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Critical Review of the Application of the Principal International Standards and Guidelines on Indoor Microclimates for the Preventive Conservation of Cultural Heritage

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Abstract: Assessments of indoor microclimates are the first act of preventive conservation of cultural heritage. Interest in this subject has led to the development of an increasing number of standards and guidelines. This critical review examines the application of the main standards and guidelines for indoor microclimates for the preventive conservation of cultural heritage and proposes their synthesis in a common framework. In this manner, this study tries to shed light on their coordination and to propose guidance for better understanding and application. Generally speaking, there are two kinds of guidelines: the first is based on the fixed values of specific parameters, used as limits for the best preservation of the various materials, whereas the second identifies the historical microclimate specific to the environment as the reference for appropriate preservation, especially in the case of organic and hygroscopic materials. After analysing different standards and guidelines, the various parameters and calculation methods are discussed and summarised in a table for a synoptic comparison.

Keywords: indoor microclimate; preventive conservation; cultural heritage; standards; monitoring

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1. Introduction and Research Aim

Indoor microclimates are the set of physical variables used to describe energy and mass exchanges in an environment over a representative period of time [1,2]. Over time, the original static concept of room climate in museums, defined by average values of temperature (T) and relative humidity (RH), has evolved considering a dynamic approach in order to pinpoint its variability and the effects that this variability may have on collections and make clear the deterioration mechanisms. This suggests the need to revise outdated concepts of room climate over the space within the room and over time as well. For standard EN 15757 [3], microclimate is the "climate on a small spatial scale. It typically refers to the microenvironment that interacts with the objects under consideration", while historical climate is the "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 acclimatized" [4]. In order to analyse the thermo-hygrometric conditions of an environment hosting artworks, it is necessary to measure environmental parameters at different points and for a sufficiently long and representative period. The environment around an artwork is influenced by boundary conditions connected to architecture, weather, and human actions, such us the adoption of HVAC (Heating, Ventilation, and Air-Conditioning) systems, lighting, opening doors and windows, cleaning, and so on [5,6]. Furthermore, microclimate monitoring should not only consist of the description of the hygrothermal behaviour of an indoor space and its possible correlation with the deterioration of cultural heritage materials, but should also become the basis for predicting the responses of materials to different microclimate stresses in order to increase the timespan between subsequent restoration interventions.

The topic is very important and debated because standards and guidelines are still fragmented and diverse, as testified by the number of publications concerning evaluations of microclimates and the standards and guidelines used for these assessments [7]. Moreover, in recent years, concerns about energy costs implied by the compliance with preservation conditions are increasing. For this aim, two approaches have been proposed: (i) HVAC full control, with high confidence in technology a and weaker focus on energy consumption, costs, and environmental sustainability; (ii) naturally stable climate conditions with passive technologies, i.e., minimum use of HVAC, with a focus on feasibility, low energy consumption, low use costs, and environmental sustainability (recommended by standards such as EN 15757). To overcome these issues, two strategies may be used [8,9]:

- Energy retrofit interventions in architecture.
- Energy-saving preventive conservation practises.

Tangible cultural heritage consists of both movable artworks and historical buildings. The relationship between the conservation of cultural artefacts and the environment they are stored in has been studied since the beginning of the 20th century [10,11].

Preventive conservation is defined in EN 15898 [12] as "measures and actions aimed at avoiding or minimising future damage, deterioration, loss and, consequently, any invasive intervention. In the field of movable heritage, 'preventive conservation' is generally indirect; namely, these measures and actions are carried out within the immediate environment of the object" by means of the so-called environmental control, which consists of the "management of one or more factors of the environment. This applies to temperature, relative humidity, light, pollution, pests, etc."

The first studies in this field date back to the 1940s, when Rawlins [13], in 1942, recommended specific T and RH for preserving museum collections. In the same year, in Italy, Royal Decree n. 1564 of 7 November 1942 [14] determined that inside libraries, archives, and places where books, prints, paintings, miniatures, manuscripts, and documents are stored, heating systems must be supplemented by devices that ensure that the air has RH between 40% and 65% in all seasons.

From the 1940s to the present day, a number of standards and studies have improved these recommendations [10,11,15,16]. While the oldest standards and guidelines are aimed at defining a series of thermo-hygrometric parameters (reference values) for the various materials, the latest ones focus on the investigation of the thermo-hygrometric conditions characterising the microclimate that the object has been immersed in for one or more years.

For instance, UNI 10829 [17] sets limits for T and RH, daily T drift (ΔT) and daily RH drift (ΔRH), maximum illuminance (Emax), maximum ultraviolet radiation (UVmax), and daily maximum light dose (LOmax), depending on the materials constituting the artwork. Conversely, *ASHRAE Handbook, 2019* [18] and EN 15757 [3] consider it to be appropriate to keep the thermohydrometric conditions very similar to those that hosted the artefact in the recent past and to which it consequently acclimatised for a given minimum period.

Verticchio et al. [19] present an international policy framework for the preservation of cultural heritage providing the microclimate specifications indicated in each document. The regulations considered are those from 1997 onward. In their work, Verticchio et al. collected standards and guidelines, but did not provide a synthesis, whereas in this paper, the regulations and guidelines were re-elaborated to adapt them to a common framework, which will be discussed further in this study.

This study takes into consideration numerous regulations and guidelines from different countries and also those that are far apart in time in order to find a way of organising them on the basis of the rationale with which they were developed.

1. Standards and guidelines establishing fixed-limit values for parameters such as T and RH, etc. The following standards and guidelines can be grouped into this category:

   - Technical Bulletin n. 5 of the Canada Conservation Institution in 1979 (CCI) by Lafontaine [20].
   - UNI 10586 [21] and UNI 10829 [17], in force in Italy since the publication of the Ministerial Decree dated 10 May 2001 [22].
   - National Museum Directors' Council (NMDC) guides [23] in 2009.
   - National Trust [24] in 2011.
   - BSI PD 5454 [25].
   - PAS 198 [26].
   - BS 4971 [27]
   - ANSI/NISO Z39.79-2001 [28].
   - Muséofiches guide by Direction de Musées de France [29], from 1993 to 2007.
   - EN 16893 [30].

As such, in the case of the first group of standards, the conditions considered to be safe are always the same for each individual type of material, with no reference to the microclimatic history of the single artefact.

2. Standards and guidelines establishing limit values for parameters such as T, RH, etc., whose range depends on the conditions of the microclimate of interest in the recent past (e.g., the latest 13-month monitoring period, as proposed by EN 15757, or 12 months, as suggested by ASHRAE 2019). The following standards and guidelines can be grouped into this category:

   - UNI 10969, 'Beni culturali—Principi generali per la scelta e il controllo del microclima per la conservazione dei beni culturali in ambienti interni' [31].
   - EN 15757, 'Conservation of Cultural Property—Specifications for T and RH to limit climate-induced mechanical damage in organic hygroscopic materials' [3].
   - *ASHRAE Handbook, 2019* [18], which is a revised version of the *ASHRAE Handbook, 2011* [32] and *2015* [33].

The references mentioned above, and many more, will be discussed in depth in this study and are presented in a common framework. Specifically, Section 2 will describe the method behind this study, which guided the collection and interpretation of the standards and guidelines presented in Section 3, starting with a brief view of the oldest references, and more space is dedicated to the assessment procedures currently used. Section 4 offers many causes for reflection for experts in this field, and Section 5 draws the main conclusions from this study and suggests ways for improving the coordination of the relevant standards and guidelines.

This review article aims to clarify a scientific and standard framework for the assessment of indoor microclimates for cultural heritage conservation in respect to the development of an increasing number of standards and guidelines.

2. Materials and Methods

This paper includes a review about the guidelines and standards on suggested indoor environment preservation conditions for artworks, whose information was appropriately elaborated.

The use of systematic procedures for the literature review was not possible in this topic. In fact, indexed papers on this topic are few and refer mainly to a limited fraction of the available guidelines and standards, since many artwork preservation guidelines and standards are set or well-established at a local level. Hence, this literature review had to follow a non-systematic procedure and, in particular, a so-called scoping review procedure, with an iterative process that considered both indexed and unindexed documents. Specifically, among non-indexed documents, guidelines, and standards, as well as position papers, presentations, and reports, were considered.

When papers and documents included uncertain data or calculation procedures, further document research was conducted in order to gather additional information and check possible interpretations in more papers or reports using an iterative approach. In some cases, this activity required more time than expected. Indeed, this iterative procedure of in-depth analysis pushed the authors to search for position papers and technical reports as well, so that hypotheses and calculation procedures underlying each guideline and standard could be better understood.

The next step consisted in synthesising the calculation procedures for the assessment of artwork preservation conditions for the collected guidelines and standards. They are often very different from each other, but the authors translated them into a common framework, which is represented by Table 1**.** and summarises the recommended T and RH for optimal preservation in terms of hourly, daily, and yearly (or seasonal) mean values, ranges, and variations. Moreover, the select documents reported in Table 1 are organised in a chronological sequence in Figure 1. The authors consider Table 1 a remarkable contribution of this literature review to the current state of the art. More information about Table 1 is given in Section 3.

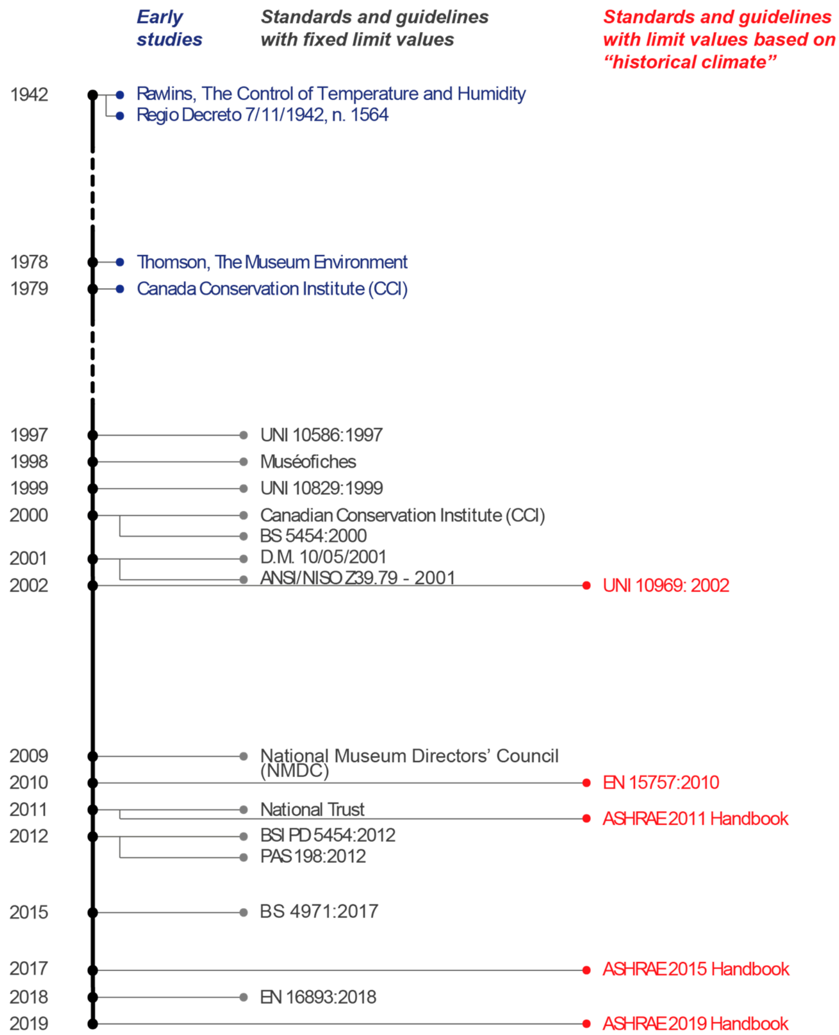

Figure 1. Timeline representing the chronological sequence of the analysed codes in Section 3.

