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Review

Hygrothermal Behavior of Cultural Heritage Buildings and Climate Change: Status and Main Challenges

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Abstract: This paper follows a bibliometric assessment methodology to provide a systematic review of studies devoted to cultural heritage (CH) buildings that simultaneously refer to hygrothermal conditions and/or behavior and climate change (CC) scenarios. Moreover, this paper aims at identifying the main research trend and research gaps in this combined research field, and to provide a critical discussion of previous works relating to CH, hygrothermal behavior, and CC. Scopus database was used for data gathering and export, followed by VOSviewer for network visualization. The advanced search on the database showed that only 36 documents have considered the study of these three subjects together, as of 2022. The majority of research has been carried out in Italy (27% of the relevant documents). This paper further describes some funded research projects on the topic of CH, hygrothermal behavior, and CC. It was concluded that the investigation on this combined research topic is very recent and scarcely unexplored, and further research is required to assess how future CC scenarios will affect the hygrothermal behavior of CH buildings. These new understandings are fundamental for all stakeholders involved in topics related to heritage conservation and assessment of the hygrothermal behavior of buildings.

Keywords: hygrothermal behavior; cultural heritage; climate change; historic buildings; bibliometric analysis

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Citation: Dias Pereira, L.; Saraiva, N.B.; Soares, N. Hygrothermal Behavior of Cultural Heritage Buildings and Climate Change: Status and Main Challenges. *Appl. Sci.* **2023**, *13*, 3445. https://doi.org/10.3390/app13063445

Academic Editors: Asterios Bakolas and Giuseppe Lacidogna

Received: 30 January 2023
Revised: 1 March 2023
Accepted: 6 March 2023
Published: 8 March 2023

1. Introduction

The debates on climate change (CC), fossil fuels depletion, and energy security are among the most dominant public and scientific topics and highlight the need for a more sustainable built environment [1]. Moreover, the improvement of the thermal performance and energy efficiency of cultural heritage (CH) buildings can revitalize their use and reduce their operational energy costs [2]. However, as remarked by Ascione et al. [3], the selection of the energy efficiency measures and refurbishment scenarios for historic buildings can be a very challenging multi-objective optimization problem subject to many constraints, such as the specific building characteristics, the architectural and functional peculiarities of the pre-existence, the historical value, the efficiency targets, and the economical availability. Thus, as further remarked by Roberti et al. [4], the refurbishment of CH buildings should balance the requirements of cultural protection, indoor comfort, and energy efficiency. Nevertheless, environmental and economic indicators must also be considered. Martínez-Molina et al. [5] further remarked that retrofitting CH buildings to present energy efficiency and thermal comfort standards is vital to enhance energy performance and sustainability and to preserve the built heritage of historic structures. In their work, these authors provided an extensive literature review on the methods and techniques that have been used to achieve high-performance refurbishments of CH buildings, namely, residential, religious, academic, palaces, museums, libraries and theaters, urban areas, and others. Finally, Cornaro et al. [6] highlighted that many historic buildings are property of public institutions, which means that the public sector has a key role in preserving cultural integrity and improving indoor thermal comfort and energy efficiency of public CH buildings.

CH buildings are part of mankind's tangible and immovable patrimony [7]. This CH subcategory englobes monuments, groups of buildings, or sites [8]. When present in literature, this subcategory is sometimes identifiable through other terminologies, namely "built heritage", "historic buildings", "historic construction", or even "historical buildings", though they do not always refer to the same construction period, "protected" or listed buildings. One of the problems CH buildings have been affronting is the degradation of the tangible patrimony through the poor quality of their hygrothermal environment. Variations on this matter are often found in the way the hygrothermal behavior is evaluated, sometimes it is denominated by "analysis", others by "performance" or "assessment", etc.

Additionally, the hygrothermal evaluation may consider different approaches, some more detailed, e.g., recurring to more advanced technologies to analyze the hygrothermal response and the interaction with the outdoor environment, while others focus on simpler performance assessments of the thermal environment requiring less equipment. In any case, such hygrothermal assessments should always take into consideration the external boundary conditions that buildings are exposed to, as the outdoor climate is an agent of influence on CH buildings. However, if for any reason, this outdoor environment changes over time, it is relevant to study its impact on buildings, especially, on those that are more vulnerable and classified. In this way, it is feasible to establish a link between the study of the hygrothermal behavior of CH buildings and the subject of CC.

According to the United Nations, CC refers to variations in typical weather patterns observed in a long-term perspective [9]. This shift in the world's climate becomes a challenge to mankind when human activity is its main driver [10]. Moreover, as suggested by Hulme [11], the unknown CC must be addressed considering neoliberal globalism, the rise of a risk society, but also ecological transformation. The shared fears of modern society towards CC have promoted research in several fields, such as geo, political, and social engineering [11–13]. Li et al. [14] further addressed the global scientific output of CC research to assess the characteristics of the research patterns, tendencies, and methods in the papers concerning changes in the observed weather up to the date.

Though CC and "Global Warming" do not have the exact same meaning, in the literature these two terms are often used to designate future weather scenarios. CC is a much broader concept, encompassing far more climatic parameters (temperature, precipitation, pollutants, etc.) and considering extreme events (rise of sea levels, floods, drought, etc.), than the concept of Global Warming that focuses only on the increase of the average global surface temperature. Thus, the distinction between these two concepts is valid and rather important when applied to the impact on CH buildings. The effect of temperature rise certainly will be noticed on the hygrothermal performance of CH buildings, but so does the increase in the air humidity. This makes CC the most appropriate concept for the present investigation.

The combined urgency in predicting the impact of CC in the world and the need to preserve cultural patrimony justifies the relevance of the present study. Some review studies have already explored parts of these scientific areas: CH buildings [15,16], and CC [14,17]. However, a comprehensive review of the impact of CC on the hygrothermal behavior of CH buildings is still brief [18]. Moreover, as pointed out by Pisello et al. [19], new multidimensional and integrated approaches for energy refurbishment of historical buildings are required, considering hygrothermal, energy, economic, and environmental analysis together. The design of energy refurbishment of CH buildings must also address historical architecture, techniques, and materials. In fact, as suggested by De Santoli [20], CH buildings require "appropriately tailored to the needs" guidelines on energy efficiency due to the peculiarities of the CH. The energy efficiency retrofit of historic buildings must also consider both long-term use and conservation in order to preserve the past and protect future resources [21]. Filippi [22] provided some remarks on the green retrofitting of historic buildings in Italy, particularly on the major operational procedures, barriers, and challenges that investors, professionals, practitioners, design engineers, and supervisory authorities can encounter when they are engaged in the green retrofitting of CH buildings. Schito and Testi [23] also stated that the design of HVAC systems for CH exhibition rooms is very challenging since artworks require optimal microclimate with specific hygrothermal conditions even in critical conditions to prevent deterioration. The passive control of CH building envelopes with large windows and skylights should also be further addressed to avoid damage to artifacts housed in these buildings in the face of future extreme weather events, as suggested by Sciurpi et al. [24].

These facts lead the authors to acknowledge that the potential impact of CC on the built heritage is still an underestimated and insufficiently studied research topic in terms of review works. Therefore, the current study follows a bibliometric methodology to address the following research questions: (i) what is the state of development of this research field?; (ii) are there any research trends in the field?; and (iii) what are the main research gaps still observed in the literature? Consequently, the main goals of this study are to determine the status and development trends in the combined field of CH, hygrothermal conditions, and CC over the last few years. Thus, the expected findings are going to support the understanding of current and future trends for all involved stakeholders on the related topic of heritage patrimony and climate change.

The structure of this article is the following: Section 2 presents the materials and methods used to perform the review subsequent to the research framework (Figure 1); in Section 3, the key findings of the bibliometric review are provided; in Section 4 is presented a detailed analysis and discussion from the obtained data and additional studies and research projects; in Section 5, knowledge gaps and future researches are highlighted. In Section 6, this paper's conclusions and limitations are outlined.

