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# HOW TO CARRY CULTURAL HERITAGE INTO THE FUTURE? A REVIEW OF RESILIENT HISTORICAL BUILDINGS

Büşra ÖZTÜRK[1,2*], Semra ARSLAN SELÇUK[3]

[1] Department of Architecture, Faculty of Architecture and Design, Selçuklu, 42100 Selçuk University (SU), Konya, Turkey
[2] Graduate School of Natural and Applied Sciences, 06570, Gazi University (GU), Ankara, Turkey
[3] Department of Architecture, Faculty of Architecture, Çankaya, 06530, Gazi University (GU), Ankara, Turkey

***Abstract***

*Climate change causes significant threats to historical buildings by altering the pattern of climate parameters such as temperature, precipitation, and humidity. In this study, a four-stage systematic bibliometric analysis was conducted in the Web of Science database to map and evaluate the primary literature, identify research gaps, and build a knowledge base on the impact and resilience of climate change on cultural heritage. According to the study's findings, the number of publications on the adaptation and resilience of cultural heritage buildings, which we are responsible for protecting against climate change, is relatively low and regional in scope. Analysing the energy resilience of historical buildings with respect to climate change is a significant gap that is not adequately addressed in the literature. In addition, studies focusing on resilience to climate change have been found to lack multidimensional analyses of resilience (energy, climate, social, and economic). As a result, the need for greater interdisciplinary collaboration and public participation in climate change research emerges. In this regard, studies on adaptation, resilience, and risk assessment of historical buildings to changing climatic conditions should be increased and supported by innovative technologies.*

***Keywords**: Cultural Heritage; Climate Change; Resilience; Systematic review; Bibliometric analysis*

## Introduction

The United Nations Framework Convention on Climate Change defines climate change as both natural climate change over comparable time periods and changes in climate resulting from human-induced activities that directly or indirectly damage the global atmosphere [1]. The Intergovernmental Panel on Climate Change (IPCC) was established in 1988 to investigate the social, economic, and technical aspects of climate change and to conduct studies on mitigating its effects. According to the IPCC report, the use of fossil fuels and human-induced activities, especially after the Industrial Revolution, have accelerated the impact of climate change [2]. Another issue affected by climate change is cultural heritage buildings, which are the shared values of all humanity. Cultural heritage comprises tangible and intangible values of universal significance to humanity, created by societies and transmitted over centuries to the present day [3]. These culturally important values are vulnerable to climate change factors, including rising temperatures, sea-level rise, extreme heat waves, and irregular rainfall regimes [4]. Damage to cultural heritage exposed to these factors can cause irreplaceable losses at the local, national, and international levels. Cultural heritage is under threat in many ways, from shaping societies' identities to providing

* Corresponding author: busra.ozturk@selcuk.edu.tr

functional services and financial contributions [5]. The resilience and vulnerability of these immovable, tangible cultural heritage structures, built centuries ago according to the materials and local conditions of their period, in today's changing conditions, is an issue that needs to be addressed.

One of the earliest studies on the vulnerability of cultural heritage to climate change is Stovel's [6] book on disaster risk preparedness of cultural heritage. Since about 2000, studies on the effects of climate change on cultural heritage have started to be investigated [7]. In addition, the 2005 report titled Climate Change and the Historic Environment addresses the historic environment's vulnerability to climate change. In the same year, the International Council of Museums and Conservation Committee (ICOM-CC) began raising awareness of the impact of climate change on cultural heritage by addressing the issue [8]. Although there is awareness of the importance of cultural heritage in mitigating climate change, it has been little examined in studies. It needs to be adequately addressed through practical applied analyses [9], [10]. It is seen that studies on cultural heritage and climate change have increased in the last 20 years and that studies on the estimated impacts on various cultural heritage building groups, including indoor and building envelope quality [11].

Within the scope of this study, the issue of achieving sufficient scientific production and analysis of the impact of climate change on cultural heritage and the resilience of cultural heritage constitutes the study's research question. For this reason, systematic bibliometric studies on the effects of climate change on cultural heritage were analyzed. A total of 13 bibliometric articles on the concepts of climate change and cultural heritage were found. All these studies differ in scope and scale. Firstly, the literature review by Fatorić & Seekamp [7] was developed in response to the lack of a comprehensive understanding in the literature of the impacts of climate change on cultural heritage and resources across various continents and disciplines. Aktürk and Dastgerdi [12] aimed to explore barriers by focusing on understanding and categorizing the main barriers to climate adaptation of cultural sites, based on studies conducted through 2020. Maldonado-Erazo et al. [13], in their study, focused on the impact of climate change on natural and cultural heritage and highlighted the insufficiency of scientific production by analyzing studies on the adaptation of places to these new conditions. Orr, Richards & Fatorić [14] focused on the impact and mitigation of climate change on cultural heritage through scientific production between 2016 and 2020 as a continuation of the article developed by Fatorić & Seekamp [7]. Quesada-Ganuza et al. [15] noted that, despite studies on the risks of climate change to social and urban systems, there are gaps in research evaluating the effects of climate change on cultural heritage with a holistic understanding. Sesana et al. [11] examined various stress factors and their temporal changes using hazard and impact diagrams of climate change on tangible cultural heritage across 100 publications published through 2020. Tavares, Alves & Vásquez [16] examined the relationship between intangible cultural heritage and urban resilience. Crowley *et al.* [17] analyzed 32 studies published over the last 15 years on disaster management, risk assessment, and cultural heritage. Adetunji & MacKee [18], in their literature review, emphasized the need for multi-sectoral, bottom-up, and localized approaches to climate risk identification and adaptation decision-making and argued for the implementation of climate risk management frameworks. Blavier et al. [19] sought to raise awareness of this issue by showing that practical, adaptable solutions to climate change are rarely addressed in the context of cultural heritage. Nguyen & Baker [20], in their study, compiled studies examining the effects of the climate crisis on assets on the UNESCO World Heritage List and emphasized the importance of these studies. Nicu & Fatorić [21] conducted a systematic review of 40 publications on the impacts of climate change and the adaptation of immovable cultural heritage in the polar regions. Salazar & Romão [22] review the existing literature on flood vulnerability assessment for cultural heritage assets and other buildings, emphasizing the need for flood risk mitigation measures (Table 1).