3. Description of Relevant Standards and Guidelines

Below is a list of institutions which are competent to issue standards, laws, or guidelines at national, supranational, or global levels. There are three main categories: standards, national laws/decrees issued by a governmental institution, and guidelines issued by professional associations. The above-mentioned documents do not have the same legal value and influence: national laws are indeed mandatory, whereas the application of the requirements of standards (which only become binding when they are incorporated into a law) is strongly recommended. Another case is that of guidelines issued by professional associations, the application of which depends on the field of application and the site being studied/worked on.

1. Standards:
   - National level: UNI (Italy), BSI (United Kingdom), DIN (Germany), AFNOR (France), SFS (Finland), SIS (Sweden), SN (Norway), UNE (Spain), ASI (Austria), SNV (Switzerland), DS (Denmark), ANSI/NISO (American National Standards Institute/National Information Standards Organisation), etc.
   - European level: CEN (European Committee for Standardisation).
   - International level: ISO (International Standards Organisation).

     As far as standardisation at European level is concerned, there is a classification of the documents issued [34]:

- The European Standard (EN), leading to full implementation, as national standard, Europe-wide, which may also serve the European regulatory purposes;
- The Technical Specification (CEN/TS), which serves as normative document in areas where the actual state of the art is not yet sufficiently stable for a European Standard;
- The Technical Report (CEN/TR) for information and transfer of knowledge;
- The CEN Workshop Agreement (CWA), which aims at bringing about consensual agreements based on deliberations of open workshops with unrestricted direct representation of interested parties;
- The Guide (CEN Guide), which gives information about standardisation principles and policies and guidance to standards writers.

2. National Laws, decrees, and documents issued by a governmental/ministerial authority.
3. Technical documents and guidelines from professional associations.

3.1. Early Studies

The study of microclimate—and the subsequent development of publications related to microclimate for conservation of Cultural Heritage—saw rapid development during World War II due to the operational issues of securing heritage buildings and cultural artworks, particularly by the curators and scientists working in the National Gallery [35,36].

Rawlins [13] was the first to understand the need for the definition of recommended boundary conditions for the appropriate conservation of cultural heritage artefacts in 1942. His work consists of basic recommendations, which can be expressed as follows:

- Recommended air T: 15.6 °C.
- Recommended RH: 60%.

According to Rawlins, environments hosting cultural heritage artefacts should always correspond to these values. However, in Table 1 these values have been accounted for as mean values at any hour.

In 1978, Thomson [37] published the first edition of the book *The Museum Environment*, mainly focused on T and RH. The second edition (1986) stressed the need for microclimate tests in order to identify the most suitable conservation conditions. The author increased the level of detail by identifying two classes of preservation, i.e., “Museums” (Class 1, considered as “appropriate for major national museums, old or new, and also for all important new museum buildings”) and “Historical buildings” (Class 2, to be used in order “to avoid major dangers while keeping cost and alterations to a minimum”), with the following recommended limit values with reference to the typical microclimate conditions in buildings in the UK and the natural typical climate in UK:

- Class 1—Museums:
    a. Temperature:
        i. In winter, air T should be kept within the range between 18 °C and 20 °C, i.e., 19 ± 1 °C.
        ii. In summer, air T should be kept within the range between 23 °C and 25 °C, i.e., 24 ± 1 °C.
    b. Relative humidity:
        i. Throughout the year, RH should be 50 (or 55) ± 5%; the level may be set higher or lower, but, for mixed collections, should be in the range 45–60%.
- Class 2—Historical buildings:

a. The main focus is on RH, which should be kept within range 40–70%. Accordingly, T can be used to stabilise RH, but it should also undergo limited variations, nonetheless, with no recommended limit value.

While Thomson's recommendations are still basic, some new information can be found, which will characterise many following studies, such as the following:

- The main focus on RH.
- The identification of levels, here expressed in terms of classes. This agrees with an emerging risk-based approach.
- The definition of different limit values based on the season, i.e., the chance to accept larger T variations in a year, but with a seasonal, and hence slow, progression, according to the local climate.

In 1979, the Canadian Conservation Institute (CCI), in Technical Bulletin n. 5 [20] recommended "minimum acceptable" limits to yearly, daily, and instant values of microclimatic parameters, as follows:

- Temperature:
  a. Maximum daily T drift of ±1.5 K from the set-point.
  b. Set-point T within the range 20–25°C, with a seasonal change-over rate of maximum 1 K per month.
- Relative humidity:
  a. Maximum daily RH drift within ±3% from the set-point value.
  b. Set-point RH within the range 38–55%, with a seasonal change-over rate of maximum 5% per month.

The optimum T for exhibition and storage areas is 21 °C, with a maximum daily fluctuation of ±1.5 K from the set-point value. The optimum RH is between 47% and 53%, with maximum daily fluctuation within ±2% from the set-point value.

3.2. Current Standards and Guidelines

As mentioned in Section 1, cultural heritage conservation standards and guidelines can be classified into two categories:

- Standards and guidelines establishing fixed limit values for microclimate parameters (i.e., T, RH, etc.).
- Standards and guidelines establishing limit values for microclimate parameters (i.e., T, RH, etc.) depending on the conditions of the relevant microclimate in the recent past (e.g., the last 13 months).

3.2.1. Standards and Guidelines Establishing Fixed-Limit Values for Microclimate Parameters

While the previously mentioned early studies were developed by small research groups, over the past 30 years, the issue of appropriate conservation has gained attention, and many institutions have proposed standards and guidelines in order to show a structured and clear path to the appropriate conservation of cultural heritage items.

Italy was one of the first countries to issue laws on preventive conservation. This fact, combined with the large national cultural heritage, make Italy among the most prominent countries in this field. The UK has also been a prominent country in the definition of environmental conditions for preserving cultural heritage. Many guidelines based on different approaches were published during 2009–2012.

UNI 10586

UNI 10586 [21] deals with the microclimate and air quality parameters of graphic cultural heritage, whose recommended values are defined on the basis of their purpose:

- Storage facilities:
    a. Hourly T within the range 14–20 °C, with maximum daily fluctuations of ±2 K.
    b. Hourly RH within the range 50–60%, with maximum daily fluctuations of ±5%.
- Exhibitions, laboratories, and consultation halls:
    a. Hourly T in the range 18–23 °C.
    b. Hourly RH in the range 50–65%.

Finally, the limit values required in order to prevent damage to cultural heritage objects in case of changes in indoor microclimates caused by HVAC operation/maintenance or movements were defined:

- Maximum daily T drift of ±2 K.
- Maximum daily RH drift of ±3%.

Muséofiches

From 1993 to 2007, Direction de Musées de France published guidelines on museum operation named Muséofiches [29], which focused on each relevant topic, including indoor air conditions (1998).

Direction de Musées de France reported the following issues in contemporary regulations: the absence of standards take into account all of the problems, sometimes even providing divergent interpretations of climate problems by the collection managers. As a consequence, another perspective is given. Instead of recommending ranges for T and RH, they define the ranges that may result in damage to artworks:

- Temperature:
    a. With values below 15 °C, in mid-season, in buildings with high inertia, a sudden increase in the outside T promotes high RH values in unheated rooms, hence causing internal surface condensation.
    b. With values above 25 °C and high RH values, mould and microorganisms grow faster.
    c. T variations within usual comfort values weakly affect the dimensional and structural variation in most organic materials if the RH is stable between 40% and 65%.
- Relative humidity:
    a. With values below 40%, the water content in the material may decrease faster, with consequent increased shrinkage.
    b. From values above 65%:
        i. The water content in the material may increase faster, with consequent increased volume.
        ii. At high temperatures, moulds and microorganisms increase faster.
        iii. Corrosion phenomena increase.
    c. The effects above increase when variations occur in a short period of time and with strong amplitudes, thus leading to artwork deterioration (deformation of wood panels, detachment of the pictorial layer of a painting, cracks on the surface of an object, etc.).
    d. In general, between 40% and 65% moisture content varies the least, provided that the variations within this range are very slow and have low amplitude,

given that this RH range corresponds to the flat part of the sorption curve for most materials.

As a consequence, the following climate safety zone is recommended:

- T range 15–25 °C.
- RH range 40–65%.
- Variations in these parameters should be limited and slow.
Moreover, the following standards are recommended:
- Watertight display cases, climate boxes, etc., are recommended to keep T and RH stable.
- Good conservation conditions can be easily kept in the case of buildings with high hygrothermal inertia and low internal loads.
- Protection against external loads can be sufficient to ensure satisfactory conditions, i.e., RH variation within a ±10% interval and slow time frame, in the case of buildings with moderate humidity inertia and low internal loads.
- An appropriate air handling system should keep RH variation within a ±5% interval in the following cases:
    - Buildings with low humidity inertia.
    - In the presence of high internal loads, even if in high inertia buildings.However, it is recommended to analyse and quantify the disruptive agents able to modify environmental conditions, i.e., internal and external loads.
- Flexible and powerful air handling systems should be provided in buildings hosting temporary exhibitions in order to ensure the environmental conditions required by the lender of the artwork.

UNI 10829

UNI 10829 [17] is an Italian standard. The regulation takes into consideration the materials that make up the most widespread works of art in Italy. The following limits are established for the various groups of materials:

- Average T (or range within which to choose the set-point value).
- Maximum daily variation in T.
- Average RH (or a range within which to choose the set-point value).
- Maximum daily variation in RH.

For example, for paintings on canvas, the T range of the room is 19–24 °C, while the maximum daily T drift is 1.5 °C. For RH, the range is 40–55%, while the maximum daily RH drift is 6%.

In the literature, it has been noted that UNI 10829 is taken into consideration when long microclimatic monitoring data are not available, the heritage materials come from a different conservation environment than the one under examination, and/or when there are extraordinary events (e.g., seismic events) that constitute a break from pre-event conditions [38], i.e., in all those cases where a new starting point needs to be determined by adopting a range of values that could be considered as universal.

However, in Table 1 of UNI 10829, it is emphasised that even if the environmental conditions given for organic and mixed objects take into account both the chemical and physical nature of the constituent material, in certain cases it might be very dangerous to keep the object in such an environment when the artefact comes from very different conditions. In these cases, T and RH limit values should be determined after having considered at least the following factors:

- Ageing.
- Any treatment applied to the material.

- The environmental conditions in which the object has been kept over time.
- Any mechanical stress.

Ministerial Decree 10 May 2001, Guideline of the Ministry of Culture, Italy

The Ministerial Decree dated 10 May 2001 [22] takes data from UNI 10829 and UNI 10586 [21] standards [21]. As such, Italian museums are required to preserve national artworks in compliance with these provisions if stricter limits are not required after a specific conservation analysis of the artefact. However, the regulations refer to the body of literature that was already changing the view, in these years, that the focus of conservation was more on maintaining a historic microclimate than on achieving limit values. However, all of this is reading between the lines compared to the clarity and simplicity of reading the table to Annex VI—Sub-ambit I.

ANSI/NISO Z39.79-2001

ANSI/NISO Z39.79-2001 [28], a US standard and conformity assessment system by the American National Standards Institute (ANSI) and National Information Standards Organization (NISO), establishes criteria for the environmental factors that contribute to the deterioration of library and archival materials hosted in temporary exhibitions for no more than 12 months.

It sets the following conservation conditions:

- Temperature:
    a. Set-point value 21 °C, but lower values may be admitted if based on better preservation results.
    b. Allowed daily drift: ± 3 K.
- Relative humidity:
    a. Depending on the preservation level:
        i. Set-point value within the range 35–50%. This depends on the preservation needs, the materials, the storage history, exhibit length, prevailing climate, the building envelope, and the HVAC system (Heating, Ventilation, and Air-Conditioning). The set-point may vary seasonally, but not more than 5% per month.
        ii. Allowed daily drift: ±5%.

However, the standard leaves much to the discretion of the conservation technician.

National Museum Directors' Council

The National Museum Directors' Council (NMDC) represents the leaders of the national collections and major regional museums in the UK. In 2009, it published a document about the guiding principles for reducing museums' carbon footprints [39].

