic with minimum, average, and maximum values divide by indoor, outdoor, and gap; (**right**) graphic with the difference between indoor–outdoor temperature, with minimum, average, and maximum values and gap between indoor–outdoor gaps (Gray is used to highlight outdoor results versus indoor results).

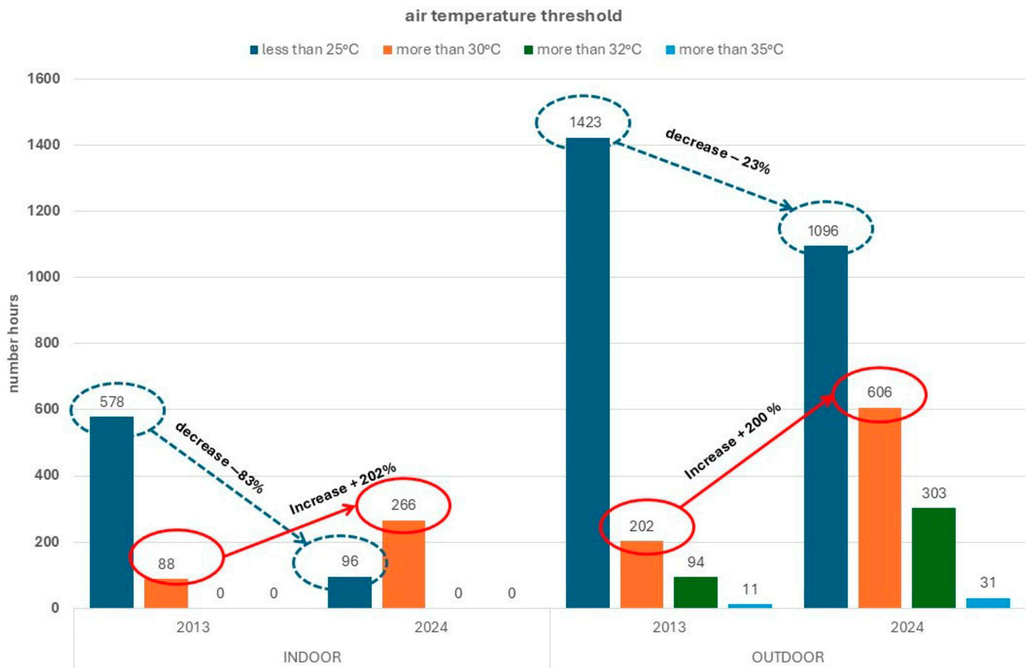

Figure 15. Indoor and outdoor air temperature thresholds. The graphics show a more than 200% increase in indoor air temperature during the summer months from 2013 to 2024, equal to an increase in the outdoor air temperature. This is determined by the outdoor air temperature climate changes from 2013 to 2024.

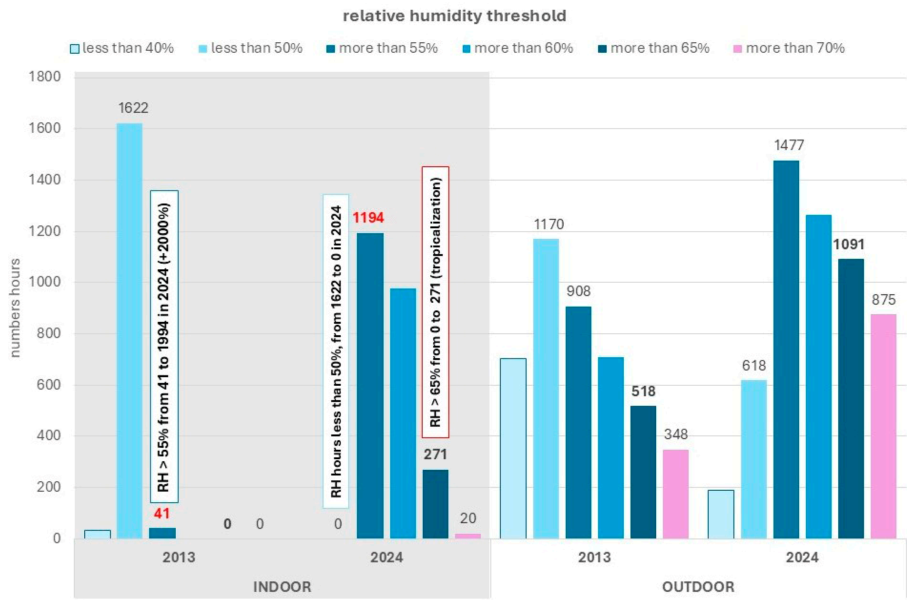

Figure 16. Indoor and outdoor relative humidity. The graphics show a decrease of "less than 50% values from 2013 to 2024, and a increase of "more than 55%" values in the same period. Furthermore, in 2024 we can see more hours with more than 65% and 70% values in the same period. This is determined by the outdoor heatwaves in 2024. (Gray is used to highlight indoor results versus outdoor results).