**Table 1.** Evaluation of the bibliometric analysis studies reviewed

| Reference | Disaster and Impact Assessment | Intercontinental Assessment | Identification of Barriers | Resilience Assessment | Functional evaluation | Risk Management and Policies |
|---|---|---|---|---|---|---|
| Fatoric & Seekamp [7] | ✓ | ✓ | | | | ✓ |
| Sesana *et al.* [11] | ✓ | ✓ | ✓ | | ✓ | |
| Aktürk & Dastgerdi [12] | ✓ | ✓ | ✓ | ✓ | | |
| Maldonado et al. [13] | ✓ | ✓ | | | | |
| Orr et al. [14] | ✓ | ✓ | | | | ✓ |
| Quesada-Ganuza *et al.* [15] | ✓ | ✓ | ✓ | | | |
| Tavares *et al.* [16] | ✓ | ✓ | ✓ | | | |
| Crowley *et al.* [17] | ✓ | ✓ | ✓ | ✓ | | |
| Adetunji & MacKee [18] | ✓ | ✓ | | | | ✓ |
| Blavier *et al.* [19] | ✓ | ✓ | | | ✓ | |
| Nguyen & Baker [20] | ✓ | ✓ | | | | ✓ |
| Nicu & Fatoric [21] | ✓ | | | | | ✓ |
| Salazar *et al.* [22] | ✓ | ✓ | ✓ | | | ✓ |

As a result of the literature review within the scope of this study, a gap has been identified regarding the resilience of cultural heritage assets against climate risks and their analysis within a comprehensive framework, evaluating them according to heritage building groups. In the bibliometric analyses, 2 articles addressed resilience. However, Aktürk & Dastgerdi [12] addressed resilience at the urban scale (cultural landscapes) through obstacles, while Crowley *et al.* [17] addressed it through the resilience of intangible values. It is necessary to address the resilience of cultural heritage to climate change, particularly in relation to its building envelope and cultural value. The difference between this study and other bibliometric studies is that it systematically compiles and analyzes articles on 'cultural heritage, climate change, and energy resilience and efficiency' without time limitations and examines studies that focus on the resilience of cultural heritage and provide concrete data and analyses. This study aims to identify gaps for future research on this subject and to analyze the current situation by conducting a content analysis of publications with the stated focus.

## Conceptual Framework

### *Climate Change*

Climate change is one of the significant and widespread challenges the world faces, with diverse impacts. Climate change alters the frequency, intensity, regularity, duration, and seasonal timing of weather and climate events [23]. The severity of the problem is increasingly recognized, as early-onset natural disasters such as extreme precipitation, flash floods, hailstorms, hurricanes, heat waves, and unpredictable forest fires are driven by climate change. In addition, climate change negatively affects human life in many ways, including physical, social, economic, and health aspects. For example, there are many health problems and deaths due to the increasing frequency of heat waves caused by climate change. It can also cause food- and waterborne diseases associated with climate change, respiratory diseases from forest fires, and disruptions to health services from factors such as floods. Climate change is a wide-ranging issue, encompassing environmental degradation and food insecurity, as well as increased mortality and the destruction of settlements [24].

According to climate data, the highest temperatures have been recorded every year for the last 20 years, and carbon emissions continue to capture heat [25]. The IPCC, in its fourth assessment report, associated climate change with anthropogenic activities, namely fossil fuel use and inappropriate land-use decisions [26]. According to the IPCC Fifth Assessment Report, current $CO_2$ emissions will persist for centuries even after emissions cease [2]. The energy sector is developing key strategies to reduce emissions and improve energy efficiency. However, the building sector is responsible for a substantial share of energy consumption and carbon emissions. In particular, there is significant energy consumption for heating, cooling, and air conditioning to maintain space comfort [27].

Due to the serious adverse effects of the building sector, developed and developing countries have begun to address deficiencies in buildings, from the shell to interior systems. The building sector aims to reduce long-term emissions that cause climate change through energy-efficiency strategies and to use renewable energy sources [28]. In addition, by developing adaptation strategies, it is aimed to develop effective solutions both by creating blue and green areas at the urban scale and by providing energy improvements at the building scale. Another critical issue is predicting and controlling extreme climatic events by implementing and monitoring all these strategies [29].

### *Cultural Heritage*

Cultural heritage is important because it reflects the experiences and history of people within a society, increases their solidarity and integrity, and ensures the continuity of their traditions. These values reflect a society's identity, culture, and history and form a foundation that bridges the past and the future [3]. The concept of cultural heritage has a broad meaning that includes both tangible and intangible values of a culture. This concept includes historical monuments, archaeological sites, objects, and cultural values such as stories and dances [30]. In the statutes of organizations such as UNESCO and ICOMOS, the concept of cultural heritage is classified as tangible cultural heritage, intangible cultural heritage, natural heritage, and underwater cultural heritage.

Research has begun with increased awareness of the preservation of all values of cultural heritage amid today's changing conditions. One of the first developments in this issue is that the World Heritage Committee met in 2005 and expressed the necessity of studies on the effects of climate change on cultural heritage [31]. As the impact of climate change intensifies, the climate that develops with unprecedented intensity and regularity poses new dangers to cultural heritage [3], [11]. In particular, tangible immovable cultural heritage values, such as World Heritage Sites, historical cities, archaeological sites, and individual historical buildings, constitute the segment with the highest risk from climate change. It is necessary to assess the risks posed by these values to climate change and to transfer them to the future in a healthy way through emergency interventions. All societies must adopt strategies to protect and raise awareness about their cultural values.

### *Climate Parameters Affected by Climate Change*

To analyze threats to cultural heritage from climate change, data on the interactions between climate change and climate parameters are essential sources. By considering these data, risk parameters for cultural heritage can be determined. When these data are analyzed, two distinct approaches to the problem emerge. In the first approach, the climate parameters are defined, followed by the identification of relevant impacts [31]. This approach is also adopted by the WHC, which analyzes climate-related risks. In the second approach, an impact-oriented approach starts by placing influencing factors at the focus point [32]. In addition, when the studies on this subject are examined, it is seen that, first, a general risk analysis is conducted using the region's climate data, and then a method is used to evaluate the effects on cultural heritage [33], [34]. In studies, factors such as temperature, precipitation, humidity, wind, and hydro-meteorological factors are generally considered as climate indicators. In Table 2, WHC lists climate risks and their impacts on cultural heritage according to its climate indicators.

Recently, parameters such as ‘resilience,’ ‘process management,’ and ‘adaptability’ have been integrated into the risk assessments of cultural heritage in combating climate change. Changing climatic conditions pose significant risks to cultural heritage's vulnerability. This issue is also addressed in ICOMOS reports, which mention the possible threats posed by various climatic factors to historical buildings (Table 2).

