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Microclimate management in libraries: A systematic literature review

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Paper Type:

Literature Review

Abstract

Background of the study: Increasingly extreme climate change requires libraries to develop microclimate management strategies to maintain valuable ecosystems.

Purpose: This study aims to systematically review the literature on best practices for microclimate management in libraries, with a particular focus on temperature and humidity control.

Method: Utilizing the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, this study screened and analyzed 25 scientific articles published between 2014 and 2024.

Findings: The results of this study show that maintaining microclimate stability in libraries requires an integrated approach combining HVAC systems, ventilation strategies, and monitoring technologies. Automated control systems and natural ventilation strategies both play critical roles in achieving effective microclimate management tailored to the specific conditions of each library.

Conclusion: Microclimate management in libraries is crucial for ensuring the long-term preservation of collections. Effective strategies tailored to local conditions not only safeguard valuable materials but also contribute to the sustainability of the storage environment. These findings emphasize the importance of integrating appropriate technologies and methods to support the continued conservation of library resources.

Keywords: microclimate, library, temperature, humidity, HVAC

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Introduction

The increasing challenges posed by severe and unpredictable climate change present a substantial and complex threat to long-tern preservation of library collection globally. Significant and often erratic fluctuations in temperature, consistently high humidity levels, and increasing frequency of extreme weather events, such as intense storms and prolonged drought, have the potential to cause irreparable damage to various library materials. This vulnerability extends from fragile paper-based artifacts, including irreplaceable books and delicate manuscripts, to modern formats like photographic films, magnetic tapes, and digital storage media, each susceptible to specific environmental stressors. Recognizing the importance of ensuring the continued accessibility and long-term sustainability of these repositories of human knowledge and cultural heritage, the development and implementation of adaptive storage environments within libraries is essential. Maintaining stable and controlled environmental conditions, particularly focusing on consistent temperature and humidity levels, is a fundamental prerequisite for preserving material degradation from physical stresses like expansion and contraction, and for inhibiting growth of destructive biological agents such as mold, mildew, and bacteria (Fabbri & Pretelli, 2014; Osunrinde & Adetunla, 2017). Therefore, the judicious selection and implementation of effective climate management system within library storage spaces are not merely advisable but crucial for achieving optimal preservation and safeguarding collection for future generations.

In the complex factors that influence the preservation of library collections, microclimate parameters, including temperature, humidity, air quality, and light intensity and spectral composition, play a critical and often synergistic role. A focused and strategic approach to preserving physical materials in a library environment involves the implementation of careful microclimate control, a practice that requires active management of environmental conditions within specific zones of the library building (Derksen et al., 2024). These target areas typically include secure storage space that houses rare and fragile materials, high use reading rooms where environmental stability impacts user comfort and the integrity of materials, and exhibition spaces where sensitive items are displayed for public access. The primary goal of microclimate control in libraries is to significantly reduce the ongoing degradation of physical collections by precisely regulating both temperature and humidity level (Coskun et al., 2024), thereby creating environmental conditions that actively prevent the germination and growth of damaging fungi (Pasquarella et al., 2020), the brittleness and weakening of paper fibers (Verticchio et al., 2022), and the gradual but irreversible fading of inks and pigments

The temperature and humidity instabilities inherent in library environments can exert substantial physical stress upon the constituent material of collections. These fluctuations can induce cyclical processes of expansion and contraction within organic materials like paper and textiles, ultimately leading to phenomena such as warping of book covers and pages, the development of cracks along fold lines, and a general increase in material fragility. Furthermore, suboptimal air quality, characterized by the presence of airborne particulate matter and gaseous pollutants such as sulfur dioxide and nitrogen oxides, can initiate and accelerate detrimental chemical degradation processes within library materials, contributing to the acidification of paper and breakdown of binding adhesives (Andretta et al., 2016; Drougka et al., 2020). Verticchio at al. (2021) explored the impact of climate by comparatively studying three historic Italian libraries, revealing that heritage collections predominantly composed of paper are particularly vulnerable to climate-induced deterioration risks, notably including the hydrolytic breakdown of cellulose, the primary structural component of paper. Similarly, Verticchio at al. (2022) highlighted the complex interplay of mechanical, chemical, and biological deterioration mechanisms directly induces by the prevailing microclimate within the historic Alessandrina Library in Rome, emphatically underscoring the fundamental role of

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environmental conditions as primary drivers of material degradation. Their comprehensive two-year study involved the continuous monitoring of both temperature and relative humidity, providing critical data for a thorough assessment of climate-induced risk to the library's invaluable holdings.

Moreover, the often-overlooked factor exposure to excessive light, particularly the high-energy components of the spectrum such as ultraviolet (UV) radiation, can inflict significant and irreversible damage upon organic library materials. Prolonged exposure to UV light can initiate photochemical reactions, resulting in the gradual fading of dyes and pigments in inks and illustrations as well as the progressive weakening and embrittlement of paper fibers and textile bindings. The effect of these diverse environmental stressors is not uniform across all types of library material, for instance while paper-based items exhibit a pronounced sensitivity to variations in both humidity and temperature, photographic materials and magnetic media possess their own unique vulnerabilities to specific environmental conditions. This differential susceptibility was clearly demonstrated in the study conducted by Verticchio at al. (2021), which highlighted the distinct responses of various material to the prevailing microclimates within the studied libraries. The critical importance of maintaining a stable and appropriate indoor climate for the long-term preventive conservation of manuscript collections was also emphatically underscored by Sahin et al. (2017) in their investigation of the Tire Necip Paşa Library in Turkey, stressing the inherent necessity of adopting a holistic and interdisciplinary approach to the complex challenges of cultural heritage preservation.