Furthermore, "Microclimate Tropicalisation" is more clearly show in the ASHRAE psychrometric chart. The comparison of the indoor microclimate in 2013 (Figure 17, left) with 2024 (Figure 17, right) confirms the modification of the indoor microclimate of the Sala del Nuti during the summer period.

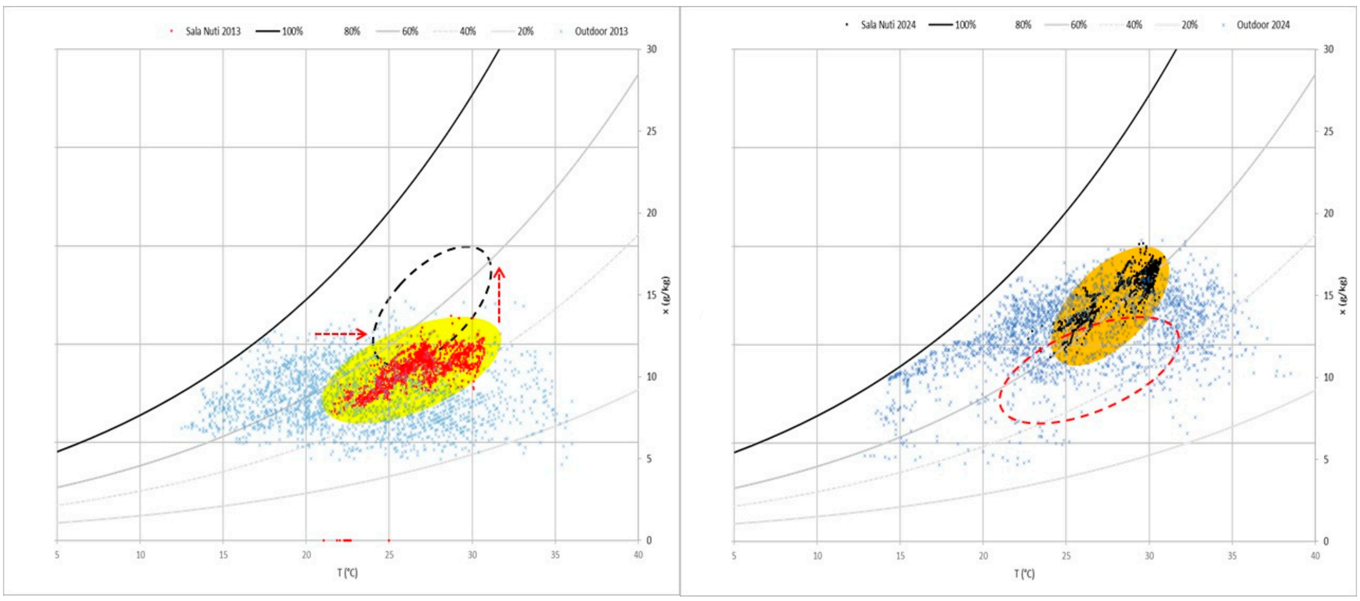

Figure 17. Sala del Nuti: results for monitoring campaign in summer 2013 and 2024 from the ASHRAE Psychrometric Chart 2013 (**left**) and 2024 (**right**). The yellow oval shows the 2013 indoor microclimate during summer, while the orange oval shows the 2024 indoor microclimate during summer. The arrows and dashed oval indicate the indoor microclimate shifting toward tropicalisation values (elevated temperature and humidity).

The new indoor microclimate, which has changed over the last decade, shows an environment with a higher water vapour content, with relative humidity around 60%, and the absence of temperature values below 25 °C.

6. Discussion

Before the widespread introduction of air-conditioning systems—a process that began in the late 19th century and expanded throughout the 20th—architectural design responded directly to the climatic needs of its context. Historic buildings can therefore be understood as physical expressions of human adaptation to environmental conditions over centuries. Much of the existing research adopting this perspective has focused on vernacular architecture [73–75] or on early anthropological studies of primitive settlements, such as those by Amos Rapoport [76–78]. The Malatestiana Library, however, represents a rare case of a purpose-built urban structure, designed specifically for the preservation and reading of books, that has remained virtually unchanged in both form and function for six centuries. Its indoor microclimate serves as a unique archive—a preserved record akin to an "architectural ice core"—offering insights into the historical relationship between architecture and climate, and providing a valuable case study for examining how contemporary climate change is beginning to influence traditionally stable indoor environments.