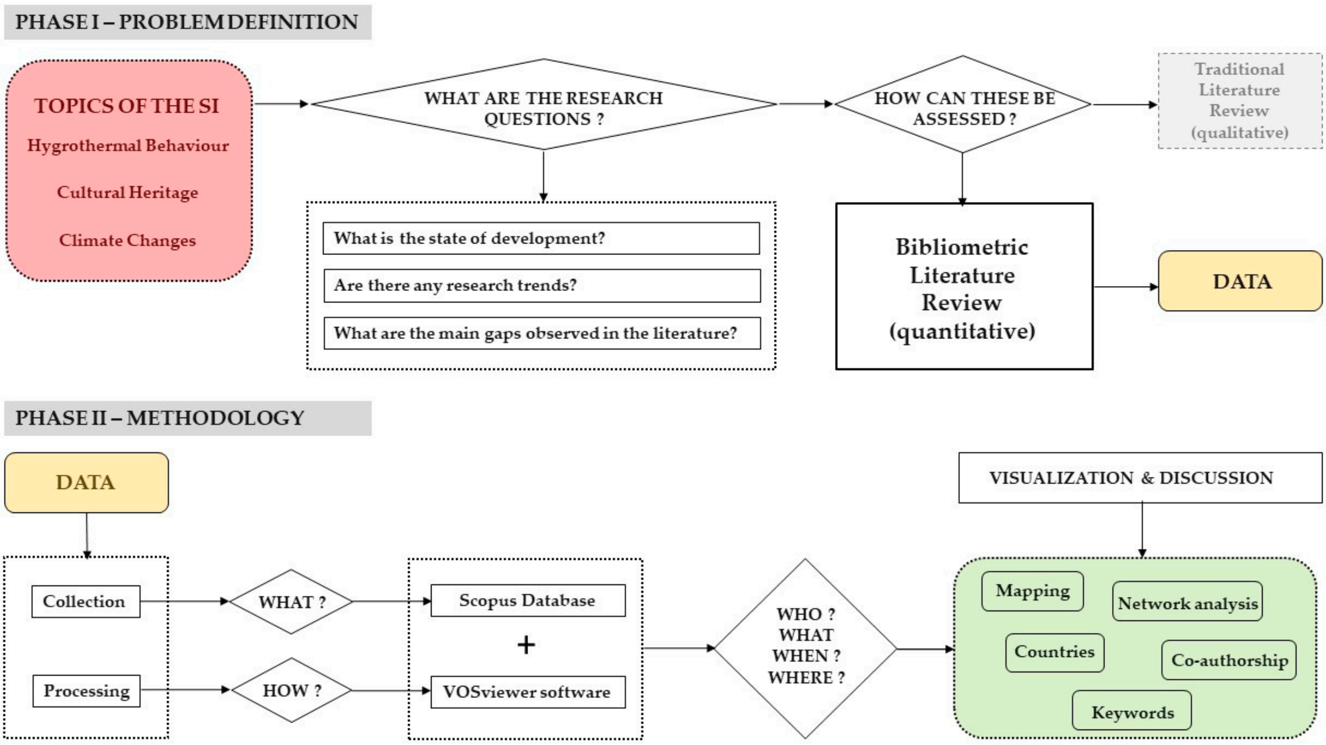


Figure 1. Research framework of the developed quantitative literature review.

2. Methodology

To fulfill the research objectives, a bibliometric analysis comprising a quantitative approach was first carried out. This type of review is becoming a popular research method among scholars, who find it useful for detecting emerging trends, reviewing outputs in the featured research field, and establishing worldwide collaboration relationships among authors, institutions, and documents [25,26]. Indeed, this bibliometric approach allows us to identify research gaps, and emerging themes, and correlate outputs in the CH scientific domain combined with the hygrothermal conditions and/or behavior and CC research areas.

Firstly, publications were collected using the Scopus database since it is scientifically established as one of the most consistent databases for covering more academic documents than any other one [27]. Documents were searched using query strings related to the study's topics combined among them with boolean operators "AND" and "OR". The initial search was circumscribed to papers published until 2022 (included), as:

(TITLE-ABS-KEY(("hygro behavio*" OR "hygro* analy*" OR "hygro* performance" OR "hygro* assessment" OR "hygro* study" OR "hygro* investigat*" OR "hygro* evaluat" OR "hygro thermal" OR "hygro thermal behavio*" OR "hygro thermal analy*" OR "hygro thermal performance" OR "hygro thermal assessment" OR "hygro thermal study" OR "hygro thermal investigat*" OR "hygro thermal evaluat" OR "thermal behavio*" OR "thermal analy*" OR "thermal performance" OR "thermal assessment" OR "thermal study" OR "thermal investigat*" OR "thermal evaluat" OR "indoor environment")) AND TITLE-ABS-KEY (("cultural heritage" OR "buil* heritage" OR "architectur* heritage" OR "tangible heritage" OR "historic* buil*" OR "historic* construction" OR "old buil*" OR "old construction" OR "heritage buil*" OR "heritage construction"))) AND PUBYEAR < 2023*

For the given query, 673 documents are found in the dataset. The extensive number of documents highlights the importance of the topic but fails to narrow in on the impact of CC on the built environment. Therefore, it was decided to introduce the "climate change" variable, resulting in the following query:

(TITLE-ABS-KEY (("hygro behavio*" OR "hygro* analy*" OR "hygro* performance" OR "hygro* assessment" OR "hygro* study" OR "hygro* investigat*" OR "hygro* evaluat" OR "hygro thermal" OR "thermal behavio*" OR "thermal analy*" OR "thermal performance" OR "thermal assessment" OR "thermal study" OR "thermal investigat*" OR "thermal evaluat" OR "indoor environment")) AND TITLE-ABS-KEY (("cultural heritage" OR "buil* heritage" OR "architectur* heritage" OR "tangible heritage" OR "historic* buil*" OR "historic* construction" OR "old buil*" OR "old construction" OR "heritage buil*" OR "heritage construction")) AND TITLE-ABS-KEY ("climat* chang*" OR "global warming" OR "weather scenario" OR "future scenario")) AND PUBYEAR < 2023*

In summary, the present search aimed at the main keywords "hygrothermal conditions", "cultural heritage" and "climate change", as synthesized in Table 1. This created a comprehensive selection of a significant number of published studies devoted to CH buildings that simultaneously refer to hygrothermal conditions and CC. The asterisk served to include in the search all possible variants of the given word with differences after the asterisk.

Table 1. Keywords that were used to group the terms related to different topics.

Keyword Group	Terms Included
Hygrothermal conditions	Hygro or thermal performance
Cultural heritage	Buildings, tangible heritage
Climate change	Future climate; climate scenario; global warming

This search was restricted to documents published before 2023, and based on different criteria, such as the typology of publication, *i.e.*, conference paper, article, conference review, book chapter, and review; the language of publication; the distribution of publications by territory and institution; the analysis of citations; and the co-occurrence of keywords. Thirty-six results were obtained in the Scopus database.

All of these 36 documents correspond to a final publication stage and were distributed over ten scientific areas: engineering, environmental science, earth and planetary sciences, materials science, energy, arts and humanities, social sciences, agricultural and biological sciences, computer science, and chemistry. Concerning the document typology, there were 17 "articles", and 15 "conference papers", plus two other "conference reviews", one "book chapter", and one "review". Of the 36 documents, one was fully bilingual, English and Italian—"Application of biological growth risk models to the management of built heritage [*Utilizzo di modelli di proliferazione biologica nella gestione del patrimonio storico*]" [28], and there was one with a bilingual abstract, German and English—"*Kastenfenster-Optimierung im historischen Bestand* [Energy performance optimization of historic box-type windows]" [29]. The analysis of this last work was naturally conditioned/limited. The results of this search are shown in Figures 2 and 3a. Scopus also includes information about Secondary Documents (7) and Patents (18) related to the research topic. Additionally, it was found that the first publication dated from 2003 (Figure 3b), reinforcing the evidence that this research topic (combining CH buildings, hygrothermal behavior, and CC) is very recent and quite unexplored: this 2003 document was the article "Thermal comfort and heritage building" by Sharma and Dhote [30].