Due to increasing energy-related issues in museums, discussions were held within the Bizot (International Group of Organizers of Large-scale Exhibitions) Group about the revision of conservation conditions in museums. After the Bizot Group meetings which took place in May and October 2008, a group of UK conservators and relevant stakeholders was convened. Many considerations favoured less strict conservation conditions, i.e., the need to lower energy consumption in buildings, the possibility of adapting the conservation criteria to the actual level of conservation for a single item, and the need for conservation criteria to also take into account the previous environmental conditions, which might have been far different from the constraints recommended by many standards and guidelines.

In this context, museums have been asked to reduce their carbon footprints, primarily in the following manner: (1) applying better tailored environmental standards, which may be based on the individual object and climate; (2) using passive methods or other simple environmental control technologies; (3) using natural and sustainable environmental controls, i.e., high thermal mass in buildings, high thermal insulation, low air exchange, display cases, glazed and backed paintings, moisture buffering technologies, etc.; and (4) building/refurbishing museums so that they consume less energy.

However, NMDC also asked for further research in order to better rate the response of individual objects and consequently better define the acceptable ranges for T and RH. NMDC also requested more research on automated environmental management.

This document proposes interim Guidelines for Hygroscopic Materials (Table 1), which consist of the following:

- Keeping a stable T (range: 16–25 °C) and RH (range: 40–60%) for most of the cultural heritage items, including hygroscopic materials (e.g., canvas paintings, textiles, ethnographic objects, or animal glue).
- Keeping a specific tight range of RH for more sensitive materials (i.e., scroll paintings on silk, panel paintings, vellum, or parchment), based on the specific material.
- Keeping wider ranges for T and RH in the case of less sensitive materials (i.e., stone, ceramics).

National Trust Guidelines

The National Trust [24] was established to promote the permanent preservation of places and artefacts of natural beauty or historic interest in the UK. In 1994, the National Trust published guidelines aimed at the optimal preservation of mansion properties, then revised in 2011 [24].

In this volume the following environmental conditions are recommended:

- T within the range 5–18 °C in winter, 5–22 °C in summer.
- RH within the range 50–65% (however, the lower limit should not be reached if it requires a T higher than 18 °C).

These conditions, allowing for a wide-ranging T variations, are often referred to as "conservation heating", i.e., the heating system is used mostly to accomplish conservation, which is mainly aimed at keeping acceptable RH for artefact conservation, thus acknowledging the main role of RH in the appropriate conservation of cultural heritage [40].

However, such conditions are far from comfortable for the staff and families who work and live there. Thus, a higher T is kept in rooms where no sensitive artefact is present. In the latest revision of these guidelines, heating is recommended to be limited to as short a time as needed, with no need for gradual heating, in contrast with the first edition, since most of the materials contained in historic houses do not respond to rapid changes in RH.

BSI PD 5454

The British Standard BS 5454, published in 2000, aimed at defining requirements for building repositories for archive collections. In 2012, it was replaced by BSI PD 5454 [25], intended as a temporary guideline until a new standard, EN 16893 [41], could replace it. However, EN 16893 has a larger scope, since it does not refer to just archives.

BSI PD 5454, published in 2000, had the following recommendations:

- Set-point T within the range 16–19 °C, to be kept within a ±1 K tolerance, according to the indications of the UK Preservation Advisory Centre [42], with no seasonal drift allowed. As such, it is a very demanding imposition, which can hardly be accomplished for a full year.
- Set-point RH within the range 45–60%, to be kept within a ±5% tolerance.

BSI PD 5454, published in 2012, is very different from the previous edition, with relaxed T and RH limits. The document makes extensive references to PAS 198 [26]. BSI PD 5454:2012 sets the following conditions, depending on material and/or type of storage:

- Paper records:
    a. T within the range 5–25 °C.
    b. RH within the range 25–60%.
- General collections of robust but more sensitive ancient materials, e.g., wax seals and gelatine photographs:
    a. T within the range 13–20 °C, with the minimum T justified by the susceptibility to phase separation of beeswax seals.
    b. RH within the range 35–60%.

This standard also encompasses recommended boundary conditions for specific cases, such as the following:

- Cool storage:
    a. T within the range 5–18 °C.
    b. RH within the range 30–50%. Materials transferred from cool storage should be wrapped in an airtight enclosure and left for 24 hours at room temperature to avoid condensation.
- Cold storage (suitable for films, but not compact discs and digital video discs):
    a. T at −15 °C and within a ±5 K tolerance.
    b. No condition for RH is given.

Finally, for archival and library collections (the same sector as BSI PD 5454:2012), BS 4971 [27] was released in 2017 and shares the same approach as EN 16893, as described in the following pages.

PAS 198

The PAS 198 [26] by PAS (UK Publicly Available Specification) aims to shift museums' policies for environmental control towards reductions in their carbon footprints. It applies to the range of materials commonly found in archives, libraries, and museums, thus going beyond the scope of BSI PD 5454:2012. The standard defines the conditions of acceptability in terms of the T and RH of the microclimate hosting cultural heritage as a function of the characteristics of the material, respectively, defining classes of chemical sensitivity and sensitivity to hydrolysis according to Annex B and Annex C of the standard.

PAS 198 outlines the risk of damage or deterioration due to heat or RH, marking the values considered to be safe with a colour scale ranging from blue to red:

- Temperature:
    a. Low-sensitivity items (with reference to chemical stability): 16–30 °C, better if <22 °C.
    b. Moderate-sensitivity items (with reference to chemical stability): 5–16°C, better if < 10 °C.
    c. High-sensitivity items (chemically unstable materials): from −20 to 5 °C, better if <0 °C.
- Relative Humidity:
    a. Low sensitivity to hydrolysis (with reference to chemical stability): 30–65%, better if <50%.

b. Medium sensitivity to hydrolysis (with reference to chemical stability): 30–55%, better if <45%.
c. High sensitivity to hydrolysis (with reference to chemical stability): 30–45%, better if <35%.

BS 4971

BS 4971 [27] provides updated recommendations about the conservation and care of archival materials and library collections. It covers the exhibition and storage aspects of conservation formerly found in BSI PD 5454:2012, which is correspondingly withdrawn.

For mixed-media collections, it suggests maintaining an annual average T below 18 °C, with admitted fluctuations ranging from 13 °C (during the coldest season) to 23 °C (during the warmest season). The RH values should be kept between 35% and 60%, with slow variations.

The standard emphasises the importance of monitoring conditions inside storage enclosures, such as boxes, as these microenvironments can offer more stability compared to external surroundings.

It reflects the sector's current needs by addressing the wide range of collection materials now held in archives and libraries. Its clauses relate to conservation policy and planning, preventive conservation, and remedial conservation. In fact, the BS 4971 has shifted focus from prescriptive environmental parameters to a more flexible risk-based approach. This approach considers the specific needs of different materials and the sustainability of maintaining particular environmental conditions.

EN 16893

In 2018, EN 16893 [30] was published. The purpose of the standard is to assist "custodians of cultural heritage collections" by defining the criteria and information needed to define conservation policies and to help them determine the specifications needed to construct or modify buildings to safely house collections. On the other hand, it is stated that these specifications were prepared for buildings specifically intended for the internal storage of all types and formats of collections and may not always be applicable in historical buildings, which may also contain cultural heritage objects, especially if protected by heritage regulations.

EN 16893 aims to eliminate the use of HVAC systems for environmental control, thus turning towards air-tight and thermally stable storage, able to provide very slow-changing humidity conditions without the need for HVAC systems.

In its introduction, this standard declares that the "environmental consideration for collections is influenced by the nature of their materials, their condition and the use to which they are put".

In Annex B and C of EN 16893, the thermo-hygrometric comfort of people and energy consumption from HVAC are related to the conservation of cultural property. Annex B and C show a methodology of representing the considered factors in order to achieve the following:

- Avoid hazardous conditions for the materials composing cultural heritage objects.
- Reduce energy use.
- Achieve comfortable conditions for users (not necessarily by achieving regulatory standards).

T and RH are analysed separately. Materials are considered starting from their vulnerability to a given degradation phenomenon (e.g., hydrolysis).

As a matter of fact, in EN 16893, the T and RH values are correlated with the state of conservation of the work and, in particular, with respect to its sensitivity to chemical and mechanical stress and potential biological colonisation. The tables in Annex B and C were first published by British Standards Institution in PAS 198 [27], then withdrawn and substituted by EN 16893. The same tables are also published in ISO/TR 19815 [43].

3.2.2. Standards and Guidelines Establishing Limit Values for Microclimate Parameters Depending on the Conditions of the Relevant Microclimate in the Recent Past

These standards are based on the concept of "historical climate". Over time, cultural objects may have acclimatised to specific environmental conditions; thus, it is dangerous to move the object from its historic RH range to another one, even if this new range is theoretically better, especially in the case of hygroscopic materials (specifically wooden objects), where a change in RH could generate permanent damage.

UNI 10969

UNI 10969 [31] introduces the importance of "historical climate" in the definition of microclimate conditions for the appropriate conservation of cultural heritage. It was withdrawn after Italy adopted EN 15757.

The standard provides guidelines for the selection and control of the microclimate for the conservation of cultural assets in indoor environments, such as museums, galleries, archives, libraries, churches, and historical buildings.

The standard indicates the investigations to be carried out on the work, with the aim of completing as detailed a picture as possible of the state of preservation and chemical-physical characteristics:

- Multidisciplinary research on the present and past state of conservation of the work, the interventions it has undergone, and the determination of the microclimate in which it is kept.
- Detailed analyses to detect any alteration phenomena taking place related to variations in environmental parameters (i.e., adsorption isotherms, analysis of the distribution and physical-chemical characteristics of the pores, and quantitative assessment of the dimensional deformations of the object).

However, it is specified that, in the presence of destructive investigations or investigations that may, in turn, trigger degradation in the material, it is necessary to analyse materials with a similar composition and past history.

This standard was superseded by EN 15757, which, however, addresses a specific topic and does not structure a preliminary investigation and intervention method.

The proposed method of intervention (which can also take the form of maintaining the status quo) is as follows:

- If there is no degradation process and the climate is "favourable", the object must be maintained in the environmental conditions to which it has adapted.
- The "original" microclimate can be improved by eliminating or attenuating one or more disturbing causes (diurnal cycles, fluctuations, brisk transitions, gradients, etc.).
- In the case of necessary variations in microclimate conditions, the parameters considered to be compatible must be determined from the chemical-physical characteristics of the object and its conservation history.
- For objects without a known past history, the suitable microclimate must be determined from the object's chemical-physical characteristics.
- The transition from one initial microclimate to the next must be carried out over a very long period of time so that adaptation to the new conditions is progressive.
- During the phases of restoration, transport, and storage, the initial microclimate conditions must be guaranteed.

The standard also establishes that it is preferable to preserve objects in their original microclimate, if it is not pathological, rather than adapting it to a standardised microclimate “to be forcibly applied throughout Italy (characterised by a great variety of local climates)”.

It is interesting to note that the regulations favour the choice of “passive remedies” to limit temporal or spatial variations in microclimate parameters: thermal insulation, use of materials and structures with high thermal and hygrometric inertia, limitation of uncontrolled heat and water vapour exchanges, filtering of solar radiation, and replacement of light sources. Active systems are only recommended in order to exclude “daily cycles” and mitigate seasonal fluctuations.

The only specifications with respect to T and RH values are as follows: T and RH must remain as stable as possible over the course of 24 h in the absence of horizontal spatial gradients.

It is unexplained why the standard was deemed to have been superseded in its entirety by EN 15757, as the latter relates to the specific field of organic and hygroscopic materials, while the former covers the cultural property, in general, of any material.

EN 15757

Standard EN 15757 [3] extends the approach of UNI 10969 [31] to the European level [44–46]. The standard establishes a calculation procedure aimed at setting the reference indoor microclimate conditions for a cultural heritage item based on its so-called “historical climate”. For this purpose, a microclimate survey of at least 13 months is required. From this, the curve interpolating the monthly averages of RH (mainly) and T can be calculated through a central moving average (CMA) in a period of 30 days, as well as the target range (i.e., the range of admitted daily fluctuations of RH and T), equal to the 7th and 93rd percentile of the fluctuations recorded in the period monitored). This standard is usually applied for RH because it is assumed to be the most determining factor in the damage of hygroscopic materials like wood, fabric, or paper [46,47]. Both T and RH are mentioned in this standard as parameters influencing the conservation of cultural heritage; Table 1 (informative) presents the method for calculating the target range for RH as a reference example, since it is the main cause of mechanical stress.