The establishment and maintenance of effective microclimate control within library environments require careful selection and integration of various technological solutions and strategic methods. Heating, Ventilation, and Air Conditioning (HVAC) systems are essential infrastructure for achieving stable temperature and humidity levels within library space, which helps to reduce the risk associated with environmental changes. In addition to these active climate control systems, monitoring systems with precise sensors and data loggers are important tools for providing continuous and detailed information on environmental conditions. The indoor environment of libraries should provide suitable conditions for preservations of objects (Kompatscher et al., 2019). This real-time data allows library staff to make timely adjustments to climate control and apply preventive conservation measures in response to environmental risk. Continuous monitoring of temperature and relative humidity is crucial for evaluating potential climate-related risks to library collections (Verticchio et al., 2022).

Despite significant advancements in microclimate management for cultural institutions, including libraries, several key research gaps require further academic investigation. There is a clear need for the development of more comprehensive and universally applicable guidelines. These guidelines should effectively integrate the variety of available control technologies. They should also strategically address the specific environmental needs of diverse library settings and various materials of their collections. Verticchio et al. (2021) highlighted the difficulties in comparing the finding of different microclimate studies. This is largely due to the lack of standardized long-term observation protocols and universally adopted methods for environmental risk assessment. Furthermore, there is a crucial need for rigorous and long-term research. This research should thoroughly evaluate the effectiveness of different microclimate management strategies. It should also examine their long-term impact on the preservation of specific library materials.

This systematic literature review is designed to address these identified research gaps in microclimate management within libraries through a systematic investigation and synthesis of existing scholarly knowledge. The purpose of this review is to identify and analyze effective strategies, technologies, and best practices for preserving library collections when facing environmental challenges. To achieve these goals, the study seeks to answer the following key

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research questions: (1) How do temperature and humidity fluctuations in libraries affect the preservation conditions of collection? (2) What role does the HVAC system play in maintaining a stable microclimate in the library? And (3) What are the most effective monitoring methods for detecting temperature and humidity fluctuations in the library spaces? Ultimately, by consolidating current research, this study aims to provide a comprehensive understanding od the critical factors that influence the preservation of library settings. Furthermore, the findings of this review are expected to yield evidence-based recommendations that will assist library professionals in formulating microclimate management strategies specifically tailored to the unique needs and available resources of their respective institutions. By synthesizing existing knowledge and identifying established best practices, this research endeavors to contribute meaningfully to ongoing global efforts dedicated to the effective and sustainable preservation of invaluable cultural and intellectual heritage for benefit of both current and future generations.

Literatur Review

Microclimate refers to the local atmospheric zone where the climate differs from the surrounding area These variations occur on a small scale, such as within urban areas, where factors like buildings, vegetation, and surfaces create distinct temperature, humidity, and air conditions (Smith et al., 2021). For instance, urban structures can alter air flow and trap heat, leading to the urban heat island effect, a notable example of microclimatic variation. Understanding microclimates is crucial for various fields, including urban planning, where it aids in designing sustainable and comfortable environments, and cultural heritage preservation, where stable microclimate are essential for artifact conservation (Dai et al., 2022).

The study of microclimate involves analyzing various factors. These include temperature and humidity, which are critical in indoor environments like libraries for preserving collections. Additionally, in urban setting, surface temperature and urban morphology play significant roles in shaping microclimates. Research methodologies to investigate microclimates very, employing techniques from field measurements to advanced modeling and remote sensing. The insights gained are applied to address challenges ranging from energy efficiency in buildings to mitigating the adverse effects of urban development on local climate conditions. Similarly, within the context of libraries and cultural heritage, microclimate denotes the specific atmospheric conditions immediately surrounding the collections, influenced by factors such as the building's architecture, materials, and nay climate control systems (Balocco et al., 2016; Verticchio et al., 2022). These localized conditions, primarily characterized by temperature and relative humidity, but also encompassing air quality and light exposure, are paramount in determining the rate of deterioration of library materials. Effective management of these microclimates is therefore essential for preventive conservation.

A critical aspect of microclimate is its dynamic nature. As demonstrated by Verticchio et al. (2022) in their study of the Alessandrina Library, microclimates within historic buildings are subject to both temporal and spatial variations. Temporal variation refers to changes over time, including daily and seasonal fluctuations in temperature and humidity, which can induce stress on materials. Spatial variations, on the other hand, refer to differences in climatic conditions within the same building, such as vertical gradients in temperature or humidity pockets near walls or windows. These variations can be influenced by factors such as solar radiation, ventilation patterns, and the presence of moisture sources. Furthermore, the interaction between building's material and the indoor environment plays a crucial role in shaping the microclimate. Kupczak et al. (2018) found that the hygroscopic nature of paper and wooden collections can buffer humidity fluctuations, while Balocco at al. (2016) utilized numerical simulations to assess how building design influences microclimatic conditions. Understanding these complex dynamics is crucial for implementing effective preservation

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strategies.