**Table 2.** Potential impacts on heritage by type of climate impact [3]

| Climate Impact Type | Impact on Cultural Heritage |
|---|---|
| **Sea Level Rise** | Rising sea levels could lead to the salinization of freshwater drinking supplies and to damage to underground archaeological sites. |
| **Coastal Flooding** | Flooding will permanently inundate some areas. In others, storm surges will increase damage to cultural heritage. |
| **Coastal Erosion** | Coastal erosion effects will increase due to sea level rise and storms, resulting in damage or loss of cultural heritage. |
| **Glacier Melt** | Melting glacial lakes can overflow and threaten settlements; the loss of glaciers can threaten water supplies vital to cities and traditional areas. |
| **Alternating Freeze-Thaw Cycles** | Changing the temperature balance changes the frequency of freeze/thaw cycles in some regions and increases the risk of structural damage to materials. |
| **Increase in Ocean Temperatures** | The increase in ocean temperatures is negatively affecting ecosystems that provide livelihoods for cultural areas. |
| **Increasing Storm Intensity** | More intense and/or more frequent storms lead to increased coastal erosion and increased damage or loss of cultural heritage. |
| **Increase in humidity** | Increased humidity is a significant threat to historical artifacts displayed indoors. Increased humidity can damage pigmented rock art, plastered surfaces, and frescoes. |
| **Heat Waves** | Heat waves are an increasing threat to human health, especially in settlements with increased relative humidity. |
| **Drought** | Drought in regions can change cultural landscapes and encourage migration and abandonment. |
| **Wind and change in its direction** | Wind can increase erosion, damage rock art and underwater archaeological sites, alter dune dynamics, and cause topsoil loss. |
| **Change in Seasonality** | Seasonal changes affect agriculture and landscape management. Longer summers and drier conditions can lead to larger forest fires. |

***Resilience of Cultural Heritage against Climate Change***

Resilience literally means the capacity to maintain, protect, or restore basic functions as soon as possible in the face of the hazard to which it is exposed [35]. IPCC defines resilience as the ability to protect the basic functioning and elements of the system against any factor or risk and to eliminate the risk, promote self-renewal, and improve or adapt [26]. However, it is not possible to eliminate the effects caused by climate change. Climate extremes affect many aspects, including exposure, vulnerability, anthropogenic and natural climate variability, and socioeconomic developments [23]. On the other hand, multidimensional methods such as developing resilience to the impacts of climate change, providing adaptation, and mitigating the effects of the risk should be addressed [36]. According to the IPCC [2] report, disaster risk management and adaptation to climate change can reduce exposure and vulnerability and increase resilience. The report shows that the risk of climate change can be significantly reduced with adaptation and mitigation strategies (Fig. 1).

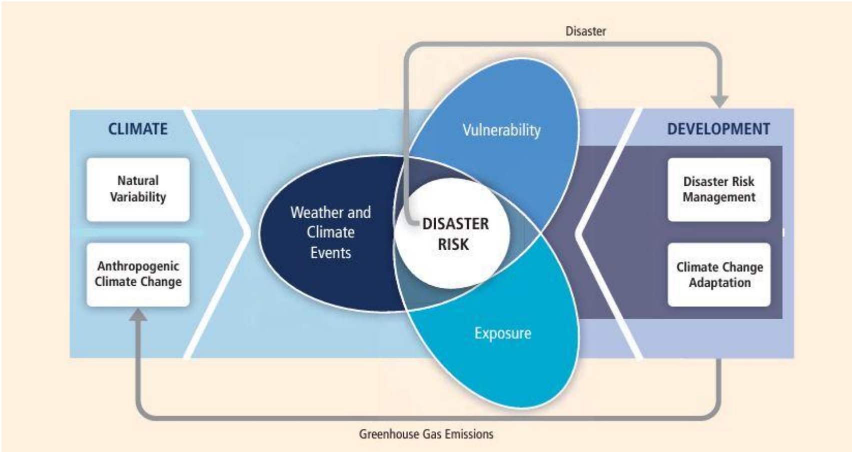


**Fig. 1.** Basic concepts of disaster risk management and adaptation to climate change [2].

Another critical issue in risk assessment against climate change is the vulnerability input. Vulnerability assessment is vital when developing adaptation strategies to predict potential climate hazards [37]. For this reason, many cities in Europe are developing vulnerability risk maps for their settlements to address climate change [38]. This mapping method will provide the opportunity to take precautions and adapt to climate change. However, studies on this subject have not yet been significantly developed in our country.

It is essential to examine, research, and implement ecological solutions and nature-based and nature-friendly strategies that cultural heritage establishes due to its natural structure. Designed centuries ago, these heritage buildings are vulnerable to today's changing climate and socio-economic conditions. For this reason, it is essential to improve the adaptation of vulnerable heritage buildings to current conditions, protect them, and ensure their sustainability. For this purpose, potential risks should be identified, resilience assessments conducted, and adaptation strategies developed. For example, the US National Park Service (NPS) has developed an adaptation plan to manage and sustain protected areas within the scope of its Climate Change Response Strategy [39]. This plan consists of basic content with four titles: Science, Adaptation, Mitigation, and Communication (Table 3).

**Table 3.** National Park Service Climate Change Response Strategy [39]

| Science | Mitigation | Adaptation | Communication |
|---|---|---|---|
| The science section focuses on data addressing broad questions about how climate change is affecting cultural heritage resources. | Mitigation refers to reducing GHG emissions and reducing the overall environmental footprint of cultural heritage. | Adaptation is the response to the question of what to do in specific situations defined by science. | Organizations focused on sharing knowledge on climate change impacts on cultural heritage, dialogue on cultural heritage at international fora, and sharing information through professional networks. |

## Methodology

In the study, a four-stage bibliometric analysis was conducted. In this process, which began with data collection, studies addressing the study's focus were identified in stages. It was then completed with a content analysis of the selected publications deemed most eligible. Through detailed content analysis, it aims to identify a gap in the literature and propose a solution to the study's research question.

***Bibliometric analysis***

Bibliometric analysis, a quantitative approach that presents references, citations, and various data according to the direction of the study to evaluate and analyze the academic literature within the scope of the determined subject, was first used in 1969 [40]. In this way, it enables researchers to identify the knowledge boundary and development trend in a particular field, present knowledge maps and diagrams, and evaluate them using mathematical methods. Bibliometric analysis provides quantitative, objective insights by offering a broad perspective on the academic publication profile from past to present [41].

In the study, Biblioshiny, a web interface using Bibliometrix 3.0 within the RStudio environment, was used to analyze data and create information maps. R software is a dynamically editable and interpretive programming language that offers statistical evaluation [42]. Within the scope of this study, data from the WoS database retrieved using the identified keywords were analyzed using the bibliometric analysis method in the Bibliometrix software.