It should be noted that while UNI 10829 (enforced by Ministerial Decree 2001) deals with “environmental conditions of conservation” for “objects of historical and artistic interest” (generic), EN 15757 only refers to “specifications concerning T and RH to limit mechanical damage caused by climate to hygroscopic organic materials”.

Standard EN 15757 is used for assessing indoor microclimate buildings with and without HVAC equipment [47].

ASHRAE Handbook

The American Society of Heating Refrigeration and Air-Conditioning Engineers (ASHRAE) has developed and updated guidelines for the design of HVAC (Heating, Ventilation, and Air-Conditioning) systems in rooms hosting cultural heritage items.

In fact, the *ASHRAE Handbook—HVAC Applications, 2011* included the Chapter ‘Museums, Galleries, Archives, and Libraries’ [32], which provides a table specifying indoor T and RH in terms of set-point values as well as of short- and long-term fluctuations. This table classifies recommended indoor microclimate conditions based on their associated risks and benefits, thus defining five classes of control ranging from Class AA (precision control) to Class D (relaxed control):

- Category AA: No mechanical damage risk to most artworks and paintings.
- Category A: Small risk of mechanical damage to vulnerable artworks.
- Category B: Insignificant mechanical damage risk to paintings and some artworks.

- Category C: Moderate risk to paintings and some artworks.
- Category D: Prevention of damp, but high risk of mechanical damage.

The same table was republished in *ASHRAE Handbook—HVAC Applications, 2015* [33].

In 2007 [48], Michalski explained that the fluctuations admitted in *ASHRAE Handbook—HVAC Applications, 2003* arose from a risk management assessment based on proofed fluctuations and/or extreme values. Such proofed fluctuations and/or extreme values are the largest T/RH fluctuations and/or extreme values the collection has been exposed to in the past without evident damage. Thus, the possibility of greater risk is very low if the objects experience smaller fluctuations. However, after the development of Acoustic Emission (AE) techniques [49,50], a new theory stated that the repetition of such conditions may still cause internal micro fractures, thus resulting in macroscopic cracks in the long term.

ASHRAE Handbook—HVAC Applications, 2019 [18] included some modifications reflecting a more realistic risk-management based approach. Compared with the 2011 and 2015 versions, it considered three types of collection and building combinations, corresponding to six types of control (AA, A1, A2, B, C, and D).

Moreover, for all types of controls, the *ASHRAE Handbook* specifies long-term limits, introduced in the 2019 version, annual average, seasonal adjustments from annual average, short-term fluctuations (30 days for RH, 7 days for T), and space gradients.

It should be pointed out that the relevant chapter of *ASHRAE Handbook—HVAC Applications* is explicitly aimed at the design of HVAC systems. Thus, critics may have something to say if the relevant table is used to classify a microclimate retrospectively, and even more-so if an HVAC is not present. More on this will be discussed in Section 4.

3.2.3. Relevant Indexes for Indoor Microclimate Assessment

Several publications use indices to characterise the indoor microclimate based on the first group of standards [51]:

- Performance Index (PI) is calculated based on the number of T and RH readings that comply with the limits given by UNI 10829 [52]. In some publications, PI is split into PI for T and PI for RH.
- Fabbri and Bonora developed the Heritage Microclimate Risk (HMR) index [53] in order to determine a single index for evaluating the indoor microclimate.
- Since 2006, Martens [54,55] developed a method called the “Climate Evaluation Chart” to chart the monitoring of data and to evaluate them based on the ASHRAE control classes. He has also developed a method for climate risk assessment by identifying the risk of biological, chemical, and mechanical damage for different organic materials. This analysis is based, for example, on the growth rate of mould on different organic materials. Similar analyses were proposed already in 2000 in the *Guidelines for Humidity and Temperature for Canadian Archives* written by Michalski [56] for the Canadian Conservation Institute and also published in the previously cited chapter, ‘Museums, Galleries, Archives, and Libraries’, of the ASHRAE handbooks.

3.2.4. Comparison of Main Regulations and Standards

For a clear comparison of the main standards and guidelines collected, a synoptic framework has been established and used to collect the limit values for the main microclimatic parameters recommended by each standard or guideline (Table 1). This synthesis required great effort due to the diverse origins and formulations of the standards and guidelines collected.

The synoptic framework established in this study considers the two most important (and monitored) parameters, i.e., air T and air RH.

In Table 1, each recommended limit value is expressed in terms of the following:

- A range (R) between the given limits in a given period of time. The range can be fixed (e.g., based on the material in question) or variable (calculated based on previous monitoring).
- A variation (V) in a given period of time. Again, the limits may be fixed or can vary based on previous monitoring.
- A mean value (M) in a given period of time. The recommended value is the average value of the parameter over a specific time period (e.g., one year). Here, too, the recommended value may be fixed or depend on previous monitoring.

The time intervals most commonly considered in the documents analysed are annual, seasonal, daily, and hourly. The limit values vary considerably in relation to the time frame.

Seasonal adjustments to the annual mean, which are used to indicate the variability in T and RH with respect to the seasonal cycle, are also described.

Specifically, the following reference time spans are considered: yearly or seasonal, daily, and hourly.

Moreover, the column 'Seasonal adjustment from annual average' was added to note recommended limits that bind values from one period to the next, typically in a season-after-season perspective. The reference value, i.e., the set-point value, is added where present. In the following pages, the authors will describe the main standards and guidelines by explaining their interpretation within the proposed synoptic framework.

For each document, the objective and scope, i.e., the type of material analysed, or the type of building being investigated, are stated. It is noted that there are two macro-categories of "scope": one addressed to the individual materials that compose the cultural object under investigation (e.g., wood, paper, stone, etc.), and a second to the type and intended use of a building (e.g., new building for art exhibitions, historic residence, etc.).

As already highlighted in the description of the individual documents examined, most describe the microclimate conditions to be considered desirable for conservation purposes, while others emphasise the values to be considered hazardous (PAS 198, EN 168:2018). Table 1 shows the recommended parameters, making it easier to read and compare the different documents.

Table 1. Synoptic framework including the main standards and guidelines on preventive conservation from 1942 to the present.

Year	Authors/ Document/Ref.	Scope	Recommended Conditions										Notes
			T Range (R)/Variation (V)/Mean (M) [°C]					RH range (R)/Variation (V)/Mean (M) [%]					
			Reference Value	Seasonal Adjustments From Reference Value	Yearly/ Seasonal	Daily/Short Term from Reference Value	Hourly	Reference Value	Seasonal Adjust-ments from Reference Value	Yearly/ Seasonal	Daily/ Short Term	Hourly	
1942	Rawlins [13]	All buildings.					M: ~15.6					M: ~60	
1942	Royal Decree, n. 1564, 7/11/1942 [14]	Libraries, archives, and places where books, prints, paintings, miniatures, manuscripts, and documents are kept.										R: 40–65	
1978	Thomson [37]	Museums "Appropriate for major national museums, old or new, and also for all important new museum buildings" (Class 1).					R: 19 ± 1 (winter)					R: 50–55 ±5	
							R: up to 24 ± 1 (summer)						
		Historical buildings "to avoid the major dangers while keeping cost and alteration to minimum" (Class 2).					Should be reasonably constant to stabilise RH					R: 40–70	
1979	Canada Conservation Institute (CCI) [20]	Museums, art galleries, and archives.	V: ±1	V: ±1.5	R: 20–25			V: ±5	V: ±2	R: 38–55	-		
1997	UNI 10586 [21]	Storage facilities.		V: ±2	V: ±2	V: ±2	R: 14–20		V: ±5	V: ±5	V: ±5	R: 50–60	
		When there are changes in indoor microclimate (moving graphic documents or HVAC insertion/maintenance).				V: ±2					V: ±3		
		Graphic document consultation, reading and exhibition rooms, and photoreproduction and restoration laboratories.					R: 18–23					R: 50–65	
1998	Muséofiches [29]	Museum operation.					R: 15–25					R: 40–65	
1999	UNI 10829 [17]	Paintings.				V: 1.5	R: 19–24				V: 6	R: 40–55	
		Wood sculptures.				V: 1.5	R: 19–24				V: 4	R: 50–60	

Table 1. *Cont.*

Year	Authors/ Document/Ref.	Scope	Recommended Conditions										Notes
			T Range (R)/Variation (V)/Mean (M) [°C]					RH range (R)/Variation (V)/Mean (M) [%]					
			Reference Value	Seasonal Adjustments From Reference Value	Yearly/ Seasonal	Daily/Short Term from Reference Value	Hourly	Reference Value	Seasonal Adjust-ments from Reference Value	Yearly/ Seasonal	Daily/ Short Term	Hourly	
2000	Canadian Conservation Institute (CCI) [48]	No damage for paintings on canvas or wood.			V: ±5		M: <30			V: ±5		M: <75	
		None to tiny damage on canvas or wood.			V: ±10		M: <30			V: ±10		M: <75	
		None to small damage on canvas or wood.			V: ±20		M: <30			V: ±20		M: <75	
		Small to severe damage on canvas or wood.			V: ±40		M: <30			V: ±40		M: <75	
2000	BS 5454 [25]	Storage and exhibition facilities for archival documents.				V: ±1	R: 16–19				V: ±5	R: 45–60	
2001	ANSI/NISO Z39.79-2001 [28]	Exhibiting library and archival Materials.	21				V: ±3	R: 35–50				V: ±5	
2001	Ministerial Decree of May 10, 2001 [22]	Wood.				V: 1.5	R: 19–24				V: 2 **	R: 40–45 */ 50–60 **	* Recommended thermo-hygrometric values for optimal conditions of chemical and physical conservation. ** Microclimatic conditions for the prevention of microbiological attacks on organic materials.
		Painted wood.				V: 1.5	R: 19–24				V: 2 **	R: 45–65 */ 50–60 **	
		Paintings.				V: 1.5	R: 19–24				V: 6 **	R: 35–50 */ 40–55 **	
2002	UNI 10969: 2002 [31]	Organic hygroscopic materials.	Historic annual average					Historic annual average					
2009	NMDC [39]	Hygroscopic materials.					R: 16–25					R: 40–60	
2010	EN 15757 [3]	Organic hygroscopic materials.	Historic annual average			Short-term fluctuation (SFT): T (n)–T CMA (n)	Target range: ∑SFT * 0.07 < V < ∑SFT * 0.93	Historic annual average			Short-term fluctuation (SFT): RH (n)—RH CMA (n)	Target range: ∑SFT * 0.07 < V < ∑SFT * 0.93 $RH CMA − 10% < V < RH CMA + 10%	The Annex A (informative) specifies—and provides an example—only about the calculation of the RH targets.