Analysis of the 2024 monitoring data highlights the significant role of architectural form, particularly the attic structure, in mediating indoor microclimate conditions. Results show that the Sala Piana exhibits higher indoor temperature peaks compared to the Sala del Nuti. Over the course of the summer, the Sala del Nuti maintained a more stable indoor environment, with temperatures approximately 0.5 °C cooler and smaller fluctuations relative to external extremes such as prolonged heatwaves and daily temperature variations. These findings suggest that the architectural configuration of the Sala del Nuti contributes to a greater resilience against recent climatic stresses.

In contrast to the stable indoor microclimate of the Sala del Nuti, the comparison between the 2013 and 2024 campaigns shows that climate change over the last decade has (had and will have) a clear effect on the indoor microclimate and, therefore, on the preservation of artefacts. First, the number of days and hours in which indoor air temperatures exceed 30 °C increases, rising from 3.7% to 11.3%. In fact, the number of hours has tripled. This condition places the microclimate under stress, mitigated by the architectural design and the large attic.

Another critical aspect concerns the shift in indoor relative humidity over time. Between 2013 and 2024, a significant transformation occurred: in 2013, the indoor microclimate was predominantly "dry," with relative humidity remaining below 50% for approximately 70% of summer hours. By contrast, in 2024, this pattern has reversed—over 60% of summer hours now exhibit relative humidity levels exceeding 55%. This indicates a notable increase in indoor moisture, even during typically drier summer periods.

The indoor environment during the summer of 2024 is also characterised by a greater frequency of temperatures above 25 °C, combined with sustained relative humidity levels above 55%. These conditions are particularly concerning as they create a more favourable environment for insect activity and infestation. For example, insects from the Blattellidae family can complete embryonic development at 30 °C and 43% RH within 15–17 days, while Anobiidae species can develop at 20 °C and 43% RH in about 23 days. The combination of elevated temperature and humidity increases the risk of biological deterioration, posing a serious threat to paper-based and wooden heritage materials.

The regulation of relative humidity in historic buildings such as the Malatestiana Library is closely tied to natural ventilation, which depends on temperature differentials between interior and exterior spaces, as well as the ability to generate airflow

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through windows or architectural openings. However, with narrowing temperature differences and more stagnant, humid outdoor conditions, achieving effective ventilation is increasingly difficult.

As a result, the historic indoor microclimate of the Malatestiana Library is undergoing a process akin to "Microclimate Tropicalisation", marked by consistently higher temperatures and humidity levels. This not only alters the preservation conditions for the library's valuable collections but also disrupts the building's historically stable climate, shifting it away from the conditions under which many of its contents have survived for centuries.

In response to the research question posed at the beginning of this study—how and to what extent climate change and microclimate alterations affect the preservation of historic buildings without air conditioning—the findings from the Malatestiana Library provide clear evidence of emerging changes. Over the past decade, climate change, particularly through the increasing frequency and intensity of heatwaves, has gradually modified the indoor microclimate of the Sala del Nuti. This alteration has occurred slowly enough to allow the manuscripts and furnishings to acclimatise to the evolving conditions, and, to date, no visible damage has been observed.

However, ongoing indoor and outdoor microclimatic monitoring will be essential for informed management decisions regarding the future use of the library spaces. These decisions may include, for example, the strategic introduction of temporary measures such as portable fans to mitigate temperature extremes without disrupting the historical integrity of the environment. Any intervention must be carefully considered in light of the building's longstanding passive conservation approach.

An important consideration emerging from this study is the question of whether climate change is altering the historical indoor climate, as defined by EN 15757 [55]—namely, the stable microenvironment to which artefacts have become acclimatised over long periods. The evidence suggests that the answer is unequivocally yes: climate change is indeed shifting these traditionally stable microclimates. Whether these changes ultimately prove beneficial or harmful will depend on two critical factors: the resilience of the materials to gradual environmental shifts, and the strategies adopted for the ongoing management and use of these heritage spaces.

The case of the Malatestiana Library, which has successfully preserved its collections in optimal condition since 1452, underscores the importance of consistent environmental stewardship. As climatic conditions continue to evolve, safeguarding the historical indoor climate—or carefully guiding its adaptation—will be crucial to ensuring the long-term conservation of irreplaceable cultural heritage.