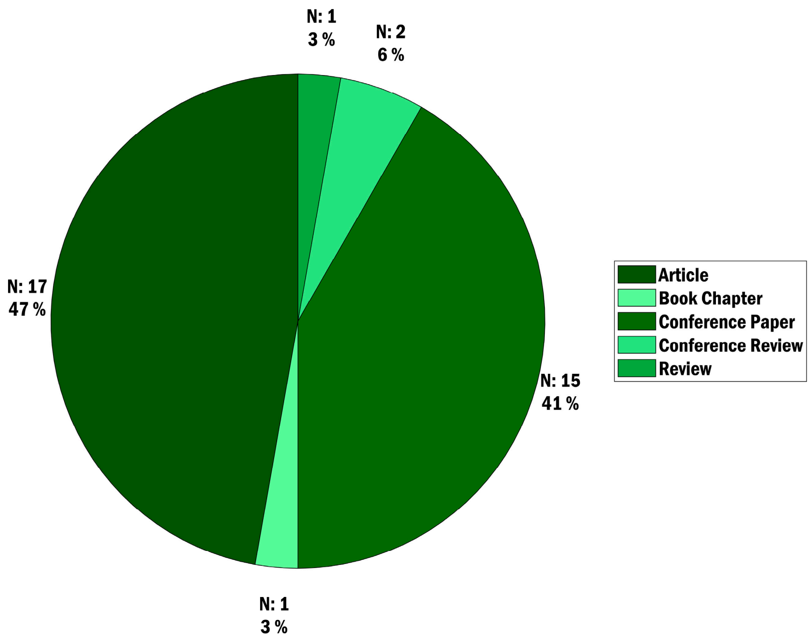
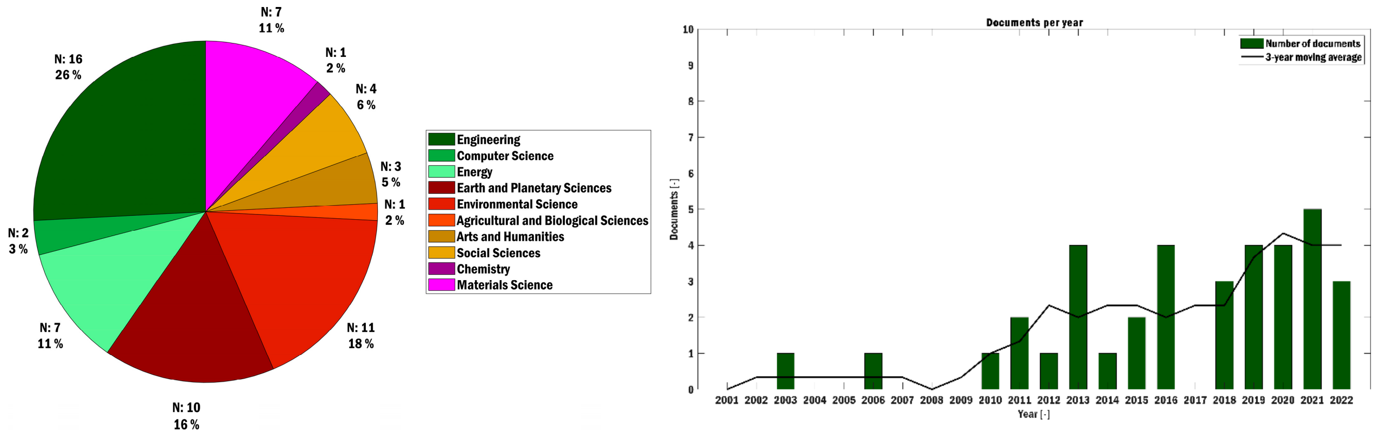


Figure 2. Document type distribution.



(**a**) (**b**)

Figure 3. Results of the second query: (**a**) the distribution of documents by main subject areas; (**b**) the number of publications per year.

Figure 4 shows the trend of publications for the top territories that published papers on this combined subject. It is in Italy that more papers were published (ten papers)—representing almost 27% of the whole world's publications until 2022, followed by Portugal (six papers) and Sweden (four papers). The Netherlands, Ireland, Greece, France, Czechia, Canada, and Austria all have two publications each.

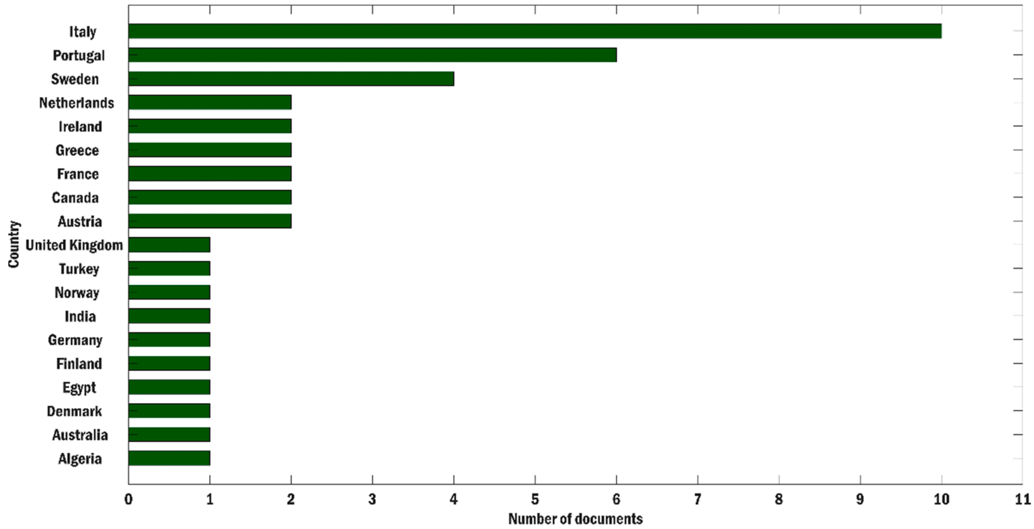


Figure 4. Number of publications during the years for the top territories until 2022.

After the preliminary data analysis in Scopus, a deeper analysis was performed using VOSviewer [31]. Though there are available various bibliometric tools, *e.g.*, BibExcel, CiteSpace, Sci2, or HistCite, VOSviewer was used to process data from the Scopus database. VOSviewer is a free software tool for establishing and visualizing bibliometric networks between stakeholders (authors, publishers, institutions), based on citations, co-occurrence of keywords, and co-authorship of scientific literature [32].

3. Results

3.1. Type of Publications and Languages of Publications

As previously shown in Figure 3b, the trend in the study of the combined topics—CH buildings, hygrothermal behavior, and CC—evidences how scarcely they have been combined. The first paper was published in 2003 [30], and until 2009 the average of publications per three years was <1.0. Moreover in 2017, any publication was found on this subject. The most common typology of the study was the "Conference Article" with 15 documents found, followed by "Article" with 17 documents (Figure 2).

Either because of the CC problematic emphasis (as the heat waves occurrence in Europe has been increasing since 2003 [33–35]) or because of the boost suggested by the European Commission—New European Bauhaus [36], European Green Deal [37], Renovation wave [38] of public and private buildings, along with the Directive amending the Energy Performance of Buildings Directive (2018/844/EU) [39]—an increasing trend is suggested (as depicted in Figure 3b). In absolute numbers, 2021 was the year in which more publications were found. All in all, there seems to have been opened a "raising awareness window" among the scientific community to the research topic.

3.2. Geographic Distribution of the Publications and Collaborations among Authors

The number of publications for the top territories is shown in Figure 4. Nonetheless, it cannot be stated the topic is limited to Europe (though it is the region with more publications). Figure 5 shows the world map distribution of the countries that published studies on the subject. It evidences that the subject is spreading all over the world; in total 18 countries, spread over four continents, are represented in Figure 5.

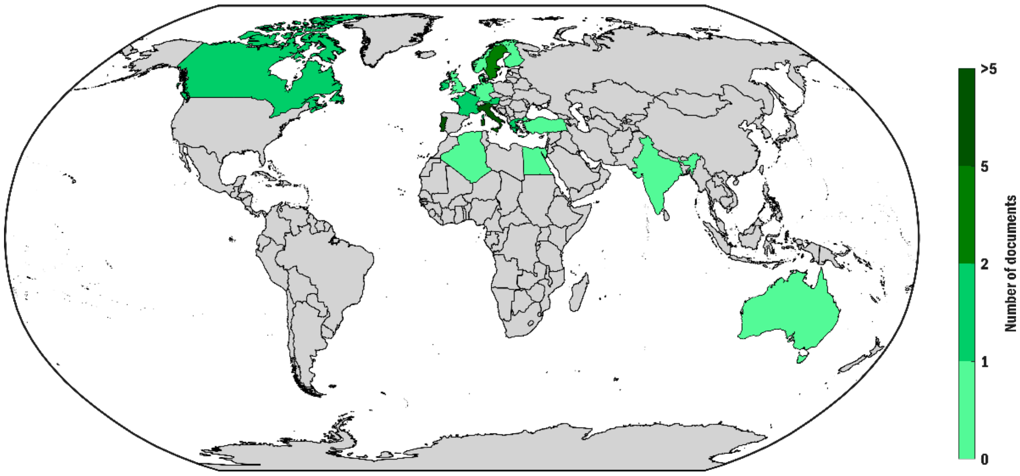


Figure 5. World map of the distribution of publications on the covered research field.

The institutions that published more documents on this topic are listed in Table 2.

Table 2. Top institutions with (minimum two) documents published on the covered research subject.