Table 1. *Cont.*

Year	Authors/ Document/Ref.	Scope	Recommended Conditions										Notes
			T Range (R)/Variation (V)/Mean (M) [°C]					RH range (R)/Variation (V)/Mean (M) [%]					
			Reference Value	Seasonal Adjustments From Reference Value	Yearly/ Seasonal	Daily/Short Term from Reference Value	Hourly	Reference Value	Seasonal Adjust-ments from Reference Value	Yearly/ Seasonal	Daily/ Short Term	Hourly	
2011	National Trust [24]	Preservation of mansion properties.					R: 5–18 (winter) R: 5–22 (summer)					R: 50–65	
2011/ 2015	ASHRAE 2011 Handbook [32], ASHRAE 2015 Handbook [33]	Museums, galleries, archives, and libraries.	R:15–25	V: ±5	-	V: ±2	R: 15–25	Historic annual average or 50	no change	-	V: ±5		Category AA
			R:15–25	−10 ≤ V ≤ +5	-	V: ±2	R: 15–25	Historic annual average or 50	V: ±10	-	V: ±5		Category A
			R:15–25	−10 ≤ V ≤ +5	-	V: ±2	R: 15–25	Historic annual average or 50	no change	-	V: ±10		
			R:15–25	V: ±10 and M: <30	-	V: ±5	R: 15–25	Historic annual average or 50	V: ±10	-	V: ±10		Category B
			R:15–25	T rarely over 30, usually below 25	-		R: 15–25	Historic annual average or 50	-	-	R: 25–75		Category C
			R:15–25	-	-	-	R: 15–25	Historic annual average or 50	-	M: <75	-		Category D

Table 1. *Cont.*

Year	Authors/ Document/Ref.	Scope	Recommended Conditions										Notes
			T Range (R)/Variation (V)/Mean (M) [°C]					RH range (R)/Variation (V)/Mean (M) [%]					
			Reference Value	Seasonal Adjustments From Reference Value	Yearly/ Seasonal	Daily/Short Term from Reference Value	Hourly	Reference Value	Seasonal Adjust-ments from Reference Value	Yearly/ Seasonal	Daily/ Short Term	Hourly	
2012	BSI PD 5454 [25]	Storage and exhibition facilities for archival documents—paper records.					R: 5–25					R: 25–60	
		Storage and exhibition facilities for archival documents—robust but more sensitive ancient materials, e.g., wax seals and gelatine photographs.					R: 13–20					R: 35–60	
2012	PAS 198 [26]	Materials with low sensitivity to T.	M: <22				R: 16–30						
		Materials with low sensitivity to hydrolysys (chemical stability to RH).						M: <50				R: 30–65	
		Materials with moderate sensitivity to T.	M: <10				R: 5–16						
		Materials with medium sensitivity to hydrolysys (chemical stability to RH).						M: <45				R: 30–55	
		Materials with high sensitivity to T (chemically unstable materials).	M: <0				R: −20–5						
		Materials with high sensitivity to hydrolysys (chemical stability to RH).						M: <35				R: 30–45	
		Non-composite, non-constrained hygroscopic items in order to avoid mechanical damage.										R: 50–65	
		No specific material to avoid mould germination at 20 °C,										M: <65	
		No specific material to avoid mould growth.										M: <55	
		In order to avoid risk of frost damage to the building structure, frozen pipes, etc.					M: >5						
2017	BS 4971 [27]	Traditional mixed archive collections.	M: <18			V: ±1	R: 13–23					R: 35–60	

Table 1. *Cont.*

Year	Authors/ Document/Ref.	Scope	Recommended Conditions										Notes
			T Range (R)/Variation (V)/Mean (M) [°C]					RH range (R)/Variation (V)/Mean (M) [%]					
			Reference Value	Seasonal Adjustments From Reference Value	Yearly/ Seasonal	Daily/Short Term from Reference Value	Hourly	Reference Value	Seasonal Adjust-ments from Reference Value	Yearly/ Seasonal	Daily/ Short Term	Hourly	
2018	EN 16893 [30]	Materials with low sensitivity to T.					M: <18						
		Materials with low sensitivity to hydrolysys (chemical stability to RH).						M: <50				R: 30–65	
		Materials with moderate sensitivity to T.					M: <10						
		Materials with medium sensitivity to hydrolysys (chemical stability to RH).						M: <45				R: 30–65	
		Materials with high sensitivity to T (chemically unstable materials).					M: <−5						
		Materials with high sensitivity to hydrolysys (chemical stability to RH).						M: <40				R: 30–65	
		Non-composite, non-constrained hygroscopic items in order to avoid mechanical damage.						M: >50				R: 30–65	
		No specific material to avoid mould germination at 20 °C.						M: <80				R: 65–100	
		No specific material to avoid mould growth.						M: <70				R: 55–100	
		In order to avoid risk of frost damage to the building structure, frozen pipes, etc.					M: >5						

Table 1. *Cont.*

Year	Authors/ Document/Ref.	Scope	Recommended Conditions										Notes
			T Range (R)/Variation (V)/Mean (M) [°C]					RH range (R)/Variation (V)/Mean (M) [%]					
			Reference Value	Seasonal Adjustments From Reference Value	Yearly/ Seasonal	Daily/Short Term from Reference Value	Hourly	Reference Value	Seasonal Adjust-ments from Reference Value	Yearly/ Seasonal	Daily/ Short Term	Hourly	
2019	ASHRAE 2019 Handbook [18]	Museums, galleries, archives, and libraries in modern purpose-built buildings or purpose-built rooms. T at or near human comfort.	Historic annual average	V: ± 5	R: 10–25	V: ± 2		Historic annual average	-	R: 35–65	V: ± 5		Category AA
		Museums, galleries, archives, and libraries in modern purpose-built buildings or purpose-built rooms. T at or near human comfort.	Historic annual average	$-10 < V < +5$	R: 10–25	V: ± 2		Historic annual average	V: ± 10	R: 35–65	V: ± 5		Category A1
		Museums, galleries, archives, and libraries in modern purpose-built buildings or purpose-built rooms. T at or near human comfort.	Historic annual average	$-10 < V < +5$	R: 10–25	V: ± 2		Historic annual average	-	R: 35–65	V: ± 10		Category A2
		Museums, galleries, archives, and libraries needing to reduce stress on their building (e.g., historic house museums), depending on climate zone.	Historic annual average	$-20 < V < +10$	M: ≤ 30	V: ± 5		Historic annual average	V: ± 10	R: 30–70	V: ± 10		Category B
		Museums, galleries, archives, and libraries needing to reduce stress on their building (e.g., historic house museums), depending on climate zone.		-	M: ≤ 25	T rarely over 30	M: ≤ 40	-	-	R: 25–75	Not continuously above 65	R: 25–75	Category C
		Collections in open structure buildings, historic houses.		-	-	-	-	M:<75	-	M: ≤ 75	Not continuously above 65	M: ≤ 75	Category D

4. Results and Discussion

A review of the available references led the authors of this review to identify several grey areas in the current state of the art of microclimate conditions for the preventive conservation of cultural heritage materials.

The main questions, notes, and interesting aspects identified by the authors are listed below:

1. Standards and guidelines differ because they reflect the world in which they are produced, with different social, cultural, and environmental contexts. In addition, standards are conditioned by the climate of the region considered and the problems associated with it, e.g., heating or cooling requirements, etc. As mentioned in the previous paragraphs, different values of T and RH have been proposed in the different standards. The original decision to maintain lower T values in northern European countries and higher T values in southern European countries was not the result of any particular study of the most favourable conditions for each material, but to recommend adherence to the climate of the region and to avoid major deviations from it, as suggested by Garry Thomson [37], who gave the most typical values for the UK and Commonwealth. In addition, looking specifically at the Italian context, a series of microclimate studies carried out since the 1980s on Giotto's Chapel in Padua [57], Michelangelo's Sistine Chapel in Rome [58,59], and Leonardo's Last Supper in Milan [60,61] have highlighted the risks associated with microclimate change in peculiar cultural heritage sites. These studies led to the publication of UNI 10969 and EN 15757, which aim to maintain the historical microclimate of the site under consideration, thus allowing for a colder environment in northern territories and a warmer and more humid one in Mediterranean ones.
2. There is no shared vocabulary definition regarding reference periods/time ranges. A reference is given in ASHRAE handbooks, but it cannot be used a priori in other standards. For instance, a short-term fluctuation is a parameter/concept that refers surely to time frames, but it is also ambiguously defined.
   Some standards and guidelines refer to short-term time fluctuation in the recommendation of limit values in T and RH conditions, but without clearly defining the corresponding time span, or the same definition (short-term time fluctuation) is applied to different time spans.
   For example, in early Italian standards (e.g., 10586 and 10829), short-term equals 24 hours, while in *ASHRAE Handbook, 2019*, "Short-term fluctuation means any fluctuation shorter than the times specified in footnote b for rate of seasonal adjustment (i.e., 30 days for RH fluctuations, 7 days for T fluctuations)".
   Also, the term "fluctuation" is variously defined in standards and guides. UNI 10829 recurs to the definition of time excursion that could be linked to fluctuation: "hourly parameter expressing the difference between the maximum and minimum values assumed by the quantity in the time interval considered (significant value for the purpose of determining the maximum excursion in the interval)". In EN 15757, a fluctuation is calculated as a difference between a current RH reading and a moving average, taking into account both the natural seasonal variability and the stress relaxation time constant of the materials [47].
3. EN 15757 and *ASHRAE, 2019* share a central interest in maintaining the microclimate conditions that, in the recent past, characterised the indoor environment of the artwork to be conserved, particularly in respect to 'proofed fluctuations', defined in *ASHRAE, 2019* as "the phenomenon whereby restrained components that have already fractured because of an excessive fluctuation in the past will not fracture further until a fluctuation exceeds that historic proofed' fluctuation". According to Michalsky [48],

the proofed RH or T is the largest RH or T fluctuation to which the object has been exposed in the past or, alternatively, just the lowest and highest RH and T of the past. According to the above-mentioned author, the risk of further mechanical damage (beyond that already accumulated) from fluctuations smaller than the proofed value is extremely low. However, the calculation methods of the "historical climate" and the definition of short- and medium–long-term fluctuations remain quite distinct.

EN 15757 defines the target range on the basis of the seasonal cycle calculation, as described by Camuffo in [46,62], while *ASHRAE, 2019* defines fluctuations are calculated from the annual average sets the annual averages, which is set at local historic annual averages [48,63]. It is made explicit in Psychrometric Depiction chart (*ASHRAE, 2019*, Chapter 24, Figure 15), which also shows that the most problematic moments of the year are concentrated in the seasonal change, when seasonal adjustments are contemplated.

Therefore, both documents developed the same topic with an identical aim, but proposed different methodologies and different levels of strictness in the control and management of environmental parameters leading to stable microclimatic conditions for objects.

4. Are air-related room parameters appropriate indicators in describing how artefacts are stressed by the host environment? The T and RH of the environment are not the only parameters to assess the mechanisms of degradation of materials. It is clear that the actually relevant T and RHs are those of (or very close to) the artefact itself. These are the temperatures actually perceived by the artefact and which determine its behaviour.

   The recent literature shows that the surface T of objects or environments is rarely monitored and/or assessed when discussing results, despite the fact that the phenomenon of condensation on cold surfaces is a very common and significant cause of deterioration and alteration in cultural heritage materials. It is well known that water is also a primary factor in the establishment of chemical (pollutants deposition) and biological degradation mechanisms. Controlling this phenomenon through monitoring therefore becomes essential, and should be a topic on which standards should place great emphasis.

   In this regard, only UNI 10829 defines surface T and provides a methodology for the spatio-temporal measurement of surface temperatures in order to identify all cold and hot spots in relation to the environmental T using IR sensors. Also, it provides values for deviation indicators to achieve "safe" and/or "optimal" environmental conditions for artefacts and the environment: for example, to avoid the surface condensation, the difference between air and surface T must not exceed 4°C.

   Also, the mean radiant T of the interior of the building envelope could take on greater importance in indoor assessments. This is a critical issue, since the RH of the air in contact with the item also depends on its own surface T.

   Currently, EN 15758 (in Chapter 6, 'Recommendations relating to variations in space of thermal quantities') [64] and EN 16242 (in Chapter 5, 'Considerations and recommendations related to measuring methods') [65] standards recommend procedures for measuring T (of the air and surface of the items) and RH, respectively, as well as base characteristics for relevant measurement instruments [49].

   Moreover, the standards and guidelines should also recommend conditions of T and RH uniformity within the room, with particular focus on T. In fact, T may vary significantly in a room because of local perturbations caused by external walls, windows (because of solar radiation, heat loss, and infiltration- or ventilation-related air flows), HVAC terminals, heat sources, etc. Hence, the T of objects nearby or facing these perturbations may be very different from the monitored values of air T and RH. In this regard, the position of the monitoring sensor is also crucial. Moreover, the T, and hence the RH, of objects close to the perturbations may vary widely in a day or throughout the year, and such variations may not be identifiable from room air sensor measurements.