The foundational work of Fabbri and Pretelli (2014) presents a compelling and insightful case study centered on the Malatestiana Library in Cesena, Italy, a distinguished UNESCO World Heritage site. Their research meticulously highlights the remarkable ability of this historical institution to have preserved its extensive and invaluable collections for centuries without the reliance on modern Heating, Ventilation, and Air Conditioning (HVAC) technology. This exceptional example powerfully underscores the enduring importance of a deep understanding of traditional microclimate control methods, which often relied on passive architectural design principles, careful material selection, and an intimate knowledge of local environmental conditions. The authors advocate for a "Heritage First" approach, a guiding philosophy that prioritizes the creation and maintenance of optimal microclimatic conditions specifically tailored for long-term preservation of that while user comfort is undoubtedly a consideration in library management, it should not supersede the fundamental imperative of ensuring the enduring preservation of the cultural heritage entrusted to the institutions' care. Notably, Fabbri and Pretelli (2014) also hypothesize that the very absence of modern, often fluctuating, HVAC systems within the Malatestiana Library may have paradoxically contributed to the exceptional state of conservation observed in its historic book rest and irreplaceable manuscript collections, suggesting a potential inherent stability in traditional, passively controlled environments.

In contrast to the reliance on traditional methods, Kompatscher et al. (2019) explored a more contemporary and technologically driven approach to microclimate management in libraries and archives. Their research delved into the potential benefits and practical implications of implementing intermittent conditioning and dynamic setpoint control strategies within these critical cultural heritage repositories. The findings of their investigation suggest that library and archive environments may possess a greater inherent capacity for flexible climate control than is often traditionally assumed. By strategically utilizing more tolerant setpoint ranges for temperature and humidity, coupled with permissible fluctuations within carefully defined limits, institutions may be able to achieve significant energy efficiencies without unduly compromising the long-term preservation of their collections. The study conducted by Kompatscher et al. (2019) specifically indicates that the adoption of dynamic setpoint control strategies has the potential to yield substantial reductions in energy consumption associated with maintaining stable indoor climates, offering a pathway towards more sustainable preservation practices.

Building upon the integration of technology in microclimate management, the work of Balocco et al. (2016) introduces a sophisticated methodology employing numerical simulation techniques to rigorously assess the suitability of indoor environmental conditions for the long-term conservation of paper-based materials. Their research demonstrates the increasing role that advanced computational tools can play in understanding the complex interactions between building physics, environmental control systems, and the material properties of cultural heritage objects. By utilizing numerical simulations, institutions can gain valuable insight into the effectiveness of different microclimate management strategies, predict potential environmental risk to collections, and make more informed decisions regarding the optimization of their preservation's efforts. This approach allows for a more proactive and data-driven approach to environmental control, moving beyond purely reactive measures.

The research conducted by Verticchio et al. (2022) provided a detailed analysis of the microclimates within the historic Alessandrina Library in Rome, employing continuous monitoring of temperature and relative humidity over an extended two-year period. Their findings offered critical insight into the specific environmental challenges faced by these institutions, particularly the impact of fluctuating temperature and humidity on their valuable

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paper collections. The study highlights the library's natural ventilation system and the limitations of its air conditioning in effectively controlling temperature year-round. By meticulously documenting the temporal variations in key microclimate parameters, their study contributes to a more nuanced understanding of the dynamic environmental conditions within historic library buildings. Similarly, Verticchio et al. (2021) undertook a comparative study of the indoor climates across three significant historic libraries in Italy. Their research highlighted the variations in microclimate environmental contexts in which heritage collections are preserved. This comparative approach underscores the importance of considering the specific architectural characteristics and geographic location of library buildings when developing appropriate microclimate observations for effective preservation planning and the assessment of climate induced risk to paper collections.

Sahin et al. (2017) focused their investigation on the indoor microclimate of the Tire Necip Paşa Library in Turkey, with a specific emphasis on the preventive conservation of its manuscript collections. Their study emphasizes the critical role of maintaining stable and appropriate temperature and humidity levels for safeguarding these delicate historical documents. The research revealed that while the library's natural hygrothermal behavior provided some protection, a chemical degradation risk was still present. The study also assessed mechanical and biological degradation risk, finding them to be relatively low in the case study library. The study suggested that while HVAC systems are a possibility, passive solutions minimize disruption to the established environmental conditions should be prioritized.

Pasquarella et al. (2020) contributed to the understanding of biological risk within library environments by examining the presence of biological particles, including fungal spores, in the De Rossi room of the Palatina Library in Parma, Italy. Their biological and microclimatic monitoring throughout the year revealed the potential hazards posed by airborne biological contaminants to both artifacts and human health. Specifically, the research highlighted a wide seasonal variability in fungal contamination, with the highest mean value observed in September, posing a direct threat of biodeterioration to the library's collection of incunabula and manuscripts. This underscores the importance of considering not only physical and chemical deterioration risk but also biological threats when developing comprehensive preservation strategies for library collections. Effective microclimate management plays a crucial role in mitigating this biological risk by controlling temperature and humidity levels that can promote the growth of fungi and other microorganisms.

Kupczak et al. (2018) further explored the inherent capacity of paper and wooden collections to influence humidity stability and energy consumption in museum and library settings. Employing sophisticated modeling techniques, their investigation focused on quantifying the moisture buffering effects of these common hygroscopic materials within enclosed spaces. The outcomes of their simulations indicated that substantial paper collections, particularly in airtight environments, can effectively dampen fluctuations in relative humidity and consequently lower the energy expenditure associated with maintaining stable indoor climates. This research provides valuable insights into the passive contribution of library and museum holdings to microclimate regulation, suggesting that the inherent properties of the collections themselves can be leveraged for more sustainable preservation strategies.