Institution	Number of Publications	Country
Politecnico di Milano	3	Italy
Chalmers University of Technology	2	Sweden
National Research Council Canada	2	Canada
Trinity College Dublin	2	Ireland
Università degli Studi di Brescia	2	Italy
Faculdade de Ciências e Tecnologia da Universidade Nova de Lisboa	2	Portugal

Additionally, it can be stated that the topic has been fairly distributed in terms of source: if the journal publication contribution was evaluated separately, the maximum number of papers published in a source was three, namely, in "IOP Conference Series Earth And Environmental Science 2020 and 2021" [40–42]. Then, follows "Energy and Buildings", with two papers [43,44]. Two other papers are found in the "International Journal of Global Warming", addressing indoor environmental conditions of CH buildings, both from 2019 [45,46]. In all the remaining sources, only one paper per year was found.

As the sample obtained from Scopus is rather small (only 36 documents in total), the analysis of co-authorship/network between countries was limited to a minimum of one single document per country. Results showed that no significant network was generated, which emphasizes the mis-cooperation between the countries working on the topic. However, as shown in Figure 6, some small cooperation was established in very recent years (as observable by the greenish and yellowish color of the links, related to the year). Herein, each country is represented by a circle, and the stronger the link, the strong would be the cooperation between the two countries in terms of the number of contributions. Indeed, when creating the map of Figure 6, only the connected countries were shown. Figure 6 also shows that the newest countries carrying out collaborative research on this topic are Portugal, Greece, and Italy.

Considering the reduced sample taken out from Scopus, to perform the co-authorship analysis, the minimum number of articles published by an author was one. VOSviewer detected 103 authors, but the largest set of related authors includes only 10 authors. The collaborations between these 10 authors are shown in Figure 7a,b. Figure 7a, the network visualization mode, suggests that these authors are grouped into two main clusters, identified by the green and the red colors. The green cluster is composed of Petitta M., Troi A., Hao I., Herrera D., and Matiu M. from Eurac Research (Italy); and the red cluster is composed of Aste N., Della Torre S., Huerto-Cardenas H.E., and Leonforte F. from the Architecture, Built Environment and Construction Engineering Department of the Politecnico di Milano (Italy). Del Pero C. is also from the last institution, and he links the two clusters. In fact, he is the author with more connections to other authors (a total of nine). The authors in the green cluster have established five connections each with other authors, and those in the red cluster have established four connections each with other authors. Figure 7b shows that the collaborations among authors are all very recent (from 2020 on). In other words, these results evidence the lack of co-authorship in the scientific community working in the field. The average publication year of the documents in the green cluster was 2020, while for the red cluster was 2021.

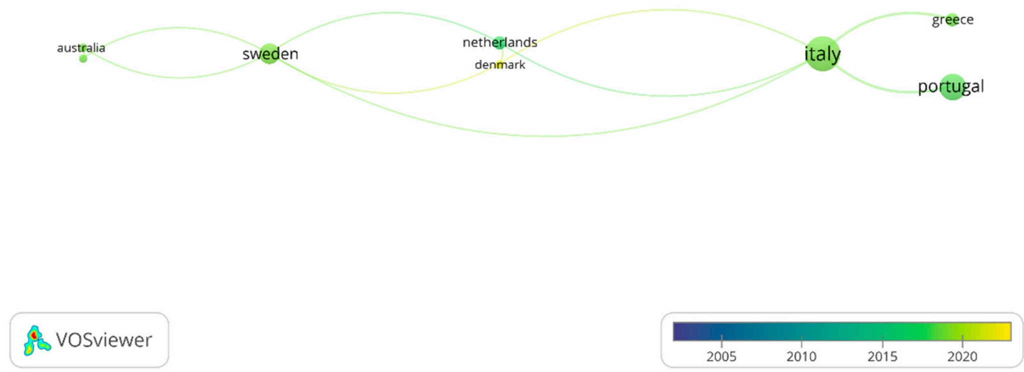
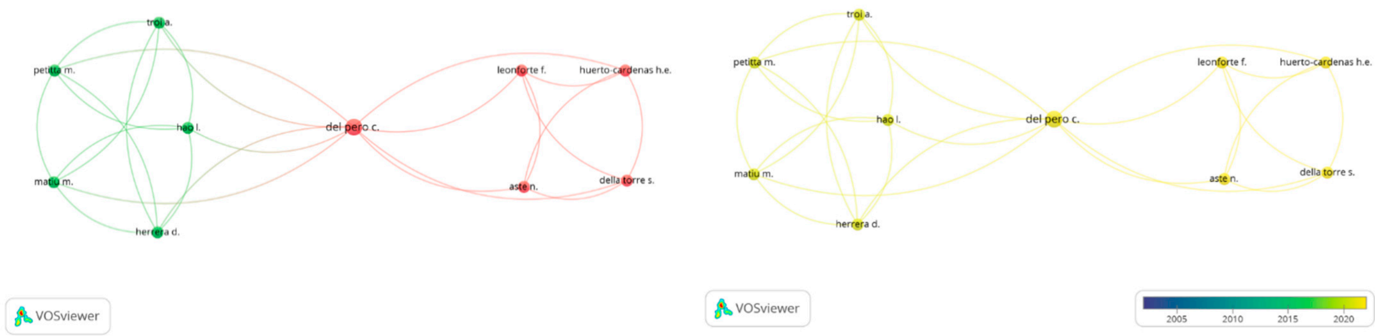


Figure 6. Countries network in the topic (overlay visualization mode). Only the connected countries are shown (2003–2022).



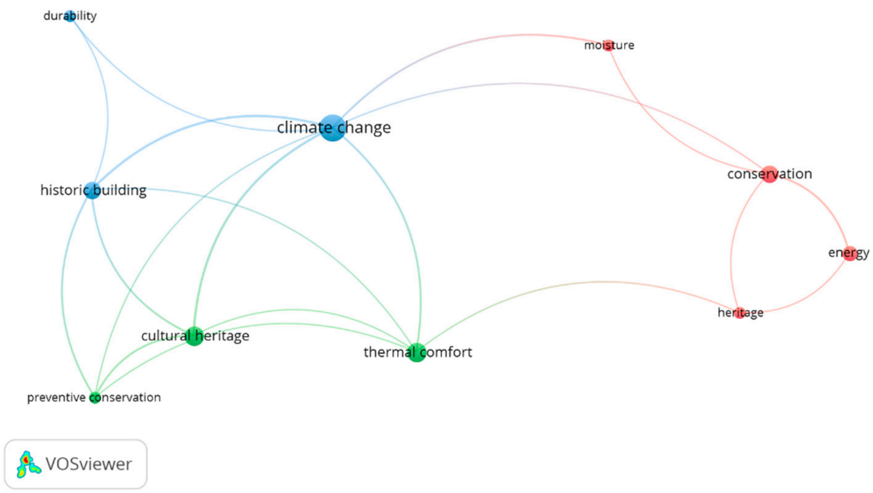
(**a**) (**b**)

Figure 7. Co-authorship analysis (ten authors relation) per (**a**) cluster, and (**b**) year of publication.

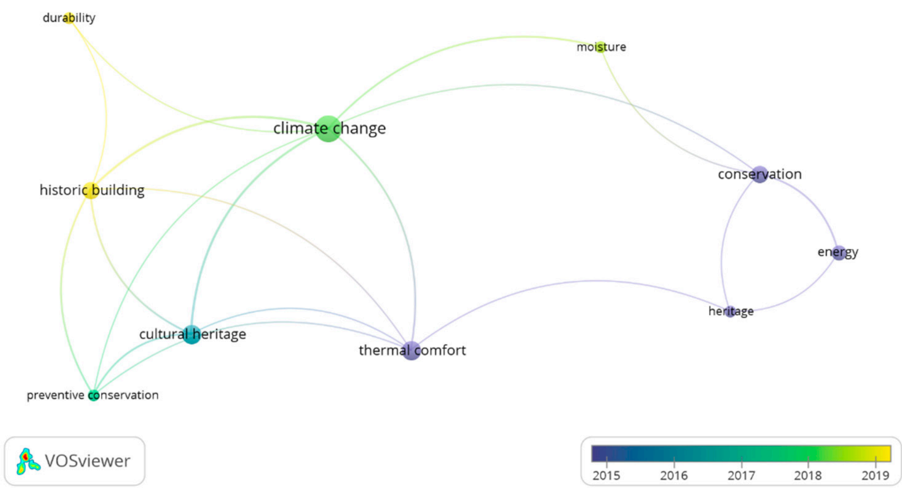
According to the Scopus search, the most productive authors in the field have all published two documents, namely: Del Pero C. [40,47], Greenan R. [48,49], Silva H.E., and Henriques F.M.A [45,50], and Tagliabue L.C. [28,41]. The remaining authors have authored just one paper each.