Finally, low surface temperatures, especially when referring to boundary surfaces or artworks installed on boundary surfaces (i.e., the walls that form the building envelope and therefore the external boundary), may be subject to critical conditions because of condensation (and consequent degradation due to dissolution and crystallisation cycles of hygroscopic salts in stone materials, mould formation, etc.) and other degradation of organic and/or hygroscopic materials due to cracking/craquelure).

5. In addition to mechanical stress, there are also chemical and biological mechanisms (or, more often, a combination of the three): in order to prevent the conditions for these mechanisms to occur, it is possible to develop methods of investigation and data analysis. For example, condensation on the cold surface of an artefact is related to the surface T of the artefact and the T and RH of the surrounding air. A point that absolutely must be emphasised is that the surface T must be constantly monitored, and it must be verified that it does not reach or, worse still, exceeds the dew T so as to avoid the formation of liquid water on the surface, which is a favourable substrate for the deposition of pollutants and the proliferation of bio-deteriogens. Similarly, an ambient air with an excessively high average RH is conducive to biological attacks on surfaces and can also favour the dissolution and crystallisation cycles of soluble salts present in masonry, architectural stone elements, and furnishings. It is understood that the ultimate responsibility for the preventive conservation of the cultural property rests with the curator or conservator.
6. T and RH limit values widely depend on the reference standard or guideline. From Table 1, it is clear that the proposed values clearly differ, with reference to the statistic (variation, mean value, range, etc.), the time window (which may refer to the year down to the instant value), and to the limit values themselves. What is the reason for such differences, which might appear as a lack of objectivity? Analogously, the description of the reasons behind T and RH limit values is usually qualitative, and most of the time it seems to derive not from detailed observation of the preservation status, but from subjective experience.

   A number of studies have recently been published on the relationship between mechanisms of organic hygroscopic material decay and degradation in relation to thermo-hygrometric conditions [49,66–76]. Such studies start from analyses of specific artefacts and arrive at recommendations for objects made of similar materials. Even if this approach may seem simplified, as real-life objects may differ widely because of their composite constitution and previous history, it would be useful to integrate the results from these studies into standards and guidelines in order to overcome certain "regulatory dogmas" in favour of principles linked to scientific results that are experimentally achieved.
7. UNI 10829 represents the most-used procedure and the usual approach for risk assessment. Different approaches have been developed in recent years based on the comparison of various T and RH ranges in the literature for different artefacts and materials and new methods for assessing temporal fluctuations of T and RH. Based on this standard, the absence of HVAC systems almost always implies a negative verification of the indoor microclimate. It is specified that this standard only considers thermal, hygrometric, and light environmental conditions. It does not, however, concern the criteria and methods for such an assessment, which is entrusted to

those responsible and experts for the conservation of the objects in question. It is further alleged that it is evident the difficulty of providing precise indications, valid for all cases, about the procedure for measuring environmental quantities. It is furthermore emphasised that the limit values specified for each material are derived from diversified and not mutually comparable sources of the technical literature, but that they have not been the subject of experimental verification and that, when using the data in this prospectus, it should therefore be checked whether there are specific rules setting out precise storage conditions for the topics of interest.

Lastly, the user is advised that, at the time of publication of the standard, specific technical standards are in force at international and/or foreign level or are in the process of being approved/revised that are based on criteria other than those used in this standard (implicit reference is made to UNI 10969).

8. There are national standards that overlap, even partially, with European ones and have not yet been withdrawn. The authors hope that, in the future, there will be an Italian and European standardisation activity aimed at resolving the doubts of the users of the standard caused by the current overlap between UNI 10829 and EN 15757, EN 15758, EN 16242, and EN 16163 (which will be updated soon) [77]. In fact, the first standard of 1999 (UNI 10829) had a wide circulation and application also due to its completeness and thoroughness in all aspects related to the assessment of indoor environment (excluding the part of environmental quality related to the presence of dust and pollutants), from monitoring to data analysis.

   UNI 10829 has the advantage of making it easier for users to apply its requirements, since it takes into account a wide range of materials (from those most commonly used in ancient or traditional buildings and architecture to more modern ones) and provides recommended reference values. Furthermore, regardless of climatic conditions, it provides a list of acceptable or optimal deviation indicators or variation values for different parameters and over different timescales in order to maintain artefacts in a safe condition.

   Over the years, the approach of UNI 10829 was substituted by historic–climate-based approaches, such as in EN 15757, which, however, concerns hygroscopic organic materials. This is a factor to be particularly taken into account, since museum collections, historical buildings, and churches, in most cases, preserve a multitude of objects of different periods and materials; therefore, museums' lack of modern standards concerns all materials except organic ones.

   The danger associated with the dissemination of UNI 10829 is that the application of this standard may still lead to the widespread belief that an ad hoc microclimate exists, regardless of the climatic history of the asset under investigation.

9. ASHRAE handbook guidelines are used for microclimate assessment for preservation purposes, but it actually has a different purpose: sizing HVAC systems. Simply stated, it is aimed at providing HVAC engineers with minimum performance requirements in the case of buildings hosting cultural heritage artefacts, not for assessing the quality of the environment for preservation. Thus, even if it is often referred to with the latter purpose, this would appear to be an improper use. In fact, HVAC sizing methods define set-points in T and RH, which should be accomplished by the HVAC system during operation, thus setting a (precautionary) minimum performance benchmark, but they are not intended to define the actual set-points of the indoor environment for preservation issues. Even more, they should not be used when referring to artworks hosted in rooms with no HVAC system, as in the case studies in Huijbregts et al. [78] and Ilies et al. [79]. Indeed, standards and guidelines defining the indoor air requirements for an appropriate preservation should be used, at least to establish

initial reference conditions, for HVAC system sizing, even if one must remember that they do not contain much information specific for the choice and sizing of HVAC system components. As an example of this misunderstanding, the ASHRAE handbook calculation procedure requires the assumption of long-term variations in average T and RH within given maximum period-to-period variations in order to define the set-point values for T and RH for each month. Instead, when using such a procedure for microclimate assessment, the microclimate assessor has to hypothesise (possibly iteratively) a set of long-term T and RH variations minimising the occurrence of out-of-range values.

10. Below are some reflections on standard EN 15757:

    a. Standard EN 15757 is fundamental when the artwork is placed in an environment whose characteristics are going to change (modification of the building envelope, HVAC system, or building management). In this case, the standard allows for the assessor to check how much the new conditions differ from the historic environment in order to prevent mechanical stress. A practical example could be the modification or insertion of an HVAC system within a museum space, a place of worship, a library.
    b. If no significant modification in the boundary conditions takes place and there is no intermitted use of a HVAC (e.g., installation of a HVAC system, modification of the building envelope, modification of room occupation, change in position, etc.), the application of EN 15757 would almost always provide positive results. In fact, remaining in the same environment will offer good results, since there are no reasons for a significant deviation from the previous year's conditions, except in the case of extraordinary situations (climate events, colder/warmer seasons than in the previous year, events in the room, etc.).

11. Quantitative indicators of the appropriateness of the microclimatic conditions are missing. The standards and guidelines provide limit values, but do not assign weighted penalties to periods out of the given limits. This could be summarised with the following question: Are all outlying boundary conditions equivalent? Boundary conditions outside of the given limits but close to them probably stress materials less than more extreme boundary conditions. Even if it is difficult to assess such penalty weights, an attempt should be made in order to allow for the assessor to evaluate how bad some microclimate conditions could be. Moreover, this could result in the possibility of better comparing the current standards and guidelines, even if they rely on different limit values, and expressing them in different terms.
12. A further critical point in the application of appropriate regulations derives from the existence of national laws defining safe environmental conditions for the conservation of artworks. These laws may, in fact, not be up to date with the latest standards and bind museum operators to inappropriate conservation conditions. For example, in Italy, the existence of Ministerial Decree 2001 makes the relevant limit values binding, since different choices would be within the exclusive responsibility of the conservator, based on a specific assessment. In many cases, this could result in conservation conditions that are not appropriate for a specific artwork. However, in this regard, the decree is used in a simplistic way and, in reality, it already contains the information promoting the use of the most recent and up-to-date standards.
    The tables indicate the values of the microclimate parameters within which the different categories of materials should be stored in order to prevent chemical–physical or microbiological damage. It is pointed out that the appropriateness of modifying the conditions of museum environments, according to what is indicated in the tables, must be carefully evaluated in relation to the state of conservation of the artefacts,

the geographical area in which the museum is located, and the real possibilities of ensuring the constancy of the values (Area VI, Sub-Area I—Annex).

13. Energy consumption and the preservation of cultural heritage are closely related, as preventive conservation practises are closely linked to energy-consuming mechanical systems. In fact, keeping strict air conditions implies strict thermal control and high energy consumption by the HVAC system, which implies high costs, even more-so with recent increases in energy prices. These costs might be too high for medium–small museums, often operating with limited funds, thus decreasing the funds available for the restoration of cultural heritage items as well as for promotion. In such conditions, guidelines should also take into account energy consumption and consider the risk deriving from similar situations. With most of the other guidelines/standards, the use of HVAC systems is necessary. For example, based on UNI 10829, which represents the most-used procedure and a well-acknowledged approach for risk assessment, the absence of HVAC systems almost always implies negative verification of the indoor microclimate. On the other hand, even when there is a HVAC system, it is difficult to maintain appropriate conditions in both T and RH, especially during winter, mainly as regards RH.
In a diffuse cultural heritage, most common in Southern Europe, keeping artworks under strict environmental conditions implies the use of HVAC systems, whereas many cultural sites still have no HVAC equipment. Consequently, the conservation of such artworks, as recommended by the standards and guidelines which do not consider the microclimatic history, would imply massive investments in HVAC system installation and energy consumption, thus turning it into a low-sustainability action.
14. Standard EN 15757 was developed to counteract a phenomenon that began in the 1950s: the installation of heating systems in museums and churches. The systems were aimed at ensuring comfort conditions for the occupants, but stressed the artworks, with repeated cycles of cooling/heating and humidification/dehumidification. Standard EN 15757 is part of the most recent generation of standards and guidelines, which define the conservation conditions based on the historical profile of the thermo-hygrometric conditions in which the artwork is being kept. However, in Italy, standard UNI 10829 is more applied than EN 15757, probably because of the following reasons:

    - The Ministerial Decree 2001, the main law regulating the management of museums in Italy, cites standard UNI 10829 as a reference for the definition of the target thermo-hygrometric conditions of conservation.
    - Standard UNI 10829 recommends thermo-hygrometric conditions that are easy to verify and define, listed in mere tables, which can be straightforwardly applied with no knowledge of the historical microclimate where the artwork is being kept. On the other hand, standard EN 15757 is more complex to apply, with recommended thermo-hygrometric conditions derived from a 1 year long thermo-hygrometric monitoring campaign of the environment hosting the artwork.
    - Standard UNI 10829 aims at defending artworks from various causes of risk (biological, mechanical, chemical, etc.), whereas standard EN 15757 considers only mechanical risks.
    - Standard UNI 10829 provides indications on the basis of the constituent materials and covers various kinds of materials.
    - Ministerial Decree 2001 was not subsequently updated or repealed.