Djabir et al. (2023) investigated thermal comfort in open-space libraries in tropical climates using Computational Fluid Dynamics (CFD). While focused on user comfort, their study underscores the complexities of managing indoor environment in specific climatic contexts, which indirectly relates to preservation concerns as extreme conditions can impact collections. Specifically, the research involved developing a CFD model and validating it with field measurements of air temperature, relative humidity, and mean radiant temperature within the Universiti Tun Hussein Onn Malaysia (UTHM) library. The study highlighted the

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importance of achieving thermal comfort for library occupants in tropical regions, where high temperatures and humidity are prevalent, noting that conditions which deviate from thermal comfort can negatively impact on the occupant's well-being and productivity. Their work highlights the need for context-aware solutions in environmental management within libraries, considering both human comfort and the potential implications for the preservation of library materials.

Schito et al. (2019) developed a procedure for identifying chemical and biological risk for books in historic libraries based on microclimate analysis. Their work provides a structured approach for assessing potential deterioration risks by analyzing environmental data. This methodology offers a valuable tool for libraries to proactively identify and mitigate threats to their collections based on their specific microclimatic conditions. The research emphasizes that historic libraries, which house old and rare books, require specific preservation strategies due to the unique challenges they face, especially with changes in use such as becoming tourist attractions. The procedure involves a monitoring campaign and the evaluation of risk indices to assess hygrothermal variations and potential biological and chemical degradations.

Collectively, these diverse studies underscore the multifaceted nature of microclimate management in libraries, highlighting the importance of understanding environmental factors, exploring various control technologies and strategies, considering the specific characteristics of library buildings and collections, and addressing both physical, chemical, and biological risks. The existing literature reveals a range of approaches, from traditional passive methods to sophisticated technological solutions, reflecting the ongoing efforts to balance preservation needs with practical constraints and evolving understanding of material degradation.

Method

Research Type

This study adopts a qualitative approach using the systematic literature review (SLR) method to provide a comprehensive synthesis of current understanding of the impact of microclimate on library collection. The study focuses on the effects of temperature and humidity fluctuations, HVAC systems function, and optimal monitoring methods. This systematic literature review adopts a qualitative synthesis approach, aims to analyze and synthesize narrative findings from existing literature to address these questions and identify key themes and insights within the field. The study was conducted using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021), a widely recognized, evidence-based guideline comprising a 27-item checklist and a four-phase flow diagram designed to enhance the rigor and transparency of systematic literature reviews and meta-analysis. PRISMA has been widely applied in various research field (O'Dea et al., 2021) due to its comprehensiveness and capacity to enhance review accuracy while minimizing researcher bias (de Barcelos Silva et al., 2020). The application of PRISMA guidelines ensures a structured and transparent process encompassing the formulation of research questions, a comprehensive literature search, rigorous study selection based on predefined criteria, systematic data extraction, analysis, and the thematic synthesis of finding to answering the research questions.

Keywords

Scopus was utilized in this study as the primary tool for sourcing relevant articles. Renowned as one of the largest and most comprehensive bibliographic databases, Scopus ensures the inclusion of high-quality articles by indexing only peer-reviewed scientific journals. Scopus covers a variety of disciplines, thus increasing the chances of finding articles that are currently the focus of research. Keywords are used to narrow the search by combining various keywords. Boolean operators are used, such as AND, and OR, to make the search more specific.

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Then, the use of wildcards asterisk (*) to expand the search scope in Scopus, this symbol allows for more flexible word variations. The following keywords were used in the search for articles that matched the title, abstract and keywords: *((" microclimat *" OR " indoor climate *" OR " environment * climate " OR " indoor microclimat *" OR " climat * control " OR " thermohygrometric * climat *") AND (" librar *"))*. Data was retrieved on October 13, 2024 through the Scopus database.

Inclusion and Exclusion Criteria

Clear and structured inclusion and exclusion criteria were established to ensure the inclusion of only relevant and high-quality studies in this systematic literature review. These criteria served as a systematic filter in the literature selection process, aiding in the identification of studies directly addressing the research questions concerning the impact of microclimate on library collection.

Table 1. The inclusion and exclusion criteria

Criteria	Inclusion	Exclusion
Time	2014-2024	Before 2014
Publication Type	Journal article	Books, book chapters, proceedings, newspapers, other papers
Language	English	Non-English
Access	Full-text access	Incomplete text access

Table 1 presents the inclusion and exclusion criteria employed in this study to select relevant literature. The inclusion criteria stipulated that reviewed articles must be published between 2014-2024, be journal articles, written in English, and have full-text access. Conversely, the exclusion criteria excluded articles publish before 2014, those in the form of books, book chapters, proceeding, newspapers, or other papers, written in languages other than English, or lacking complete text access. These criteria ensured that only resent primary research studies in the English language journal format with full accessibility were analyzed in this review.

Data Collection

Figure 1 illustrates the flow of publications through the different stages of this systematic literature review. The initial identification phase involved a literature search from the Scopus database, yielding a total of 246 articles. After removing data before filtering and identifying zero duplicate articles, these 246 articles were then subjected to the screening and selection phase. During this stage, a total of 221 articles were removed based on predefines exclusion criteria, including being publish before 2014 (n=92), being non-journal articles (n=60), being non-English articles (n=6), and not being in accordance with the research focus (n=63). Ultimately, 25 articles met the inclusion criteria and were included in the final review.