3.3. *Keywords Co-Occurrence Analysis*

The co-occurrence of keywords highlights the main areas of research. Therefore, aiming at identifying subtopics, the authors' keywords were used to create a map. To reduce redundancy, keywords plurals were merged (*i.e.*, "historic building" and "historic buildings"). Figure 8a shows the co-occurrence of the author keywords of the 36 documents selected, filtering the keywords with a minimum occurrence of two times: of the 128 keywords, 10 meet the threshold, generating three clusters (red, green, and blue). It can also be seen that there is not a significant size difference between the three clusters (the bigger the circles, the more frequently the keywords appear in the publication set from Scopus).



(**a**)



(**b**)

Figure 8. Author keywords co-occurrence analysis: (**a**) network visualization; (**b**) overlay visualization.

Nonetheless, it is visible that the blue cluster, headed by "climate change" (the keyword that has the highest link strength and number of occurrences, meaning that it is the keyword most interrelated)—which includes the keywords "historic building" (the second keyword with higher link strength), and "durability"—is the one that relates more to the other two. This cluster is closer to the green cluster than to the red one (shorter distance between the circles), which is led by "cultural heritage" (the third keyword with higher link strength), and it includes the keywords "thermal comfort" and "preventive conservation".

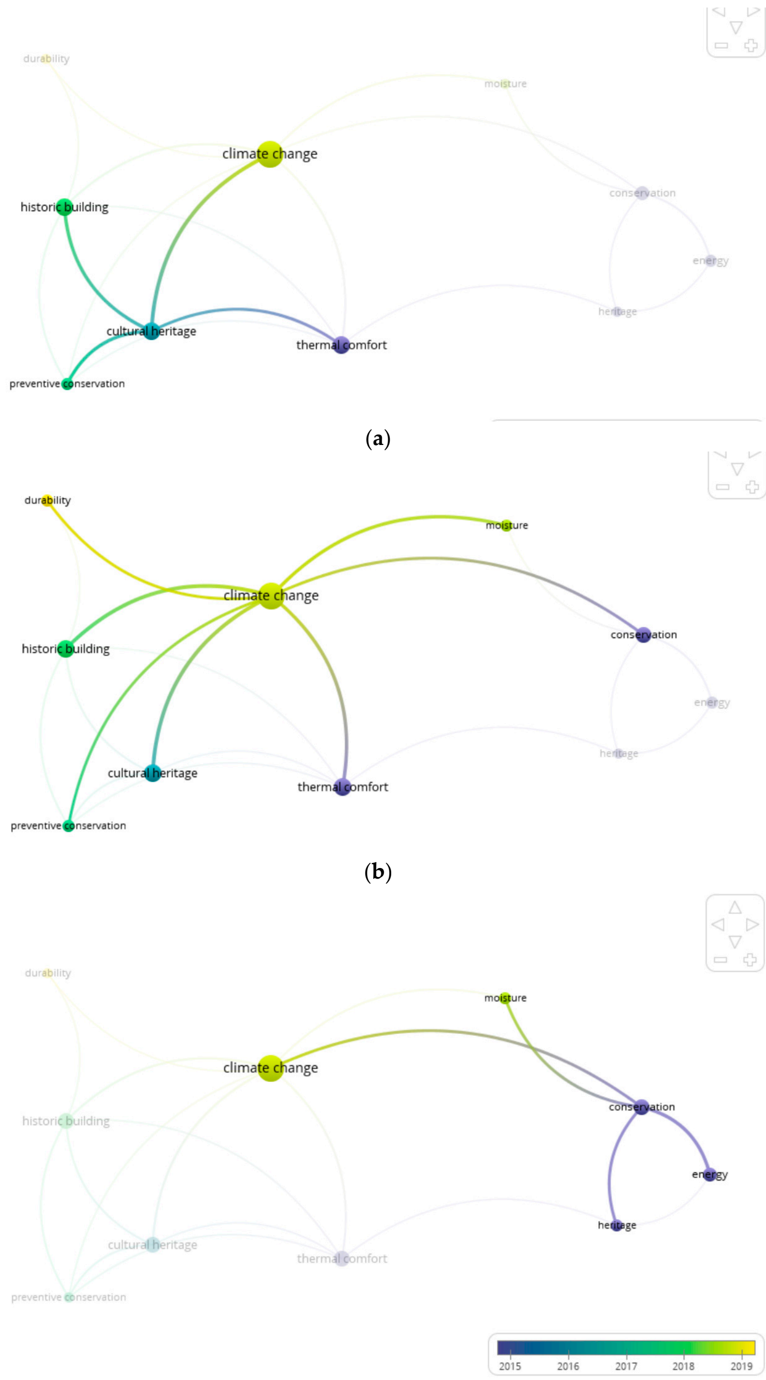
Figure 8b shows that the link between the keywords "historic building" and "durability" with the keyword "climate change" is a fresh topic of research, evidencing a recent concern of the scientific community on this matter.

Table 3 synthetizes the author keywords with the highest number of occurrences.

Table 3. Top-five authors' keywords with the highest number of occurrences (and link strength).

Keyword	Number of Occurrences	Total Link Strength
Climate change	12	13
Historic building	5	9
Cultural heritage	5	8
Thermal comfort	5	6
Conservation	4	5

Figure 9 allows for a deeper analysis of Figure 8, through the highlighting of the keywords heading the three clusters, resulting from the previous co-occurrence analysis of authors' keywords. Highlighting the keyword "cultural heritage" (Figure 9a), it may be suggested that the studies are firstly based on "preventive conservation", and "thermal comfort" (microclimate analysis), and then related to "historic building" and "climate change". The overlay visualization (Figure 9b) evidences the youth trend of this topic, i.e., the joint consideration of "cultural heritage", "climate change" and "historic buildings" research areas.



(a) (b) (c)

Figure 9. Network visualization of author keywords co-occurrence and links of the "leading" keywords (**a**) "Cultural heritage"; (**b**) "Climate change"; (**c**) "Conservation".

Figure 9b, clearly evidences that the most recent keywords are related to "climate change", from a perspective of long-term use of historic buildings, i.e., "cultural heritage" as a subject to take into consideration to keep the "historic buildings" into use, embracing "durability" and "moisture". The oldness and smaller relevance of "conservation" are depicted in Figure 9c.

To further provide a big picture of the topic under investigation, Figure 10 shows the co-occurrence of all the keywords, filtering the keywords with a minimum occurrence of three times (of the 374 keywords, 25 meet this threshold).

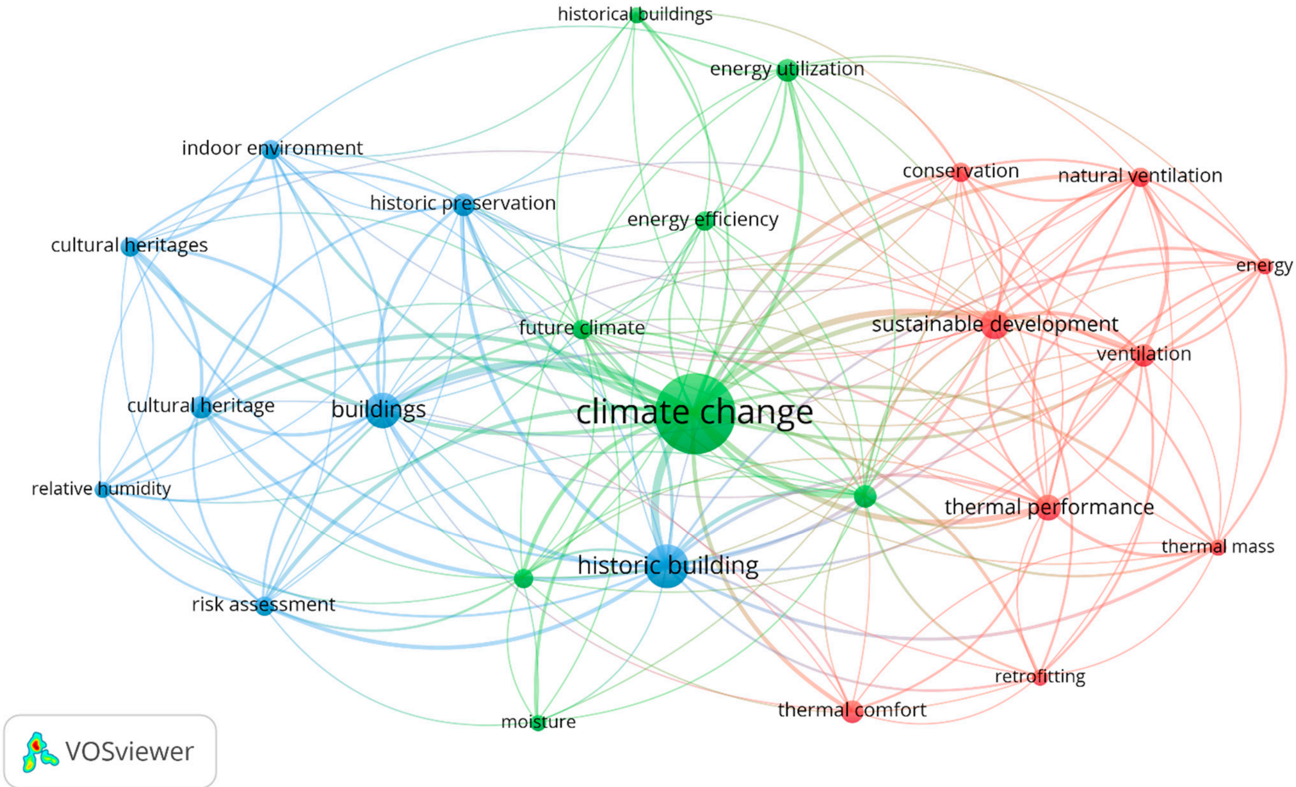


Figure 10. Co-occurrence analysis of all the keywords (network visualization).