***Data collection***

In the study, data for bibliometric analysis were obtained from the Web of Science (WoS) database. It has advanced search features for metadata within the WoS database and for organizing search results. For this study, a comprehensive search query was performed in all fields in the WoS database. In the search query, *'climate change' AND 'cultural heritage' or 'historical building' or 'heritage building' AND 'energy' or 'energy efficient' or 'energy resilient'* keywords were used. As a limitation in the bibliometric analysis, the publication type was limited to articles, and the language of publication was limited to English. There was no limitation on the year range in the study. In this query, 491 studies were reached.

In the study, a 4-stage systematic bibliometric analysis was conducted on WoS to collect data (Fig. 2).

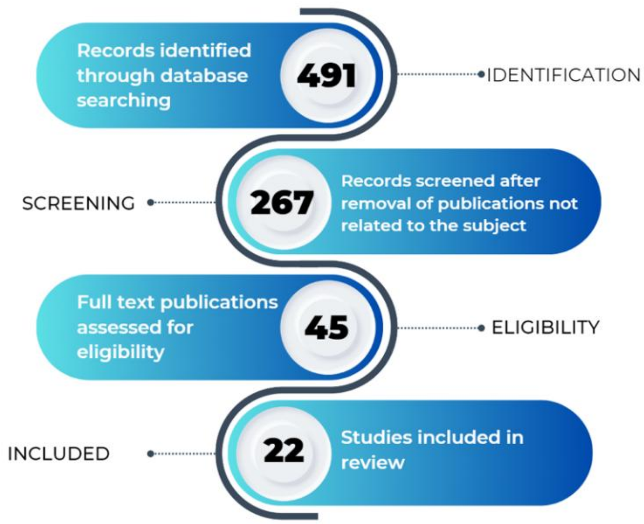


**Fig. 2.** Flowchart of the systematic bibliometric review

In the first stage, 491 studies were identified through the keywords. With a topic-oriented search query using exact keywords in WoS, 267 publications were retrieved. These publications were analyzed through the Biblioshiny program. In the second stage, 45 publications were identified by selecting studies that focused on the concepts of cultural heritage and climate change. By analyzing these publications, studies on cultural heritage, climate change, and energy resilience were identified, and content analysis was conducted. Bibliometric analyses were performed to identify research gaps, challenges, and requirements in this area.

## Results and discussion

Within the scope of the study, a bibliometric analysis of 267 articles obtained via topic-based search using the determined keywords was conducted. Since the study's growth over time is essential, no time restriction was applied in the analysis. According to the findings obtained from the results of the analysis, it is seen that the trend of this research topic has increased in recent years, especially in 2019 and later, and has decreased again in recent years (Fig. 3). According to Web of Science categories, the top five categories were Construction Building Technology (123), Environmental Sciences (98), Engineering Civil (81), Environmental Studies (76), and Energy Fuels (58) (Fig. 4).

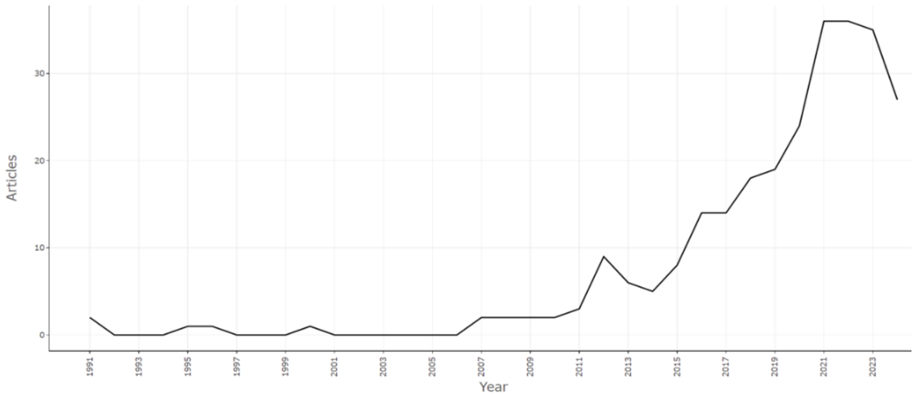


**Fig. 3.** Number of articles by year

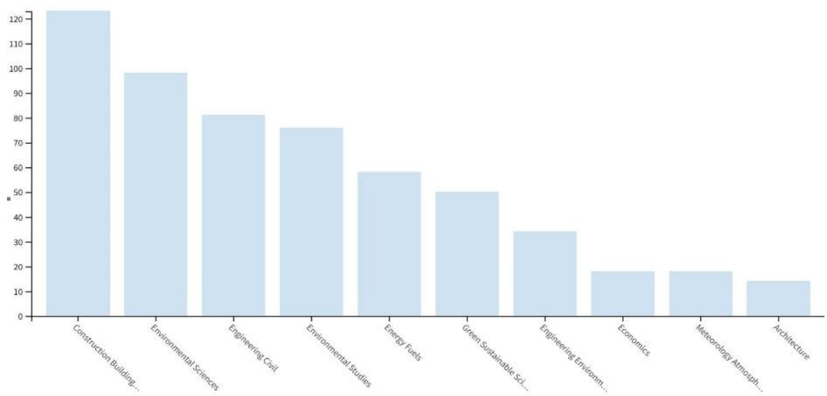


**Fig. 4.** Number of articles by WoS Categories

### *Data screening and inclusion criteria*

As a result of the WoS database search, 267 studies were retrieved from 94 sources. The data obtained in the survey, conducted without time limitations, cover the years 1991 to 2024 (Fig. 5). The publication language of the studies was limited to English, and the document type was limited to articles. General data of the determined studies are given in Figure 5. The top five sources with the most publications are Energy and Buildings (N = 33), Sustainability (N = 22), Building and Environment (N = 16), Building (N = 14), and Energy Policy (N = 12) (Fig. 6).