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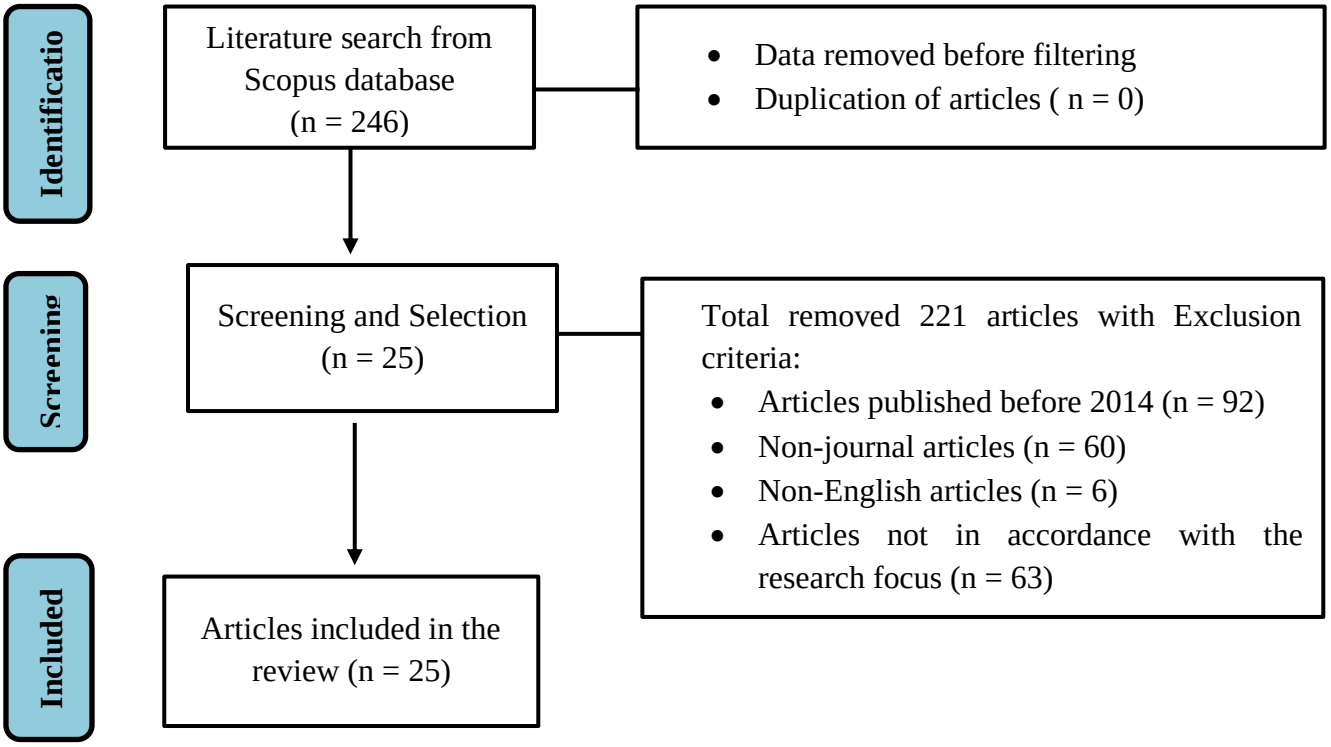

Figur 1. The flow of publications through different stages of the systematic literature review

Data Analysis

Data analysis in this study employed a thematic analysis approach that involves a systematic coding process to identify relevant patterns and themes form the selected literature. Following the screening and selection of articles based on predefined inclusion and exclusion criteria as outlined in Tabel 1 dan Figure 1, each pertinent article underwent in-depth analysis. This process commences with open coding, where significant selections of text were assigned initial, descriptive label or codes. These initial codes were subsequently grouped and further categorized through axial coding to identify relationship between codes and to develop broader theme that represents the key finding across the body of literature.

Subsequently, the development themes were reviewed and interpreted to understand trends, variations and consistencies across studies concerning the impact of microclimate on library collections. This involved manual content analysis to extract specific information such as research methodologies, sample characteristics, HVAC system usage, measurement timeframes and object, as well as the main finding from each article. The synthesis of these themes was then narrated to address the research questions and provide a comprehensive overview of the current understanding regarding the investigated topic as reflected in the existing literature.

Result and Discussion

Results

Journal Distribution Analysis

Table 2. Journal Distribution

No.	Journal	n	Percentage (%)
1	Journal of Cultural Heritage	5	24
2	Energy & Buildings	6	20

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3	Heritage Science	3	12
4	Building and Environment	2	8
5	Applied Science	1	4
6	Aerobiology	1	4
7	CFD Letters	1	4
8	Energy	1	4
9	Microorganisms	1	4
10	Aerosols and Air Quality Research	1	4
11	JARFMTS	1	4
12	Sustainable Cities and Society	1	4
13	J PREV MED HYG	1	4
14	Building Simulation	1	4
15	Journal of Building Engineering	1	4
16	Heritage	1	4

Source: Data analysis 2024

Publications on the topic of microclimate are distributed across various journals, most of the articles were published in journals that focused on cultural heritage preservation and environmental conservation of historic buildings. This shows that microclimate management and library collection preservation have attracted significant attention in research related to the conservation and management of historic buildings.

Journal of Cultural Heritage and Energy & Buildings are the two journals with the highest contribution of articles in this analysis, with 24% and 20% of the total articles respectively. The dominance of the Journal of Cultural Heritage can be explained because the focus of this journal is on the preservation and management of cultural heritage, which is in line with the issue of microclimate in libraries and the preservation of vulnerable collections. Meanwhile, Energy & Buildings plays a role in discussing building management from an energy and environmental perspective, relevant to studies on HVAC and climate control in libraries (Coskun et al., 2024).