4. Discussion

4.1. Most Influential Publications and Research Projects

The ten most cited documents found in the Scopus database are presented in Table 4. Those with more than 10 citations are discussed. The most cited paper is "*A proposed method to assess the damage risk of future climate change to museum objects in historic buildings*" by Huijbregts et al. [51] in the journal "Building and Environment", with 103 citations. This paper was developed within the *Climate for Culture* project [52], funded by the European Commission (Table 5). The authors evaluated the impact of CC on the indoor environment of four museum rooms in two different non-insulated historic buildings with monumental value in the Netherlands and Belgium, by combining weather data from a future outdoor climate scenario REMO with the indoor climate simulation program HAMBase. The indoor environment assessment was based on ASHRAE guidelines for indoor climate conditions related to museum collections, and the damage risk for mold growth and mechanical degradation was determined by a specific climate risk assessment model for museum objects. It was concluded that CC significantly increases both indoor temperature and relative humidity. The later has the largest impact on the damage potential to museum objects because it may significantly increase mold growth and, in some cases, the mechanical degradation of vulnerable objects.

Table 4. Ten most cited papers on the topic.

Rank	Cit. *	Title	Year	Author	Journal	Ref.	Classification and Methodology	Limitations
1	103	A proposed method to assess the damage risk of future climate change to museum objects in historic buildings	2012	Huijbregts, Z., Kramer, R.P., Martens, M.H.J., van Schijndel, A.W.M., Schellen, H.L.	Building and Environment	[51]	Simulation/Numerical Evaluation of the indoor hygrothermal environment. Risk assessment of conservation conditions.	Future climate predictions were limited to large-scale datasets. Risk assessment models were not developed for the actual museum artifacts.
2	26	The retrofitting of the Bernardas' Convent in Lisbon	2014	Martins, A.M.T., Carlos, J.S.	Energy and Buildings	[43]	Simulation/Numerical Analysis of surface and materials temperature. Assessment of thermal comfort.	Does not include an analysis of climate change or its impact, considering only a typical summer and winter day. Only accounts with internal insulation of opaque envelope.
3	19	Simulations of moisture gradients in wood subjected to changes in relative humidity and temperature due to climate change	2018	Melin, C.B., Hagentoft, C.-E., Holl, K., Nik, V.M., Kilian, R.	Geosciences	[53]	Simulation/Numerical Analysis of materials temperature and relative humidity in wooden objects.	The simplified model assumes a semi-infinite flow domain limiting its application to smaller penetration depths—most applications to small thicknesses. Requiring further validation for thicker layers.
4	15	Climate change and traditional buildings: The approach taken by historic Scotland	2010	Curtis, R.	Journal of Architectural Conservation	[54]	Review Summarize typical building envelope elements and passive strategies applied in historic buildings of Scotland.	Justifies the importance of historic constructions in Scotland using the buzzword of climate change, but does not actually reflects on the impact of changing the envelope to prepare buildings for climate change.
5	12	Effects of climate change on the future of heritage buildings: Case study and applied methodology	2021	Huerto-Cardenas, H.E., Aste, N., Del Pero, C., Della Torre, S., Leonforte, F.	Climate	[47]	Monitoring/Experimental Simulation/Numerical Analysis of surface and materials temperature. Risk assessment of conservation conditions.	Implementation of the simulation model to evaluate hygrothermal stratifications in huge volume buildings and the definition of a long-term protocol to mitigate the negative effects

Table 4. *Cont.*

Rank	Cit. *	Title	Year	Author	Journal	Ref.	Classification and Methodology	Limitations
6	10	Thermal comfort and heritage building	2003	Sharma, A., Dhote, K.K.	Journal of the Institution of Engineers (India): Architectural Engineering Division	[30]	The manuscript is not available.	
7	9	Energy retrofit solutions for heritage buildings located in hot-humid climates	2018	Silvero, F., Montelpare, S., Rodrigues, F., Spacone, E., Varum, H.	Procedia Structural Integrity	[55]	Simulation/Numerical Evaluation of the indoor hygrothermal environment. Assessment of thermal comfort. Analysis of internal and external surfaces' temperature.	Does not include an analysis of climate change or its impact. The solutions tested were not implemented in a parametric way. Other solutions could be considered when optimizing the best solution configuration.
8	9	Contribution to the thermal renovation of old buildings: Numerical and Experimental approach for characterizing a double window.	2015	El Mankibi, M., Cantin, R., Zoubir, A.	Energy Procedia	[56]	Monitoring/Experimental Simulation/Numerical Analysis of internal and external surfaces' temperature.	Does not include an analysis of climate change nor its impact in a real case study (historic building).
9	9	The use of windows as environmental control in "Baixa Pombalina's" heritage buildings	2015	Nunes de Freitas, P., Guedes, M.C.	Renewable Energy	[57]	Questionnaires/Surveys 249 questionnaires regarding the habits of occupants when opening windows in 18 office buildings.	Does not include an analysis of climate change or its impact. Does not account for an experimental part to confirm window openings by occupants.
10	8	Hygrothermal analysis of historic buildings: Statistical methodologies and their applicability in temperate climates	2016	Silva, H.E., Henriques, F.M.A.	Structural Survey	[50]	Monitoring/Experimental Evaluation of the indoor hygrothermal environment. Risk assessment of conservation conditions.	Does not include an analysis of climate change or its impact.

* Number of citations.

The second most cited paper, with 26 citations, is "*The retrofitting of the Bernardas' Convent in Lisbon*" by Martins and Carlos [43] in "Energy and Buildings". This paper emphasizes the importance of the knowledge and use of heritage as vital elements for their safeguarding. Moreover, the authors evaluated the thermal performance of the historical walls of the Bernardas' Convent in Lisbon, Portugal; and discussed in which way the ideals and realities of retrofitting these walls may be divergent, in particular when it concerns actual thermal comfort standards.

The third paper is "*Simulations of moisture gradients in wood subjected to changes in relative humidity and temperature due to climate change*" by Melin et al. [53] in "Geosciences". This paper contributed to the knowledge of climate-induced damage to heritage objects housed in historic buildings through simulation. The authors pointed out that hygroscopic materials, such as wood, gain and release moisture during changes in relative humidity and temperature that may result in permanent damage caused by swelling and shrinking. Two different methods to simulate the influence of CC were performed (the hygrothermal building simulation software WUFI® Pro and the simplified model), and the results of the simulations were then compared to previously measured data (monitored at different depths inside wooden samples subjected to fluctuating climate over time). This paper is the less cited of the three, but it is also the most recent one.

The fourth paper with more than 10 citations is from 2010. The study of Curtis [54] "*Climate Change and Traditional Buildings: The Approach Taken by Historic Scotland*" was published in the "Journal of Architectural Conservation". Here, the author showed how the combined work of Historic Scotland—on-site and laboratory-based research program -, and others, were able to identify a range of ways by which traditional fabric can be upgraded, starting with the identification of the thermal properties of the traditional building envelope. Indeed, this work provided a framework on the thermal performance of the traditional building envelope in Scotland together with an outline for future research: how it can be improved without compromising the essential vapor dynamic that characterizes traditional construction?; and, how to address embodied energy issues? The author also concluded that passive systems (namely natural ventilation) may be preferred and that new internal linings and finishes can play an important role in moisture attenuation.

Huerto-Cardenas et al. [47] study, placed fifth, investigated how future CC can affect the indoor environment of huge masonry buildings such as the Duomo di Milano, in Italy. They also evaluated the resulting risk for the conservation of the artworks housed in this type of building (e.g., stone sculptures, some organic materials, paintings, wooden objects, etc.). For the simulations, the authors defined possible future climate scenarios based on the Intergovernmental Panel on Climate Change (IPCC) projections.