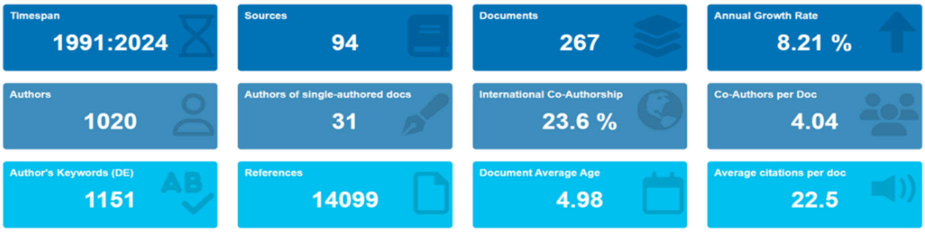


**Fig. 5.** The primary data information in the Bibliometrix software

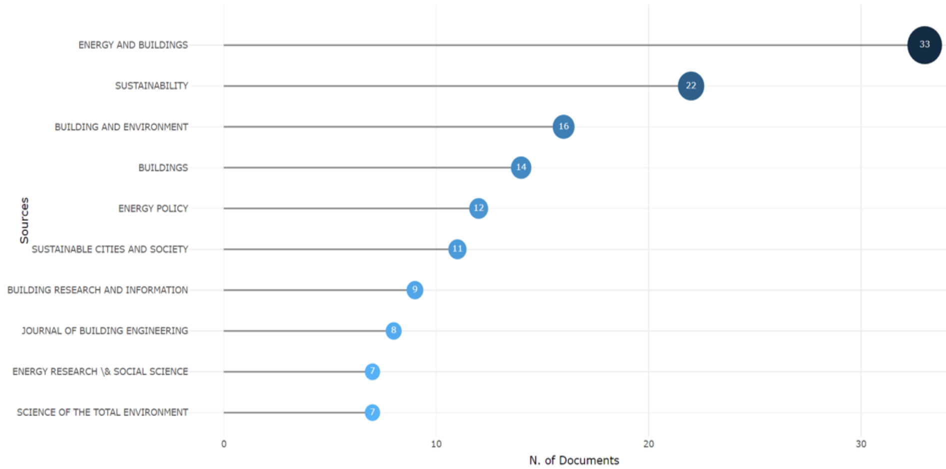


**Fig. 6.** The 10 sources with the most publications in this field

***Most frequent words***

Keywords that define the general content of the research topic enhance comprehensibility. According to the data, words that repeat frequently show a tendency in this area. The diagram showing the most commonly used keywords in the context of this research is shown in Figure 7. According to the diagram, climate change (70), energy efficiency (22), thermal comfort (18), energy (15), and sustainability (13) are the first five most frequently used keywords (Fig. 7). In this ranking, it is seen that the frequency of the concept of cultural heritage is low. The relationship between energy and climate change is given intensive attention, while cultural heritage remains in the background.

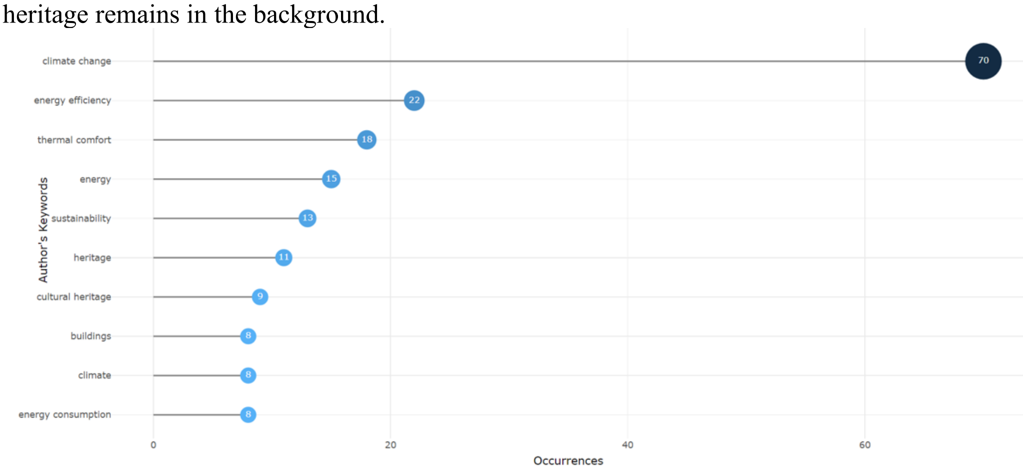


**Fig. 7.** Top 10 most frequently used Author's Keywords numbers

***Most relevant authors***

The author with the most studies in this field is Lucchi (N = 4). It is seen that the number of publications is not concentrated on a particular author and is distributed evenly (Fig. 8). When the ratio of authors' works by year is examined, the 10 most productive authors are listed in Figure 8. The size of the dots in the diagram represents the number of publications. Looking at the number of articles published over the years, it is evident that the author Blumberga (3) has been making regular contributions to this field for a long time. Additionally, it is seen that Lucchi will produce intensively in this area in 2023 (Fig. 9).

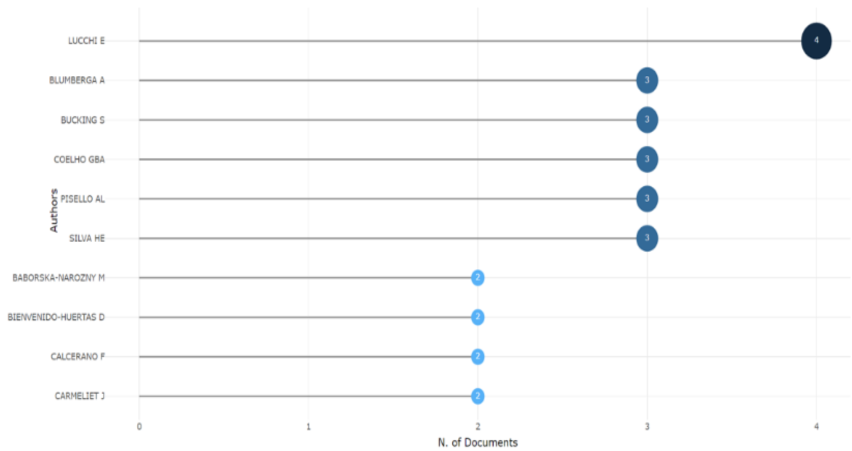


**Fig. 8.** Most relevant authors

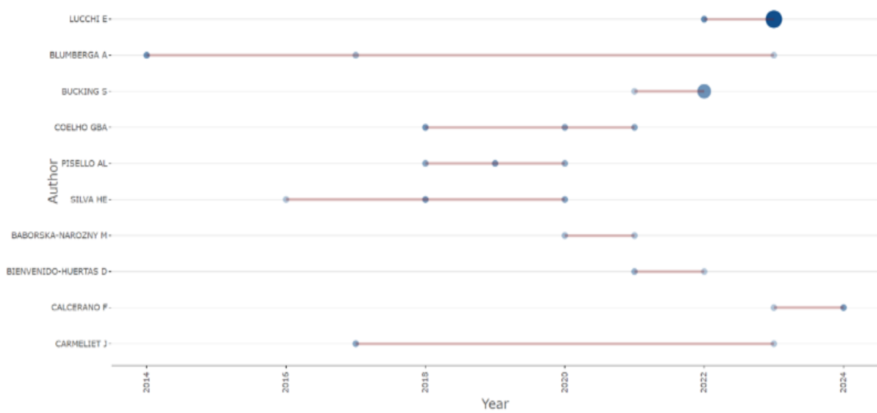


**Fig. 9.** Authors' Production over Time

***Most relevant countries***

Figure 10 shows the corresponding author's cross-country collaborations. According to this graph, the highest number of co-authors is in China. The turquoise color in the graph represents single-authored studies (SCP), while the orange color represents co-authored studies (MCP). The countries with the highest numbers of single-author studies in this field are the USA (31), the United Kingdom (23), and Italy (21). The countries with the most publications in co-authored studies are China (8), the United Kingdom (5), Canada (5), Spain (5), and the USA (4) (Fig. 10).