The diverse distribution of journals in this study suggests that microclimate topics in libraries require a cross-disciplinary approach. Journals such as the Journal of Cultural Heritage and Energy & Buildings show strong dominance as their broad themes include heritage conservation and energy efficiency in historic buildings, which are in line with the main objectives of this SLR. Meanwhile, contributions from disciplines such as microbiology and environment enrich the research with additional perspectives that can improve the understanding of the determinants of microclimate quality.

These results underscore that planning for microclimate management in libraries should consider findings from multiple disciplines, from HVAC engineering and building architecture to biological and environmental aspects that may affect the storage conditions of collections. This comprehensive and multifaceted approach will provide more comprehensive guidance for achieving a stable, safe, and energy-efficient environment in libraries.

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Country Distribution Analysis

Table 3. Country Distribution

No.	Country	n	Percentage (%)
1	Italy	13	52
2	Malaysia	2	8
3	Austria	2	8
4	Greece	2	8
5	Türkiye	2	8
6	Australia	1	4
7	Poland	1	4
8	Dutch	1	4
9	Argentina	1	4

Source: Data analysis 2024

Most articles come from research conducted in European countries, with a clear dominance by Italy. The analysis shows that countries with a rich cultural heritage and many historical buildings, such as Italy and Austria, have a great interest in research on microclimate management in libraries. The focus of this research is mainly on the preservation of valuable collections that are sensitive to microclimate changes.

Italy ranked highest with a contribution of around 44% of the total articles. This indicates that Italy, as a country with many historical libraries and valuable cultural heritage collections, has a great concern for the aspect of microclimate preservation. Various studies from Italy explore the use of HVAC systems, microclimate monitoring techniques, and humidity control to maintain safe conditions for sensitive library collections. (Moretti et al., 2024; Verticchio et al., 2021). This significant interest is also in line with the large number of cultural sites and historical libraries in Italy that require technology-based conservation solutions for long-term protection.

The country distribution in this article shows that countries with rich cultural history and historical buildings, such as Italy and Austria, are leading the research on microclimate management in libraries. This research is not only relevant for the preservation of national cultural heritage but also enriches global knowledge on the best strategies for the conservation of sensitive library collections. In tropical countries such as Malaysia, research is more focused on addressing local climate challenges, such as high temperatures and extreme humidity, which require different approaches from countries in temperate or cold climates.

This varied distribution also underlines that library microclimate research requires an approach tailored to each country's local climate, challenges, and needs. Studies conducted in these regions enrich the perspective on best practices that can be adapted in microclimate contexts, both for temperate environments such as Europe and tropical environments such as Southeast Asia.

Discussion

In library management, a stable microclimate is essential to protect valuable collections

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such as books and manuscripts from physical and biological damage. Based on the analysis of 25 reviewed articles, this finding formulates standard procedures for managing microclimate in libraries. These procedures include measuring, monitoring, and controlling temperature and humidity, as well as strategies for saving energy and using renewable energy to maintain optimal conditions in the library.

Preparation in Microclimate Management

In microclimate management in libraries, careful initial preparation is essential to protect valuable collections from degradation. The first preparatory step involves identifying critical areas that are susceptible to microclimate fluctuations, such as storage rooms, reading rooms, and areas exposed to direct sunlight or natural ventilation. These areas usually experience higher temperature and humidity fluctuations that can potentially damage sensitive materials such as paper and leather (Fabbri & Pretelli, 2014). Areas with direct sunlight are prioritized because UV radiation accelerates paper degradation, leading to yellowing and embrittlement. Therefore, monitoring these points plays an important role in maintaining the stability of the overall environmental conditions.

Selecting the right measuring device is a key factor in ensuring the accuracy and reliability of microclimate data. Most studies recommend the use of dataloggers for continuous temperature and humidity monitoring. The recommended dataloggers have high precision, with an accuracy of ±0.35°C for temperature and ±2.5% RH for humidity (Coskun et al., 2024; Moretti et al., 2024). These data loggers can record changes in temperature and humidity over a specified time span, helping to detect small fluctuations that can have a major impact on long-term microclimate conditions.

Measuring instruments that are often used in microclimate management studies in libraries such as HOBO UX100-003 this device can monitor temperature and humidity continuously with very high accuracy. This device is used in many studies to monitor temperature and humidity with a measurement interval of every 15 minutes, making it suitable for detecting microclimate changes that occur in real-time. (Schito et al., 2019). Testo 175 H1 model features high-precision measurements and a large enough memory to store long-term data. This instrument can be used for continuous monitoring at close intervals. Rotronic HygroLog HL-20 is used to monitor temperature, humidity and dew point with a high degree of accuracy and is equipped with a computer interface for further data analysis. it has been used in many historical libraries that require accurate data for microclimate management (Verticchio et al., 2021). Eltek RX250AL datalogger has advantages of long-term data storage and stable accuracy for temperature and humidity monitoring. It is often installed in libraries that require strict humidity management and biological risk monitoring.

Installation of Measuring Instruments

The installation of temperature and humidity measuring devices must follow strict procedures to ensure that the data produced is accurate and representative of the microclimate conditions in the library. This includes selecting a strategic location and avoiding areas that can cause data distortion, such as being too close to heat sources or ventilation.

Research shows that the measuring device should be installed at a height of 1.2 to 1.8 meters from the floor. This height is considered ideal because it is in a zone that reflects room conditions more accurately and can represent the environmental conditions where the collection is stored (Balocco et al., 2014; Verticchio et al., 2022). This height setting also ensures that the measurement results are not too influenced by external factors such as heat radiating from the floor or cold from the ceiling.