The sixth article, among the most cited (*top+ >10 citations)*, was not accessible. The only available information was the abstract, which investigates different passive strategies adopted by ancestors in the past to tackle outdoor fluctuations in a case study in India.

It is relevant to mention that most influential papers used CC as motivation when explicating the importance of the subject but did not actually consider CC in their analysis. This highlights that there is still the need to study the impact of CC. Moreover, there is now a trend in recent studies to consider the impact of future changes on the climatic conditions of heritage buildings.

The main contributions of the other documents selected in the Scopus search are outlined in the next section. References [58,59] are not discussed in great detail as they concern the proceedings of two international conferences.

Additionally, a complementary survey was conducted, motivated by the most cited document [51], an output of the European project *Climate for Culture* [52].

Table 5 provides an overview of the main goals of some funded projects in the covered research field. These projects stress the importance of looking at historic buildings as a value from an economic, energy, and environmental point of view. This is also stressed by the European Commission SUIT project [60]. Indeed, this project proposed some guidelines for the sustainable development of urban historical areas through an active integration within towns, and more specific guidance for the environmental assessment of the impacts of certain plans, programs, or projects upon the heritage value of historical areas, in order to contribute to their long-term sustainability [60].

Table 5. Previous projects within the topic of CH, Hygrothermal conditions, and CC.

Name	Ref.	Start End	Description
NOAH'S ARK	[61]	June 2004 May 2007	In the project *Global CC Impact on Built Heritage and Cultural Landscapes* (NOAH'S ARK), CC is anticipated to be globally expressed with variations in temperature and precipitation, extreme climatic events, alterations of soil conditions and groundwater, and modifications in sea level [61]. As a result, a range of direct and indirect effects are expected to be observed in the built environment, such as the acceleration, delay, or worsening of building decay. CC impacts can be identified on individual processes. However, it is difficult to assess the overall risk of a monument on the basis of currently available data. The NOAH'S ARK project aimed to address this challenge [61].
SMOOHS	[62]	December 2008 November 2011	In the project *Smart Monitoring of Historic Structures* (SMOOHS) it was recognized that the conservation of historic structures presents a fascinating and diverse range of scientific challenges; in particular, the need to protect them effectively from environmental degradation [62]. Diagnostic monitoring thus far has been largely limited to the acquisition of climate parameters and air pollution levels used as input into functions or models predicting damage. The limitations of the approach in assessing precisely the risk of damage to a concrete historic structure in its specific environment lead inevitably to a search for scientific methods of direct tracing damage: non-invasive, continuous, simple, economic, and capable of operating in real-world conditions [62].
CHARISMA	[63]	October 2009 March 2014	The project *CH Advanced Research Infrastructures: Synergy for a Multidisciplinary Approach to Conservation/Restoration* (CHARISMA) aimed to build a new user-friendly platform of existing large-scale facilities or small/medium installations open to users and to develop a set of the widest number of scientific methodologies and techniques, in order to enable the European heritage science community to upgrade the research for diagnostics, analysis, and assessment of materials of CH, identification of artistic techniques, identification of the cause and effects of deterioration processes, and in-situ monitoring during and after restoration [63].
Climate for Culture	[52]	November 2009 October 2014	The project *Climate for Culture* estimated the impacts of changing climate conditions on historic buildings and their vast collections in Europe and the Mediterranean. A multidisciplinary research team of 27 partners aimed to identify the damage potential of CH most at risk, so as to encourage the development of strategies to mitigate the effects of CC, including through policymakers and the Intergovernmental Panel on CC (IPCC) reports. Furthermore, the project provided insight into the possible socio-economic impact of CC, given the importance of CH to Europe's economy [52].
3ENCULT	[64]	October 2010 March 2014	3ENCULT bridged the gap between the conservation of historic buildings and climate protection. It also recognized that energy-efficient retrofit is important, both for improving comfort and reducing energy demand (in terms of money and in terms of resources) and for structural protection of CH buildings. 3ENCULT demonstrated that it is feasible to reduce the energy demand in historic buildings to 1/4 or even 1/10, depending on the case and the heritage value.
HERCULES	[65]	Decemebr 2013 November 2016	The project *Sustainable futures for Europe's HERitage in CULtural landscapES: Tools for understanding, managing, and protecting landscape functions and values* (HERCULES) strived the empowerment of public and private actors to protect, manage and plan for sustainable cultural landscapes at local, national, and Pan-European scales. HERCULES aimed at increasing understanding of drivers, patterns, and social-ecological values of European cultural landscapes and to use this knowledge to develop, test, and demonstrate strategies for their protection, management, and planning [65].
STORM	[66]	June 2016 May 2019	STORM provided critical decision-making tools to all European CH stakeholders responsible to face CC and natural hazards. The project improved existing processes related to three identified areas: prevention, intervention and policies, planning, and processes [66].
ROCK	[67]	May 2017 Decemebr 2020	The project *Regeneration and Optimization of CH in creative and Knowledge cities* (ROCK) aimed to develop an innovative, collaborative, and circular systemic approach for the regeneration and adaptive reuse of historic city centers. Implementing a repertoire of successful heritage-led regeneration initiatives, it also tested the replicability of the spatial approach and of successful models addressing the specific needs of historic city centers [67].
PROCULTHER	[68]	January 2019 December 2019	The project *Protecting Cultural Heritage from the Consequences of Disasters* (PROCULTHER) aimed to evaluate how CH could be protected from the consequences of disasters.

Table 5. *Cont.*

Name	Ref.	Start End	Description
ARCH	[69]	June 2019 August 2022	ARCH developed a disaster risk management framework for assessing and improving the resilience of historic areas to CC and natural hazards. Tools and methodologies were designed for local authorities and practitioners, the urban population, and national and international expert communities [69].
SHELTER	[70]	June 2019 May 2023	The project *Sustainable Historic Environments hoListic reconstruction through Technological Enhancement and community-based Resilience* (SHELTER) aims at developing a data-driven and community-based knowledge framework that will bring together the scientific community and heritage managers with the objective of increasing resilience, reducing vulnerability, and promoting better and safer reconstruction in historic areas.
CRAFT	[71]	December 2020 March 2022	CRAFT developed a novel CC risk assessment framework for CH in Turkey.

4.2. Beyond the Preliminary Search—Other Significant Contributions from the Scopus Database

Hao et al. [40] numerically evaluated the impact of CC on a typical Alpine historic two-story single-family house. For that purpose, the performance of a reference house was simulated and compared before and after retrofitting, and for "present" and "future" climate scenarios, according to three parameters, namely energy demand, indoor comfort, and moisture safety of the envelope. Wells et al. [72] numerically evaluated the moisture response and expected durability of a heritage masonry building located in Ottawa, Canada, under future climate conditions. For that purpose, hygrothermal modeling was used to assess how projected changes in temperature and precipitation loads predicted by CC models can influence the durability of retrofitted masonry heritage buildings, considering the introduction of moderate levels of insulation on the interior wall surfaces. In another study, Sahyoun et al. [73] also evaluated the durability of internally insulated historical solid masonry under future climates in Ottawa, Canada. Tagliabue et al. [41] focused on the indoor comfort conditions of old educational buildings in different climate zones (Brescia in Italy, Thessaloniki in Greece, and Southampton in the UK) during the cooling season. These authors investigated some retrofitting measures to improve building thermal performance during heat waves and assessed some adaptative indoor thermal comfort models. Darda and Madani [74] evaluated the impact of the rehabilitation of Algerian earthen built heritage with modern building materials.

Coelho et al. [45] evaluated the impact of CC on the indoor climate of high thermal inertia CH buildings through simulation, targeting the conservation of artifacts and the thermal comfort of visitors. The hygrothermal model of the Saint Christopher church in Lisbon, Portugal, was firstly validated against measured results and then used coupled with several weather files to simulate future indoor conditions. Then, the indoor climates were analyzed using adaptive thermal comfort and risk-based models. Silva and Henriques [50] (the tenth most cited paper) evaluated and compared the applicability and efficiency of two statistical methods to define sustainable targets of temperature and relative humidity in a historic building (the Chapel of Albertas) located in Lisbon, Portugal. Similarly, Weyr et al. [75] used the IPCC global warming projections to evaluate the internal microclimate of buildings located in the historic center of Prague, Czech Republic, during summer. Gherri et al. [76] have also used the IPCC future predictions for the 2050 climate scenario to assess how Venetian vernacular open spaces (*Campi*) and the surrounding CH buildings, canals, and green public areas can contribute to building climate resilience.