    However, there are also important reasons to support the use of standard EN 15757 as a partial replacement for UNI 10829:

- In Europe, Standard EN 15757 must be used for the defence of hygroscopic organic materials (i.e., wood, canvas, paper, etc.) from mechanical stresses (i.e., stresses that depend on variations in T and RH), thus covering most of the critical conservation issues.
- Standard EN 15757 is a European standard, so it should replace the previous national counterparts.
- Standard UNI 10829 provides tables with limits in Table 1 (i.e., not in the main body, which is the most significant part of a standard) and entitles Table 1itself "Suggested reference values, in conditions of stable climate and when lacking of specific recommendations, aimed at the design of air-conditioning systems dedicated to rooms hosting artworks". Hence, it is clear that the limits given in UNI 10829 are not aimed at conservation condition assessments, but at Heating, Ventilation and Air-Conditioning (HVAC) sizing. Moreover, as expressed in Table 1 itself, the values given in the table are taken from different and reciprocally incomparable sources and were not experimentally checked. Finally, the note accompanying the tables states that, in the case of organic and mixed materials, keeping/taking the artwork within/to the given T and RH conditions may damage the artwork.
- Moreover, within the text of Ministerial Decree 2001, the following points would allow the use of standard EN 15757:

    a. In the Chapter entitled 'Articolazione dell'Ambito VI' (i.e., 'Development of Topic VI').
    b. In Section 5, '5. Politiche di ricerca e studio' (i.e., 'Research and study strategies'), the collaboration of museums with Universities and Research Institutes is promoted, in order to take advantage of the most recent tools and procedures, hence of the most recent standards (and standard EN 15757 is much more recent than standard UNI 10829).
    c. In 'Sottoambito 1—Norme per la conservazione e il restauro, comprendenti l'esposizione e la movimentazione' (i.e., 'Subtopic 1—Standards for conservation and restoration, including exhibition and transport'):
    d. In '1. Documentazione per la conservazione' (i.e., '1. Documents for conservation'), the text refers to monitoring activities taking place at Pinacoteca di Brera (Milan), Museo Civico Correr (Venice) and Galleria Doria Pamphili (Rome), which set the foundation for next standard EN 15757.
    e. In '2. Parametri ambientali' (i.e., '2. Environmental parameters'), the text admits that it is difficult to set absolute limits for environmental parameters and that the included tables should be interpreted based on the conservation status of the artwork and on the boundary conditions and historical climate.
    f. In the table, the decree warns about the decision to modify the thermo-hygrometric conditions aiming at the achievement of the T and RH conditions set in the tables, depending on the site and status of conservation.

15. The regulatory and legislative panorama regarding the microclimate for the conservation of movable cultural heritage and the materials of the architectural components of historic buildings is various and complex to manage. As previously stated, the development of guidelines and standards reflects the different social, cultural, and environmental contexts they belong to, here including climate and heating/cooling energy consumption and costs. In this regard, the approach based on the microclimate history is able to provide a common framework for cultural heritage conservation assessment

which automatically can be differentiated based on climate and can limit energy consumption and costs for the achievement of the appropriate conservation level.

The differentiating factor is, therefore, annual microclimate monitoring, the only tool capable of guiding operational decisions or assessing risk conditions for cultural property on the basis of real data rather than a priori hypotheses. On the other hand, microclimate assessment without microclimate monitoring of sufficient duration is not advisable and is no longer scientifically supported by recent studies. It is therefore desirable that, taking into account the above considerations, the path followed by technicians, scientists, restorers, etc., should always be that of diagnostic investigation, and that the documents in force in the future should follow a univocal path in this direction, withdrawing those regulations, technical documents, and guidelines that are no longer up to date and that cause confusion among those involved.

5. Conclusions

This paper presents a critical historical analysis of the main standards and guidelines developed from the 1940s to the present, highlighting the evolution of the methods and requirements in the assessment of microclimate conditions for cultural heritage preservation.

The general trend is from fixed-limit values to limits defined after long-term monitoring, which aim to keep the environment within conditions where the artwork has acclimatised over time. In addition, this second approach aims at a more sustainable use of cultural assets and lower use of energy.

This paper establishes a framework to compare the standards and guidelines for the assessment of the indoor microclimate for cultural heritage preservation, highlighting the critical issues and discussing the inconsistencies in their application due to misunderstandings of terminology and uncommon language.

The definition of the framework required great effort because of the lack of a shared vocabulary among the standards and guidelines, as well as the vastly different approaches and implementations. Thanks to this framework, this study shows that the application of the aforementioned standards and guidelines raises conflicts in the choice of limit values for microclimate assessment.

Moreover, the available standards/guidelines do not establish any index to quantify the quality of the microclimate, i.e., it is not possible to quantitatively assess how good/bad the microclimate is, but it is only possible to calculate how many hours/days are spent within recommended limits, with no reference to the amount of compliance/non-compliance, depending on how close/far they are from the given limits.

In the future, the authors will apply these results to real case studies in order to quantify the differences among the aforementioned standards and regulations.

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References

1. Pretelli, M.; Fabbri, K. Historic Indoor Microclimate. In *Historic Indoor Microclimate of the Heritage Buildings*; Springer International Publishing: Cham, Switzerland, 2018; pp. 73–83.
2. Camuffo, D. *Microclimate for Cultural Heritage: Measurement, Risk Assessment, Conservation, Restoration, and Maintenance of Indoor and Outdoor Monuments*; Elsevier, Ed.; Elsevier Science B.V.: Amsterdam, The Netherlands, 2019; ISBN 9780444641069.
3. *EN 15757:2010*; Conservation of Cultural Property—Specifications for Temperature and Relative Humidity to Limit Climate-Induced Mechanical Damage in Organic Hygroscopic Materials. CEN (European Committee for Standardization): Brussels, Belgium, 2010; ISBN 9780580609060.
4. Fabbri, K. Historic Climate in Heritage Building and Standard 15757: Proposal for a Common Nomenclature. *Climate* **2022**, *10*, 4. [CrossRef]
5. Bernardi, A. *Microclimate Inside Cultural Heritage Buildings*; Il Prato: Florence, Italy, 2008; ISBN 8863360324.
6. Camuffo, D. *Microclimate for Cultural Heritage*; Elsevier, Ed.; Elsevier Science B.V.: Amsterdam, The Netherlands, 1998.
7. Elkadi, H.; Al-Maiyah, S.; Fielder, K.; Kenawy, I.; Martinson, D.B. The Regulations and Reality of Indoor Environmental Standards for Objects and Visitors in Museums. *Renew. Sustain. Energy Rev.* **2021**, *152*, 111653. [CrossRef]
8. Zannis, G.; Santamouris, M.; Geros, V.; Karatasou, S.; Pavlou, K.; Assimakopoulos, M.N. Energy Efficiency in Retrofitted and New Museum Buildings in Europe. *Int. J. Sustain. Energy* **2006**, *25*. [CrossRef]
9. Fabbri, R.; Gabrielli, L.; Ruggeri, A.G. Interactions between Restoration and Financial Analysis: The Case of Cuneo War Wounded House. *J. Cult. Herit. Manag. Sustain. Dev.* **2018**, *8*, 145–161. [CrossRef]
10. Lucchi, E. Review of Preventive Conservation in Museum Buildings. *J. Cult. Herit.* **2018**, *29*, 180–193. [CrossRef]
11. Luciani, A. Evolution of Thermo-Hygrometric Standards for Cultural Heritage Preservation. An Overview. In *Indoor Environment and Preservation. Climate Control in Museums and Historic Buildings*; Del Curto, D., Ed.; Nardini Editore: Florence, Italy, 2010.
12. *EN 15898:2019*; Conservation of Cultural Heritage—Main General. Terms and Definitions. CEN (European Committee for Standardization): Brussels, Belgium, 2019; ISBN 9780539005684.
13. Rawlins, F.I.G. The Control of Temperature and Humidity in Relation to Works of Art. *Mus. J.* **1942**, *41*, 279–283.
14. Gazzetta Ufficiale del Regno d'Italia. *Regio Decreto n.1564/1942. Approvazione Delle Norme per L'esecuzione, Il Collaudo e L'esercizio Degli Impianti Tecnici Che Interessano Gli Edifici Pregevoli per Arte o Storia e Quelli Destinati a Contenere Biblioteche, Archivi, Musei, Gallerie, Collezioni e Oggetti D'interesse Culturale ("Approval of Regulations for the Execution, Testing, and Operation of Technical Systems Affecting Historically Significant Buildings...")*; Gazzetta Ufficiale del Regno d'Italia: Rome, Italy, 1942.
15. Brown, J.P.; Rose, W.B. Humidity and Moisture in Historic Buildings: The Origins of Building and Object Conservation. *APT Bull.* **1996**, *27*, 12. [CrossRef]
16. Frasca, F.; Boccacci, G.; Casalino, C.; Bertolin, C.; Camuffo, D.; Siani, A.M. L'evoluzione Degli Studi Microclimatici per La Conservazione Di Manufatti in Ambiente Museale Nel Corso Degli Ultimi 20 Anni. In *La. Conservazione Preventiva e Programmata. Venti Anni Dopo il Codice dei Beni Culturali: 39. Convegno di Studi, Bressanone 2-5 luglio 2024*; Driussi, G., Morabito, Z., Eds.; Arcadia Ricerche: Marghera, Italy, 2024; pp. 499–510. ISBN 978-88-95409-28-3.
17. *UNI 10829:1999*; Beni Di Interesse Storico Artistico—Condizioni Ambientali Di Conservazione. Misure Ed Analisi (in English: "Works of Art of Historical Importance—Ambient Conditions for Conservation—Measurement and Analysis"). UNI (Ente Italiano di Normazione): Milano, Italy, 1999.
18. ASHRAE (American Society of Heating Refrigerating Air-Conditioning Engineers). Museums, Galleries, Archives, and Libraries, Chapter 24. In *ASHRAE Handbook—HVAC Applications*; ASHRAE: Atlanta, GA, USA, 2019.
19. Verticchio, E.; Frasca, F.; Bertolin, C.; Siani, A.M. Climate-Induced Risk for the Preservation of Paper Collections: Comparative Study among Three Historic Libraries in Italy. *Build. Environ.* **2021**, *206*, 108394. [CrossRef]
20. Lafontaine, R.H. Environmental Norms for Canadian Museums, Art Galleries and Archives. In *Technical Bulletin 5*; National Museums of Canada, Canadian Conservation Institute, Ed.; Canadian Conservation Institute: Ottawa, ON, Canada, 1979; ISBN 0-662-50400-3.
21. *UNI 10586:1997*; Condizioni Climatiche per Ambienti Di Conservazione Di Documenti Grafici e Caratteristiche Degli Alloggiamenti (in English: "Climatic Conditions for the Conservation of Graphic Documents and Characteristics of Housings"). UNI (Ente Italiano di Normazione): Milano, Italy, 1997.