Ensuring that the measuring devices are not exposed to direct sunlight or near

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mechanical ventilation is an important step in installation. Direct sunlight can increase the meter's temperature unnaturally, causing the measurement results to be higher than the actual conditions. In addition, mechanical ventilation, such as fans or HVAC vents, can affect local humidity and produce biased data. For this reason, it is recommended to install the meter in a shaded location and not too close to major air circulation points (Ceres et al., 2024).

Placing measuring devices in different areas is also important to provide a comprehensive picture of the microclimate variations in the library. Storage Room has more stable climate conditions because it is not frequently accessed. However, measuring devices should be placed at several points in the storage room, such as near the door, in the middle of the room, and between shelves. It can help detect climate fluctuations that may occur when the door is opened or closed (Schito et al., 2019). Monitoring climate conditions in the reading rooms is important because air circulation and human activity are higher in this rooms to ensure visitor comfort while protecting collections from the impacts of increased temperature and humidity due to visitor activity (Andretta et al., 2016). Position the meter at a safe distance from areas near windows or spaces frequently exposed to direct sunlight, particularly in locations where windows are challenging to close. This setup facilitates precise monitoring of the impact of sunlight on surrounding temperatures. The information gathered can guide decisions on implementing additional protective measures, such as installing blinds or applying heat-blocking films, to ensure a stable microclimate and safeguard sensitive materials (Drougka et al., 2020). Avoid placing measuring devices close to ventilation or HVAC systems. To ensure accurate data collection, the devices should be positioned at a sufficient distance from the vents. This placement helps prevent distortion of measurements and allows for a clear understanding of how the HVAC system impacts the room's microclimate, including temperature and humidity levels (Coskun et al., 2024).

Measurement and Monitoring

Continuous measurement and monitoring of microclimate conditions in libraries is essential to ensure the stability of an ideal environment for the preservation of collections. The use of data loggers with short measurement intervals, i.e. every 15 to 30 minutes, is highly recommended. This continuous monitoring allows libraries to detect small changes that can have a significant impact on the condition of collections, especially in collections that are vulnerable to temperature and humidity fluctuations (Derksen et al., 2024; Diulio et al., 2019; Drougka et al., 2020).

Research suggests that to maintain the stability of micro conditions in libraries, the ideal daily fluctuation tolerance is ±1°C for temperature and ±5% for relative humidity (RH).(Khean et al., 2023; Kompatscher et al., 2019; Kupczak et al., 2018). These tolerance limits are important because significant differences in temperature and humidity can cause physical damage to paper, including structural weakness and material weathering. For example, too high a temperature can accelerate the hydrolysis process in paper, while excessive humidity can cause organic matter to become brittle or damp , increasing the risk of the growth of damaging microorganisms (Moretti et al., 2024).

Continuous monitoring plays a vital role in detecting biological risks such as mold growth or insect infestation. High humidity conditions above 65% RH, especially in areas with inadequate ventilation, can create an environment conducive to the growth of harmful microorganisms. Microorganisms such as Aspergillus and Penicillium fungi can thrive in humid environments and can lead to the degradation of organic matter in historical books or documents (Schito et al., 2019). Evidence suggests that excessive humidity can increase the risk of biological damage in libraries without adequate climate control. (Derksen et al., 2024).

Thermohydrometer and microbiological monitoring are also important to anticipate

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risks associated with biodeterioration. Research shows that the combination of monitoring temperature, humidity, and airborne microorganisms can provide a more comprehensive understanding of the library environment. With this monitoring, libraries can detect changes in microorganism levels before they reach dangerous levels. For example, research by Pasquarella et al. emphasized the importance of conducting regular air and surface sampling to detect potentially damaging bacteria and fungi (Pasquarella et al., 2020). This microbiological monitoring, especially in areas with high humidity, allows libraries to take preventive measures such as increasing ventilation or reducing environmental humidity more quickly.

Integration of data from multiple measuring devices is also essential to monitor and understand microclimate fluctuation patterns in libraries. Library conditions can be monitored in real-time with the help of software, and data can be stored and analyzed which can be useful for decision making. (Drougka et al., 2020; Verticchio et al., 2021, 2022). This long-term analysis provides better insight into possible fluctuation patterns in the library microclimate and helping librarians manage environmental risks more effectively (Ceres et al., 2024).

HVAC and Ventilation System Control

Heating, Ventilation, and Air Conditioning (HVAC) system equipped with automatic sensors is a fundamental step in managing and maintaining stable temperature and humidity in the library. Research shows that the optimal temperature for a valuable collection storage room ranges from 18–22°C, with an ideal relative humidity between 45–60%. This condition has been proven effective in slowing down the degradation process of paper materials and preventing the risk of damage due to uncontrolled environmental fluctuations (Coskun et al., 2024; Moretti et al., 2021). In addition, an efficiently regulated HVAC system can optimize energy use through adaptive settings, namely adjusting work intensity based on the actual needs of the room, thereby reducing energy waste and operational costs (Tronchin & Fabbri, 2017).

Automatic sensors in the HVAC system serve as a continuous monitoring component to ensure that microclimate conditions remain consistent. These sensors are able to detect small changes in temperature and humidity that may occur due to internal or external factors and activate the HVAC system to adjust in real-time. Thus, the HVAC system can operate only at the capacity needed, preventing overheating or overcooling that can have a negative impact on the collection. This technology is very useful, especially in libraries with historical collections vulnerable to environmental damage (Schito et al., 2019).