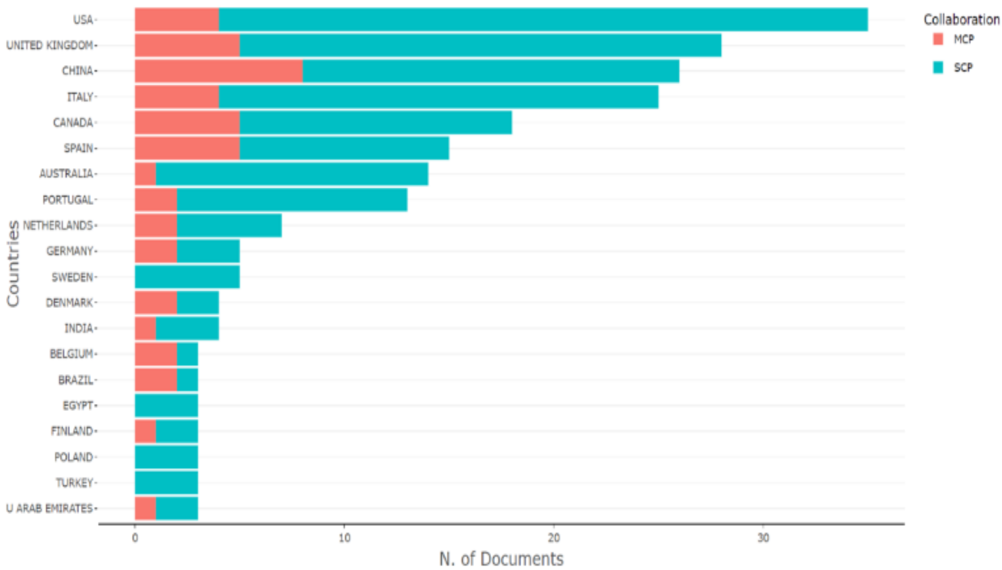


**Fig. 10.** Rates of single- and co-authored studies by country of corresponding author

***Country scientific production and Country collaboration map***

The map of the countries that published the most on the study area is shown in Figure 11. According to Figure 11, the intensity of blue increases in direct proportion to the number of publications for that country. In this context, most publications were from the USA (121), China (102), the UK (95), Italy (74), and Spain (61), respectively (Fig. 11). Figure 12 shows international cooperation in studies on the research topic between countries. The darkness of the blue color represents the density of articles per country. In addition, the thickness and frequency of the brown lines represent cooperation between the countries they indicate. According to the analysis, the countries that cooperate the most are China-UK (4), UK-Belgium (4), and USA-Canada (4) (Fig. 12).

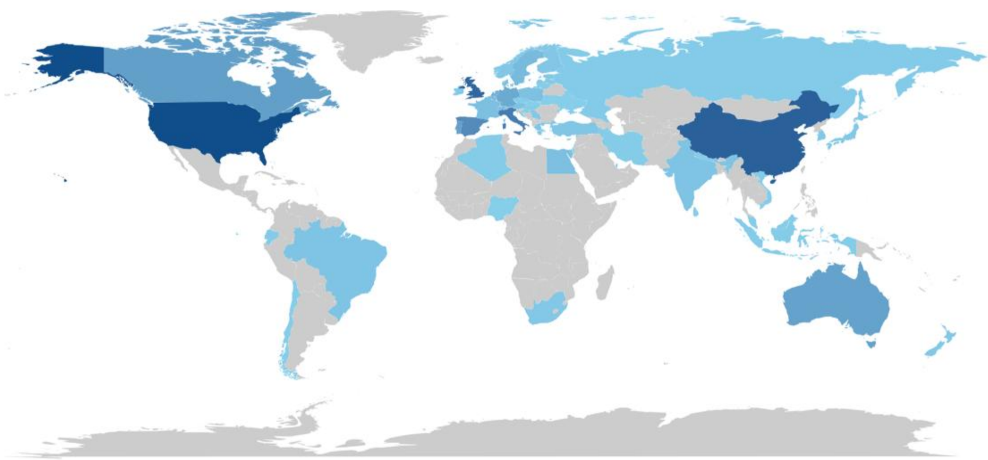

**Fig. 11.** Country Scientific Production for Articles

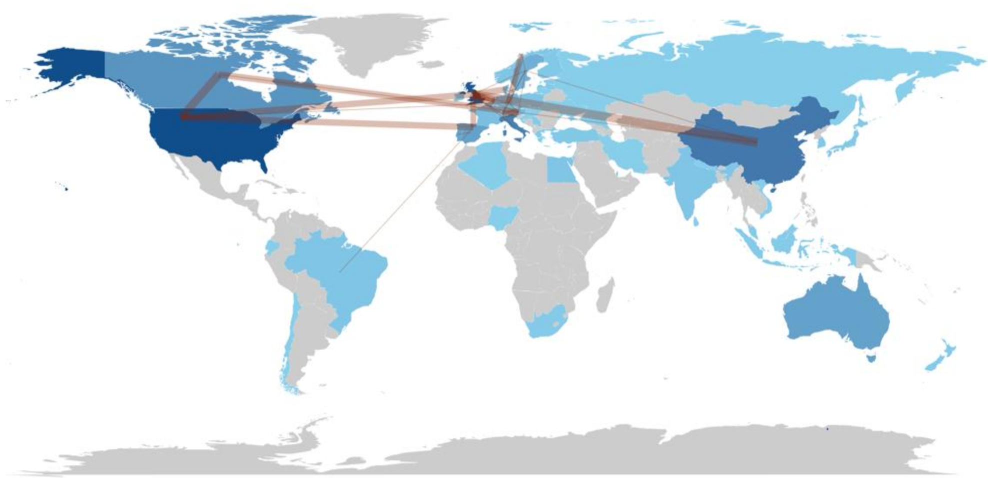

**Fig. 12.** Country Collaboration World Map for Articles

***Three field plots***

Three-area graphs enable a clearer view of relationships based on the specified parameters. In this study, the graphic presenting the relationship between the regional impact of the articles, the keywords used, and the common keywords in this field is shown in Figure 13. The height of the rectangular columns in the graph represents the frequency of use of 'countries,' 'keywords,' and 'keywords plus.' The line thickness between the columns varies with the number of connections (Fig. 13).