7. Conclusions

This study set out to address a key research question: how and to what extent do climate change and microclimate alterations affect the preservation of historic buildings and cultural heritage sites without air conditioning, both currently and in future projections? While existing policy documents, such as UNESCO's Policy Document on Climate Action for World Heritage, and much of the scientific literature have largely focused either on mitigating heritage's contribution to climate change or on catastrophic events, the gradual, less visible impacts of climate change on indoor environments in historic buildings have remained underexplored.

We do not aim to demonstrate climate change in this study, as the IPCC and thousands of researchers and articles have demonstrated it; we use as evidence a specific case study applied to a unique heritage building. That is because Malatestiana Library has an unique and specific historic indoor microclimate which has never changed over the centuries, as the buildings, furniture, and manuscript have all remained the same over the last 500 years. We note that some have changed in the last 10 years, which we have reported.

This study aimed to fill that gap by providing empirical evidence from a unique case: the Malatestiana Library, a UNESCO Memory of the World site that has preserved a remarkably stable indoor microclimate for over five centuries without architectural, functional, or technological alterations.

The findings of the 2024 monitoring campaign demonstrate that climate change—particularly the intensification of heatwaves over the past decade—has begun to modify the historical indoor climate of the library. These changes have occurred gradually, allowing artefacts and furnishings to acclimatise without immediate visible damage. Nevertheless, the evidence of "Microclimate Tropicalisation" signals a trend that demands careful monitoring and adaptive management strategies.

Moreover, the research highlights the broader role of cultural heritage buildings as long-term records of environmental change. Like ice cores or dendrochronological samples, historic structures offer valuable archives of past climates. However, unlike natural records, heritage buildings reflect layers of architectural, social, and technological adaptation over time, particularly with the introduction of modern infrastructure in the 20th century.

The Malatestiana Library, by contrast, offers a rare, unaltered benchmark for understanding how historic microclimates respond to contemporary climatic pressures. The study's findings reinforce the importance of developing risk assessment tools—such as Heritage Microclimate Risk (HMR) and Predicted Risk of Damage (PRD) indices [79–81]—to support conservation decision-making [82].

The Malatestiana Library is a UNESCO heritage site, and they have neither technical systems, such as HVAC or lighting, nor insulation; e.g., the walls and windows are the same as those originally built and they cannot be modified. The only adaptive conservation strategies that can be used concern the number of visitors (currently 25 people an hour) during day hours with natural light. The passive conservation strategies that should be adopted regard numbers or visitor access and the manuscript/furniture depository, as we report in this section.

At present, the Malatestiana shows no signs of deterioration attributable to microclimatic change, but ongoing monitoring is crucial, particularly given the potential risks posed by increasing visitor numbers and shifting climatic conditions. Looking forward, climate change introduces complex new challenges for the heritage sector, including the need for continuous monitoring, the management of visitor impacts, and the careful balancing of conservation needs with public access. Adaptive, proactive strategies will be essential to safeguarding irreplaceable cultural heritage in an era of accelerating environmental transformation.

We can conclude now that the monitoring results and the comparison between 2013 and 2014 heat waves allow us to consider future conservation and management strategies. In fact, Malatestiana Library is both a library and a museum, with original furniture and manuscripts preserved in their original locations. Regarding that which still requires longer monitoring, consisting of that on which no visible damage is observed yet, the trend are concerning; if, in the future, changes in the indoor microclimate occur, conservation/management strategies should be:

(a) to reduce or prohibit visitors (in which case the library would no longer function as a museum, only as an archive); or
(b) to remove manuscripts and/or furniture, in which case the museum would focus only on the architecture, similar to the San Marco Library in Florence, Italy. Any other strategies, for example, installing a heating, ventilation, and air-conditioning (HVAC) system, would not be respectful of the building's and library's history.

Future research should focus on several key areas, including:

a. The relationship between architecture and climate change, exploring not only the impact of cultural heritage on climate but also the reverse—how climate change affects cultural heritage;
b. The broader effects of climate change on cultural heritage, including both the indoor microclimate and the preservation of smaller cultural heritage items;
c. The interaction between outdoor and indoor microclimates, and the factors that promote the birth, growth, and proliferation of biological pollutants (e.g., insects, moulds, etc.) and hygrothermal performance under current and future climates [74];
d. The evaluation of adaptation processes of historic and artistic artefacts to ongoing climate change, including the potential role of air-conditioning systems in these processes;
e. The relationship between the indoor microclimate, thermal comfort for visitors/tourists, and their willingness to tolerate discomfort during visits;
f. The effects of ongoing climate change on the acclimatisation processes of cultural heritage, historic buildings, and individual artefacts.

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