Stark [77] evaluated the visual impact of additional shading elements on the façades of a residential historic building in Mladá Boleslav, Czech Republic. A survey focused on inhabitants of heritage buildings was initially conducted to determine to what extent they perceive overheating, what sorts of shading devices are used more often, and what would they expect from potential retrofitting. Then, the authors assessed the influence of several shading elements in terms of visual impact on façade composition in relation to described composition principles with regard to indoor environment quality. In another study, Nunes de Freitas and Guedes [57] (the ninth most cited paper) investigated how the control and regulation of windows by the occupants of office and residential buildings of "Baixa Pombalina", the downtown and historic district of Lisbon, Portugal, can increase thermal comfort and minimize the use of mechanical devices during cooling and heating seasons. For that purpose, a questionnaire-based survey was developed to assess how bioclimatic strategies, such as natural ventilation, and adaptative actions (opening windows), can be used as indoor environmental control strategies. El Mankibi et al. [55], the eighth most cited paper, experimentally and numerically characterized the thermal behavior of a double window to be used for the thermal renovation of old buildings.

Valkhoff [78] evaluated the environmental impact of 20 exterior walls that can be used in the renovation of heritage timber-framed houses in the SW of France. Indeed, this work discusses the most appropriate and sustainable insulation techniques for the renovation of this sort of building. This means techniques and materials that do not have a harmful impact on the environment and, on the other hand, do not have a negative impact on the aesthetic and vernacular qualities of the construction, or on the structure of the building.

Milić et al. [44] proposed and applied a novel development of the change-point model for predicting the thermal performance of buildings using selected time periods based on time-dependent variations in climate and user behavior to a 73-historic-buildings residential district in Linköping, Sweden.

Silvero et al. [56], the seventh most cited paper, assessed the thermal performance of a residential heritage building located in the historic center of Asunción, Paraguay. Additionally, they evaluated several retrofitting solutions for the building envelope in order to determine which ones are the most efficient solutions. The authors also pointed out that finding the most suitable intervention in a particular heritage building is a very complex challenge since the best solutions must assure the original characteristics of the historic building. Gallo [79] further highlighted that working in historic buildings requires specific knowledge about the use of traditional materials and techniques, which goes against the more standardized modern construction principles. In fact, the author claimed that large-scale interventions in historic city centers should comprise training courses for specialists that also include the subjects of energy, environment, and indoor air quality.

Chantzi and Dotsika [80] evaluated the performance of four different compositions designed for restoring mortars of historic buildings, considering the compatibility-coherence-reversibility with the authentic ancient matrix and the resistance to CC, in particular to extreme climatic conditions. Tidblad [81] reviewed the effects of climate and pollution on the atmospheric corrosion of heritage metallic artifacts in Europe.

Choidis et al. [82] investigated the mold risk of timber elements of historic constructions located in Vestfold, Norway, due to CC. The mold growth risk at the interior surface of historic masonry buildings was evaluated by Paolini et al. [28] for two different climate conditions, namely Milan (Italy) and Barcelona (Spain), considering varying ventilation rates and the number of visitors, as well as climate anomalies. Libralato et al. [42] performed a multiyear hygrothermal performance simulation of the envelope of a historic building (the "Palazzina Sommariva") located in Udine, Italy, to evaluate the effects of the short-term CC on the hygrothermal performance and moisture-related risk of a brick wall with and without insulation.

Bayomi et al. [83] evaluated the potential implications of increased overheating hours on human health in an old low-income residential neighborhood with many historic buildings in Cairo, Egypt. Turhan et al. [46] studied the indoor microclimate of an unconditioned historic library in Izmir, Turkey, for existing conditions and future climate data. They used the measured and predicted results to determine possible chemical degradation risks on library collection and human comfort, and they concluded that adding light and considering some adaptative mechanical solutions can be used to mitigate these CC effects.

5. Knowledge Gaps and Future Research

Reviewing the papers related to the combined topic—Hygrothermal Conditions—Cultural Heritage—Climate change, published until 2022, allowed to run a global debate on the trends and limitations of this triangle, aiming at pointing out future research directions. The answers to the initial research questions are listed as follows:

(i) the state of development of this research field is in its infancy. Examining the articles resulting from the literature review, it can unquestionably be stated that this combined topic is practically unexplored. Not only does the first publication on the matter dates from 2003, as the average number of publications per year is still very small;

(ii) the analysis and discussion on this matter suggest that until recently, greater research emphasis has been related to the traditional view of cultural heritage protection from a preventive conservation perspective and that only the papers published in more recent years openly address CC—and still without considering the refurbishment and/or (re)adaptation of CH buildings for climate changes;

(iii) the main research gap is definitely the lack of in-depth studies on climate scenarios. "Climate change" is used many times as a motivational buzzword but without direct applicability, e.g., evidence of its real impact is lacking.

Following this purpose, the authors recall Curtis' question [54], on the thermal performance of the traditional building envelope in Scotland, still unanswered:

(1) how it can be improved without compromising the essential vapor dynamic that characterizes traditional construction?

(2) how to address embodied energy issues?

The risk to CH buildings from CC is expected to increase in the future, and so, the inclusion of the following aspects should be considered in future analytical and/or numerical models, as well as in the laboratory or in-situ experimental campaigns, namely:

- the impacts of the variations of temperature and precipitation profiles;
- the variation in the air pollution level;
- the forecast of extreme climatic events (e.g., heatwaves, droughts, storms, floods, seasonal shifts in climate, etc.);
- the variation in sea levels;
- the modification of soil conditions and groundwater, etc.

In summary, this combined topic is very new and quite unexplored, and further research is required to assess how future CC scenarios will affect the hygrothermal behavior of CH buildings, in order to enable the scientific community to gain improvement in the investigation for diagnostics, namely through:

- analysis and assessment of CH materials;
- identification of artistic techniques;
- identification of the reasons and effects of deterioration processes regarding the indoor environment;
- adaptation of preventive conservation standards/guidelines to future climate scenarios.
- in-situ monitoring before, during, and after intervention in CH buildings.

These new understandings are also fundamental for all stakeholders and practitioners involved in topics related to heritage conservation/rehabilitation and assessment of the hygrothermal behavior of historic buildings, as they will allow to better predict the delay, acceleration, or worsening of CH buildings' decay.

6. Conclusions

The focus of this study is to provide a bibliometric analysis and systematic review of previous studies devoted to CH buildings that simultaneously refer to hygrothermal conditions and/or behavior and CC scenarios. Despite its contributions, this study has inevitably its limitations.

The Scopus database was used for data gathering and export, and VOSviewer was used for network visualization. It was concluded that only 36 documents (in English) have considered the study of the three subjects together (CH, hygrothermal conditions and/or behavior, and CC), up to 2022. Moreover, the research on this combined topic has been carried out mainly in Italy (27% of the relevant documents). By combining data from several sources, researchers may obtain a more complete picture of this topic: it can be completed through other databases, such as Google Scholar or Web of Science, for example.

Notwithstanding its limits, this article was able to identify future areas of research, as deeply presented in Section 5: *Knowledge Gaps and Future Research*. Besides the previously mentioned research gaps, other future research needs could be mentioned, e.g., the inclusion of mechanical devices for heating and cooling, and active ventilation and dehumidification systems, considering the increase in energy consumption and costs. Another topic that requires further investigation is the evaluation of the possible socio-economic impact of CC on CH buildings, given the importance of CH to the economy of many cities. CH buildings will only endure if they are maintained as comfortable living spaces. Therefore, retrofitting and rehabilitation considering different CC scenarios are crucial for improving the thermal behavior and energy efficiency of CH buildings, but also revitalizing CH urban areas, and creating jobs.

CH buildings constitute an important part of the CH of humanity that must be transmitted to future generations in all the richness of their authentic architecture, techniques, and materials, which requires new approaches and policies that consider CC to design new strategies for their assessment, retrofitting/rehabilitation, protection, and management; and ultimately, to increase the resilience and reduce the vulnerability of CH buildings.

Author Contributions: Conceptualization, L.D.P. and N.S.; methodology, L.D.P.; investigation, L.D.P., N.B.S. and N.S.; writing—original draft preparation, L.D.P., N.B.S. and N.S.; writing—review and editing, L.D.P., N.B.S. and N.S.; visualization, L.D.P., N.B.S. and N.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data is available on request from the corresponding author.

Acknowledgments: The first author's contribution was carried out in the framework of Project UIDP/50022/2020—LAETA—Laboratório Associado de Energia, Transportes e Aeronáutica, with the financial support of FCT/MCTES through national funds (PIDDAC). The work of the second author was financed by the Portuguese Foundation for Science and Technology (FCT), with funds from the "European Social Fund" (FSE) and "Programa Por Centro" part of the Government Funds, under the MIT Portugal Program—doctoral Grant "SFRH/BD/151356/2021".

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

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