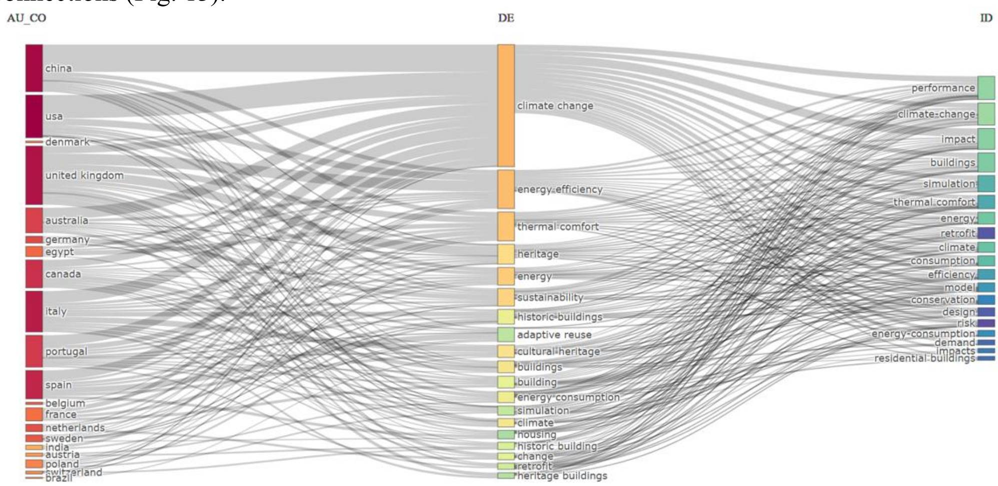


**Fig. 13.** Three-field plot graphics show the relationship between countries (left), the author's keywords (middle), and keywords plus (right)

***Factorial Analysis***

Factor analysis is a method that describes variability by creating component subsets based on underlying relationships. When the studies are examined using keyword-based factor analysis, the majority are classified into 4 meaningful clusters (Fig. 14).

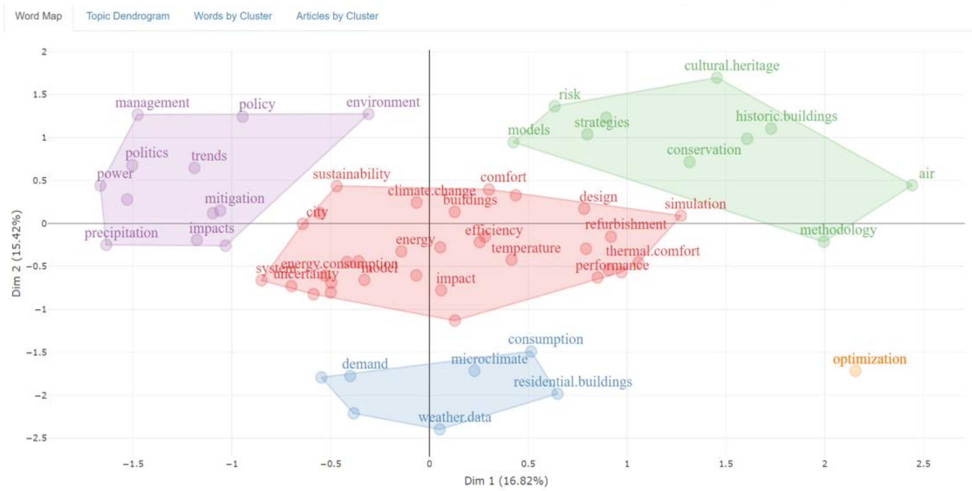


**Fig. 14.** Factory analysis of studies

It is evident that the concepts of cultural heritage and climate change, which constitute the focus of this study, do not fall into the same cluster in most publications. This situation necessitates selecting studies that address the study's focus from among 267 publications using the re-elimination method. For this purpose, the third stage of the bibliometric analysis of the survey was completed, and studies focusing on both keywords were identified. 45 studies addressing the concepts and relationships between ‘Cultural Heritage,’ ‘Historical Building,’ ‘Historic Building,’ and ‘Climate Change’ were identified.

***The publications in the field through content analysis***

Out of 45 studies that addressed the concepts of 'cultural heritage,' 'historical building,' 'historic building,’ and ‘climate change' and their relationship, the last 22 studies that included the third keyword group, ‘energy,’ ‘energy efficient,’ ‘energy resilient,’ and ‘resilience,’ were determined, and content analysis was conducted. Only 8 of the 22 studies addressed the concept of 'resilience,' which is central to this study's research question. Historical structures, climate change, and the concept of resilience should be considered as a whole; analyses should be conducted, suggestions developed, and scientific production on this subject should be increased. Detailed information on the 22 articles included in this study is presented in Table 4.

**Table 4.** Content analysis of the 22 articles analysed

| Reviewed Reference | Methods | Aim and Main Topic |
|---|---|---|
| Bienvenido-Huertas *et al.* [9] | Artificial neural networks | The study aimed to assess the potential conservation risks posed by poor indoor microclimates in historic buildings in their current state. |
| Sahyoun, Ge and Lacasse [43] | Simulation | The paper aims to develop an alternative method for selecting annual humidity references that accounts for changing climatic conditions. |
| Lamberti, Contrada and Kindinis [44] | Simulation | The paper aims to identify solutions for indoor environmental quality and energy conservation, and to examine the impact of climate change on them. |
| Cavalagli *et al.* [45] | Simulation, risk mapping | A new method for mapping the risk of material degradation in masonry buildings is proposed to improve resilience. |
| Gutiérrez-Carrillo *et al.* [46] | Digital twins | The paper develops a replicable and easy-to-use multianalytic methodology that proposes the use of standard monitoring. |