22. Ministero per i Beni e le Attività Culturali. *Atto Di Indirizzo Sui Criteri Tecnico–Scientifici e Sugli Standard di Funzionamento e Sviluppo dei Musei. D.M. 10 Maggio 2001 (in English: "Directive on the Technical-Scientific Criteria and Standards for the Operation and Development of Museums")*; Ministero per i Beni e le Attività Culturali: Rome, Italy, 2001.
23. Background, A.; Nicholas, S.; Jones, M.; Principles, B.D.G.; Group, T.B. NMDC Guiding Principles for Reducing Museums' Carbon Footprint. In *Proceedings of the UK National Museum Directors Council*; Guiding Principles for Reducing Museums' Carbon Footprint; NMDC: New Delhi, India, 2008.
24. *The National Trust Manual of Housekeeping: Care and Conservation of Collections in Historic Houses*; Elsevier: Swindon, UK, 2011.
25. *BSI PD 5454:2012*; Guide for the Storage and Exhibition of Archival Materials. British Standards Institution: London, UK, 2012.
26. *Pas 198:2012*; Specification for Managing Environmental Conditions for Cultural Collections. British Standards Institution: London, UK, 2012.
27. *BS 4971:2017*; Conservation and Care of Archive and Library Collections. BSI Standards Publication: London, UK, 2017.
28. *ANSI/NISO Z39.79-2001*; Environmental Conditions for Exhibiting Library and Archival Materials. National Information Standards Organization—NISO: Baltimore, MD, USA, 2001.
29. Direction des Musées de France—DMF. *Muséofiches*; Direction des Musées de France—DMF: Paris, France, 1998.
30. *EN 16893:2018*; Conservation of Cultural Heritage. Specifications for Location, Construction and Modification of Buildings or Rooms Intended for the Storage or Use of Heritage Collections. CEN (European Committee for Standardization): Brussels, Belgium, 2018; ISBN 9780580921896.
31. *UNI 10969:2002*; Principi Generali per La Scelta e Il Controllo Del Microclima per LA Conservazione Dei Beni Culturali in Ambienti Interni (in English: "Cultural Heritage—General Principles for the Choice and Control of the Microclimate for the Conservation of Cultural Heritage in Indoor Environments"). UNI (Ente Italiano di Normazione): Milano, Italy, 2002.
32. ASHRAE (American Society of Heating Refrigerating Air-Conditioning Engineers). Museums, Galleries, Archives and Libraries, Chapter 23. In *ASHRAE Handbook–HVAC Applications*; ASHRAE: Atlanta, GA, USA, 2011.
33. ASHRAE (American Society of Heating Refrigerating Air-Conditioning Engineers). Museums, Galleries, Archives and Libraries, Chapter 23. In *ASHRAE Handbook–HVAC Applications*; ASHRAE: Atlanta, GA, USA, 2015.
34. European Committee for Standardization (CEN) CEN Deliverables. Available online: https://boss.cen.eu/reference-material/guidancedoc/pages/del/ (accessed on 28 October 2024).
35. Rawlins, F.I.G. The National Gallery in War-Time. *Nature* **1943**, *151*, 123–128. [CrossRef]
36. Plenderleith, H.J. Preservation of Museum Objects in War-Time. *Nature* **1943**, *152*, 94–97. [CrossRef]
37. Thomson, G. *The Museum Environment*; Butterworths: London, UK, 1978.
38. de Rubeis, T.; Nardi, I.; Muttillo, M.; Paoletti, D. The Restoration of Severely Damaged Churches—Implications and Opportunities on Cultural Heritage Conservation, Thermal Comfort and Energy Efficiency. *J. Cult. Herit.* **2020**, *43*, 186–203. [CrossRef]
39. National Museum Directors' Conference—NMDC. *NMDC Guiding Principles for Reducing Museums' Carbon Footprint*; NMDC: New Delhi, India, 2009.
40. Staniforth, S. *Conservation Heating to Slow Conservation: A Tale of the Appropriate Rather Than the Ideal*; The Getty Conservation Institute: Tenerife, Spain, 2007.
41. *BS EN 16893:2018*; Conservation of Cultural Heritage. Specifications for Location, Construction and Modification of Buildings or Rooms Intended for the Storage or Use of Heritage Collections. British Standards Institution—BSI: London, UK, 2018.
42. Walker, A. *Basic Preservation Guidelines for Library and Archive Collections*, 5th ed.; Preservation Advisory Centre, Ed.; The British Library: London, UK, 2013; ISBN 0712348425.
43. *ISO/TR 19815:2018*; Information and Documentation—Management of the Environmental Conditions for Archive and Library Collections. ISO (International Organization for Standardization): Geneva, Switzerland, 2018.
44. Camuffo, D. Clima e Microclima: La Normativa in Ambito Nazionale Ed Europeo. *Kermes Riv. Restauro* **2008**, 49–67.
45. Camuffo, D. Il Clima Storico per La Conservazione Dei Beni Culturali: Materiali Organici e Variazioni Microclimatiche. *UC Unificazione Certificazione* **2014**, *9*, 11–12.
46. Fassina, V. *Normativa Tecnica Italiana ed Europea*; Nardini Editore: Rome, Italy, 2022.
47. Camuffo, D.; Della Valle, A.; Becherini, F. The European Standard EN 15757 Concerning Specifications for Relative Humidity: Suggested Improvements for Its Revision. *Atmosphere* **2022**, *13*, 1344. [CrossRef]
48. Michalski, S. The Ideal Climate, Risk Management, the ASHRAE Chapter, Proofed Fluctuations, and Toward a Full Risk Analysis Model. In Proceedings of the Roundtable on Sustainable Climate Management Strategies; The Getty Conservation Institution, Ed.; The Getty Conservation Institution: Tenerife, Spain, 2007; pp. 1–19.
49. Jakieła, S.; Bratasz, Ł.; Kozłowski, R. Acoustic Emission for Tracing Fracture Intensity in Lime Wood Due to Climatic Variations. *Wood Sci. Technol.* **2008**, *42*, 269–279. [CrossRef]
50. Aicher, S.; Hfflin, L.; Dill-Langer, G. Damage Evolution and Acoustic Emission of Wood at Tension Perpendicular to Fiber. *Eur. J. Wood Wood Prod.* **2001**, *59*, 104–116. [CrossRef]

51. Bienvenido-Huertas, D.; León-Muñoz, M.; Martín-del-Río, J.J.; Rubio-Bellido, C. Analysis of Climate Change Impact on the Preservation of Heritage Elements in Historic Buildings with a Deficient Indoor Microclimate in Warm Regions. *Build. Environ.* **2021**, *200*, 107959. [CrossRef]
52. Corgnati, S.P.; Filippi, M.; Perino, M. A New Approach for the IEQ (Indoor Environment Quality) Assessment. In Proceedings of the 3rd International Building Physics Conference—Research in Building Physics and Building Engineering, Montreal, QC, Canada, 27–31 August 2006; Concordia University, Ed.; Concordia University: Montreal, QC, Canada, 2006.
53. Fabbri, K.; Bonora, A. Two New Indices for Preventive Conservation of the Cultural Heritage: Predicted Risk of Damage and Heritage Microclimate Risk. *J. Cult. Herit.* **2021**, *47*, 208–217. [CrossRef]
54. Martens, M.H.J.; van Schijndel, A.W.M.; Schellen, H.L. Evaluation of Indoor Climates Using the Climate Evaluation Chart. In Proceedings of the Lyon EPIC Conference, Lyon, France, 20–22 November 2006; pp. 523–528.
55. Martens, M.H.J. *Climate Risk Assessment in Museums: Degradation Risks Determined from Temperature and Relative Humidity Data*; Technische Universiteit Eindhoven, Ed.; Technische Universiteit Eindhoven: Eindhoven, The Netherlands, 2012.
56. Michalski, S. *Guidelines for Humidity and Temperature in Canadian Archives*; Canadian Conservation Institute: Ottawa, ON, Canada, 2000; ISBN 0-662-29509-9.
57. Camuffo, D.; Schenal, P. Microclima All'interno Della Cappella Degli Scrovegni: Scambi Termodinamici Tra Gli Affreschi e l'ambiente. In *Ministero dei Beni Culturali ed Ambientali: "Studi Sullo Stato di Conservazione Della Cappella Degli Scrovegni in Padova, Volume Speciale del Bollettino d'Arte*; Poligrafico dello Stato: Rome, Italy, 1982; pp. 107–209.
58. Camuffo, D.; Bernardi, A. Dinamica Del Microclima e Scambi Termoigrometrici Tra Pareti e Atmosfera Interna Nella Cappella Sistina. *Boll. Monum. Musei Gall. Pontif.* **1986**, 211–257.
59. Camuffo, D.; Bernardi, A. The Microlimate of the Sistine Chapel. *Eur. Cult. Herit. Newsl. Res.* **1995**, *9*, 7–32.
60. Camuffo, D.; Bernardi, A. The Microclimate of Leonardo's Last Supper. *Eur. Cult. Herit. Newsl. Res.* **1991**, *14*, 39–75.
61. Camuffo, D.; Bernardi, A. Analisi Microclimatica al Cenacolo Vinciano. *Boll. Geofis.* **1991**, *14*, 1–100.
62. Camuffo, D. *Microclimate for Cultural Heritage*, 2nd ed.; Camuffo, D., Ed.; Elsevier: Amsterdam, The Netherlands, 2014; pp. xi–xii. ISBN 978-0-444-63296-8.
63. Michalski, S. The Power of History in the Analysis of Collection Risks from Climate Fluctuations and Light. In Proceedings of the ICOM Committee for Conservation 17th Triennial Meeting, Melbourne, Australia, 17–19 September 2014; pp. 15–19.
64. *EN 15758:2010*; Conservation of Cultural Property—Procedures and Instruments for Measuring Temperatures of the Air and the Surfaces of Objects. CEN: Brussels, Belgium, 2010.
65. *EN 16242:2012*; Conservation of Cultural Heritage—Procedures and Instruments for Measuring Humidity in the Air and Moisture Exchanges between Air and Cultural Property. CEN: Brussels, Belgium, 2012; ISBN 9780580740145.
66. Califano, A.; Zanola, A.; Di Terlizzi, I.; Baiesi, M.; Bertolin, C. Preliminary Evaluation of the Climate-Induced Fatigue in Wood: A Physical and Computational Approach. *Forces Mech.* **2023**, *11*, 100186. [CrossRef]
67. Riparbelli, L.; Mazzanti, P.; Helfer, T.; Manfriani, C.; Uzielli, L.; Castelli, C.; Santacesaria, A.; Ricciardi, L.; Rossi, S.; Gril, J.; et al. Modelling of Hygro-Mechanical Behaviour of Wooden Panel Paintings: Model Calibration and Artworks Characterisation. *Herit. Sci.* **2023**, *11*, 126. [CrossRef]
68. Bratasz, Ł. Allowable Microclimatic Variations in Museums and Historic Buildings: Reviewing the Guidelines. In *Climate for collections. Standards and uncertainties*; Ashley-Smith, J., Burmester, A., Eibl, M., Eds.; Archetype Publications: Munich, Germany, 2013.
69. Bratasz, L. Acceptable and Non-Acceptable Microclimate Variability: The Case of Wood. Basic environmental mechanisms affecting cultural heritage. Understanding deterioration mechanisms for conservation process. *COST Action D* **2010**, *42*, 49–58.
70. Bratasz, Ł. Allowable Microclimatic Variations for Painted Wood. *Stud. Conserv.* **2013**, *58*, 65–79. [CrossRef]
71. Bratasz, Ł.; Kozłowski, R. Laser Sensors for Continuous In-Situ Monitoring of the Dimensional Response of Wooden Objects. *Stud. Conserv.* **2005**, *50*, 307–315. [CrossRef]
72. Soboń, M.; Bratasz, Ł. A Method for Risk of Fracture Analysis in Massive Wooden Cultural Heritage Objects Due to Dynamic Environmental Variations. *Eur. J. Wood Wood Prod.* **2022**, *80*, 1201–1213. [CrossRef]
73. Bratasz, Ł.; Harris, I.; Lasyk, Ł.; Łukomski, M.; Kozłowski, R. Future Climate-Induced Pressures on Painted Wood. *J. Cult. Herit.* **2012**, *13*, 365–370. [CrossRef]
74. Krzemień, L.; Łukomski, M.; Bratasz, Ł.; Kozłowski, R.; Mecklenburg, M.F. Mechanism of Craquelure Pattern Formation on Panel Paintings. *Stud. Conserv.* **2016**, *61*, 324–330. [CrossRef]
75. Janas, A.; Mecklenburg, M.F.; Fuster-López, L.; Kozłowski, R.; Kékicheff, P.; Favier, D.; Andersen, C.K.; Scharff, M.; Bratasz, Ł. Shrinkage and Mechanical Properties of Drying Oil Paints. *Herit. Sci.* **2022**, *10*, 181. [CrossRef]
76. Janas, A.; Fuster-López, L.; Andersen, C.K.; Escuder, A.V.; Kozłowski, R.; Poznańska, K.; Gajda, A.; Scharff, M.; Bratasz, Ł. Mechanical Properties and Moisture-Related Dimensional Change of Canvas Paintings–Canvas and Glue Sizing. *Herit. Sci.* **2022**, *10*, 160. [CrossRef]

77. *EN 16163:2014*; Conservation of Cultural Heritage. Guidelines and Procedures for Choosing Appropriate Lighting for Indoor Exhibitions. CEN: Brussels, Belgium, 2014; ISBN 9780580740145.
78. Huijbregts, Z.; Kramer, R.P.; Martens, M.H.J.; van Schijndel, A.W.M.; Schellen, H.L. A Proposed Method to Assess the Damage Risk of Future Climate Change to Museum Objects in Historic Buildings. *Build. Environ.* **2012**, *55*, 43–56. [CrossRef]
79. Ilieș, D.C.; Marcu, F.; Caciora, T.; Indrie, L.; Ilieș, A.; Albu, A.; Costea, M.; Burtă, L.; Baias, Ș.; Ilieș, M.; et al. Investigations of Museum Indoor Microclimate and Air Quality. Case Study from Romania. *Atmosphere* **2021**, *12*, 286. [CrossRef]