| Reviewed Reference | Methods | Aim and Main Topic |
|---|---|---|
| Bonazza *et al.* [47] | Mapping | The paper presents Europe-wide maps of quantitative predictions of the surface retreat of carbonate rocks due to changes in precipitation. |
| Moisio *et al.* [48] | Simulation | The study revealed the importance of building protection in reducing the impacts of climate change by comparing four scenarios over the school structure. |
| O'Brien *et al.* [24] | Using good practices | The paper notes that a model for developing climate adaptation strategies to reduce climate risk to cultural heritage is needed. |
| Bonazza & Sardella [10] | Risk Mapping | This paper examines methods for projecting the impacts of climate change and provides a quantitative assessment. |
| Fiorini *et al*. [49] | Machine Learning-Based Monitoring | The study aims to develop tools to understand the mechanisms underlying surface deterioration of heritage buildings in extreme climates. |
| Lei *et al.* [50] | Simulation | The study focuses on the current and future thermal comfort in historical two-room apartments in China for two different Chinese climate zones. |
| Coelho *et al.* [51] | Simulation | The article aims to quantify energy consumption and its future development to demonstrate the positive impact of passive retrofitting measures. |
| Figliola *et al.* [52] | Simulation | The paper aimed to determine passive cooling strategies based on natural ventilation levels and the envelope surfaces exposed to radiation. |
| Pioppi *et al.* [53] | Numerical Modelling | This study aims to present a method for studying the microclimate of cultural heritage sites that combines field observations and numerical modelling at multiple levels. |
| Keller *et al.* [54] | Simulation | The paper proposes a complex assessment and intervention strategy to improve urban resilience through a multidisciplinary approach. |
| Parkinson *et al.* [55] | TNC Oceanographic proprietary software | The paper aimed to demonstrate the specific set of environmental conditions to which most archaeological sites were exposed and the geomorphic change. |
| Silvero *et al.* [56] | Simulation | The paper aims to assess the impact of climate change on the thermal performance of buildings. |
| Cantatore and Fatiguso [28] | Simulation | The paper proposes a methodology for energy retrofit actions in historical areas, in line with "resilience thinking". |
| Cassar *et al.* [57] | Uncrewed Aerial Vehicle | The paper focuses on carbon-reduction strategies for traditional roofs to address climate change. |
| Vahmani *et al.* [58] | Forecasting model | The article demonstrates the role of cool roofs in mitigating global climate change. |
| Kumari R & Kitchley [59] | Mapping | This paper aims to assess the contextual vulnerability of Madurai, an ancient city of high social and cultural value. |
| Santamouris *et al.* [60] | Thermal remote sensing | The article aims to develop an urban climate change resilience plan for the historic centre of Athens. |

The studies included in the content analysis within the scope of this study are grouped based on their similarities and differences. While some studies analyze a historical element (historical roof, historical wall, etc.), others work on a large scale within a single historical structure or a historical region. In large-scale studies of historical areas, the mapping method is typically used, and analysis primarily focuses on historical surface deterioration. It has been revealed that as the research scale decreases, more precise results can be achieved through more detailed analyses (by generating various scenarios through simulation). In addition, while some studies focus only on indoor air quality, most focus on the building envelope. When studies are examined by the methods used in their analyses, the simulation method is the most widely used. In addition, 3 articles have attempted to predict outcomes under various scenarios using the IPCC's future weather forecast data and artificial intelligence. The mapping method, one of the other methods used in the studies, aims to identify risk factors and prioritize emergency areas. In addition, there are studies that collect data through field measurements and remote sensing systems during the data-collection phase. According to the concepts the studies focused on as research questions, most (10 articles) focused on 3 keywords: historical structure, climate change, and thermal comfort. 8 studies were reached on historical structure, climate change, and resilience, which are the research questions of this study. The distribution of the 22 studies across various categories is shown in Table 5.

**Table 5.** Distribution of the analysed studies according to their qualifications

| Scale | Study Focus | Research Region | Methods |
|---|---|---|---|
| Historical Element (4) | Resilience (8) | Envelope (16) | Simulation (12) |
| Historical Building (11) | Thermal Comfort (10) | Indoor Quality (6) | Artificial Intelligence (3) |
| Historical District (7) | Surface Degradation (4) | | Mapping Method (4) |
| | | | Remote sensing (3) |

## Conclusion

Global climate change and its effects are the most critical global problems of our day. The multidimensional impacts of climate change harm human life in many ways and are increasing by the day. The effects of climate change on cultural heritage buildings are increasingly important, especially for protecting social and cultural sustainability. It is essential to ensure the resilience of cultural heritage buildings to current conditions by developing strategies that are compatible with climate change. Managers, cultural heritage protection organizations, and conservationists have a great responsibility in this regard. On an international scale, essential reports and policies are being developed to protect cultural heritage from the impacts of climate change. In particular, many organizations, such as ICOMOS, UNESCO, IPCC, DMM, and NPS, meet regularly on this subject and conduct research. Climate- and location-specific studies are organized on a regional basis to develop adaptation interventions for cultural heritage based on climate parameters and to create risk maps. However, studies on this subject in our country are still at a very early stage. In this regard, protecting cultural heritage and addressing climate change by ensuring its sustainability are urgent priorities.

A bibliometric analysis was carried out to address the research question: ‘Is there enough scientific production and practice on the impact and resilience of climate change on cultural heritage?’ The analysis shows that the publications focus on ‘climate change and energy’ and ‘cultural heritage and energy.’ While 45 publications could be selected for studies focusing on cultural heritage and climate change, 22 studies on cultural heritage, climate change and resilience, and energy that contain all three keyword groups at the same time could be selected. However, the finding that 8 articles fell within the scope of resilience indicated insufficient scientific production on this subject. It has been observed that most studies on resilience have been conducted at a large scale, with a focus on urban resilience. In addition, the analysis shows that existing studies are regionally concentrated in certain countries (such as England, China, and North America), and that there is collaborative scientific production between these countries. However, climate change is a global issue, and every society should raise awareness and conduct research into how this factor affects its cultural heritage.

It is necessary to conduct detailed studies to ensure that cultural heritage buildings, which are the common heritage of societies and have documented value, are minimally affected by global climate change and can be preserved and passed on to future generations. In this context, it is essential to develop adaptation strategies that include social participation to increase the resilience of cultural heritage against climate change. In particular, organizing working groups to protect each community's values, developing risk maps, and producing participatory action plans will help manage this crisis. While providing these methods, integrating digital technologies and artificial intelligence into the process will contribute. In this way, it will be possible to evaluate the current situation and develop instant solutions based on the historical building's or environment's current climate data. In addition, interoperability with Internet of Things (IoT) technologies, integrated without damaging the historical texture, will enable rapid receipt of news about immediate disasters. It is expected that the effects of this crisis can be mitigated through the strategy plans developed at the national and international levels. The development of both scientific studies and analytical applications, especially in the field of 'resilience and adaptation,' will be necessary for cultural heritage.

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