Some libraries rely on natural ventilation as a complementary method to control the microclimate, especially in historic buildings that may have structural limitations for installing a full HVAC system. Natural ventilation allows for good airflow and can help lower temperatures at certain times, reducing reliance on HVAC and, in turn, saving energy. However, natural ventilation must be carefully monitored to avoid causing extreme fluctuations in temperature and humidity, which can damage sensitive collections (Fabbri & Pretelli, 2014).

Humidity control through natural ventilation should be integrated with an automatic sensor system to monitor the humidity level in the room. This is important to prevent excess humidity that can lead to biological risks, such as mold and microbial growth, which threaten the sustainability of library collections. Research by Derksen et al. showed that uncontrolled humidity above 65% can encourage the proliferation of microorganisms, which is very detrimental to organic materials such as paper (Derksen et al., 2024). Therefore, libraries that use natural ventilation as part of their microclimate strategy need to equip them with automatic humidity sensors to ensure that humidity fluctuations remain within safe limits.

Energy efficiency is one of the important aspects of managing the microclimate in the library, especially in the use of HVAC systems that play a major role in maintaining temperature and humidity stability. Adaptive HVAC systems have been shown to reduce energy

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consumption by adjusting the workload according to the real-time environmental needs in the library. Thus, this system only works at the required capacity, so there is no energy waste (Tronchin & Fabbri, 2017).

Microclimate Simulation and Modeling

Microclimate simulation and modelling are very effective tools in optimizing environmental management systems in libraries, especially in historic buildings that require strict structural and aesthetic protection. Simulation methods, such as Computational Fluid Dynamics (CFD) and Building Energy Simulation (BES), are recommended to comprehensively understand and predict microclimate conditions before installation or renovation of climate management systems. This approach allows the design of HVAC systems that are more suited to the environment's specific needs in libraries, especially in historical buildings, taking into account the influence of natural or mechanical ventilation (Balocco et al., 2014).

CFD simulations, for example, provide a detailed analysis of the distribution of temperature, humidity, and air movement throughout the library. With these simulations, managers can monitor the effectiveness of natural ventilation and predict optimal airflow patterns. CFD simulations are particularly useful in maintaining microclimate stability, as they can provide high-precision data without requiring physical modifications to the building, which is essential for preserving the structural integrity of historic buildings (Balocco et al., 2014).

Modeling also plays an important role in evaluating the impact of renewable energy, such as the use of solar panels or energy-efficient ventilation, on the library microclimate. Libraries with renewable energy sources supported by CFD and BES models tend to have better control over the microclimate. BES models, in particular, are used to assess energy needs and project HVAC system loads based on external climate data and space use patterns within the library (Coskun et al., 2024; Tronchin & Fabbri, 2017).

In addition to optimizing energy efficiency, this modelling also serves as a strategic tool in maintaining the sustainability of library collections. By predicting microclimate changes due to ventilation or energy fluctuations, managers can take more effective preventive measures to protect collections from the threat of physical and biological degradation that can be caused by environmental instability (Coskun et al., 2024).

Risk Evaluation and Routine Maintenance

Maintenance of HVAC systems are crucial aspects of library microclimate management, which aims to maintain optimal environmental conditions for the conservation of collections. Routinely evaluating temperature and humidity data, at least monthly, allows libraries to identify and respond to fluctuations or trends in environmental conditions. When data shows significant fluctuations, the HVAC system may need to be recalibrated to restore stability, or additional humidity control systems may need to be installed to enhance collection protection (Andretta et al., 2016). In this way, libraries can address potential problems before they become risks that threaten the preservation of sensitive materials, such as manuscripts and historical documents.

Routine monitoring for biological risks, such as mold growth and insect infestation, is also essential in library environments, especially in areas where humidity is difficult to control. High and fluctuating humidity can create conditions conducive to the growth of potentially damaging microorganisms, such as Aspergillus and Penicillium, which are known to cause the deterioration of paper and other organic materials (Schito et al., 2019). If there is any indication of biological contamination, preventive measures, such as special cleaning and dehumidification, should be taken immediately to prevent further spread. Some studies also recommend the use of pesticides and regular management to prevent insect infestation, which can physically damage collections and reduce their

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aesthetic value (Kompatscher et al., 2019)

Conclusion

In conclusion, this study underscores that effective microclimate management in libraries necessitates a holistic and integrative approach, encompassing the strategic implementation of HVAC technology, optimized ventilation strategies, and the consistent application of monitoring technologies to ensure the long-term preservation of valuable collections. The integration of automated control systems alongside natural ventilation techniques has demonstrated efficacy in maintaining stable temperature and humidity levels, which is paramount in mitigating both physical and biological deterioration of library holdings. Furthermore, an adaptive strategy that carefully considers local environmental conditions and the unique characteristic of each library is essential for achieving optimal preservation outcomes.

The findings of this review also highlight the critical role of training and capacity for librarians and library managers in comprehending and effectively managing microclimate control technologies. A thorough understanding of HVAC system and monitoring techniques empowers libraries to proactively maintain microclimate stability and minimize the risk of damage to their collections. While this review offers a framework for developing comprehensive microclimate management plans, emphasizing the integration of technology, regular monitoring, and locally adapted strategies, it acknowledges the limitation of relying predominantly on simulations and theoretical models within the analyzed literature. Consequently, future research should prioritize empirical evaluations of these strategies in a diver's real-world library setting to generate more relevant and broadly applicable findings. Moreover, further interdisciplinary research is warranted to investigate the long-term impact of microclimate on library collections, synergizing insights from environmental science, engineering, and conservation to ensure the enduring accessibility of cultural heritage materials for future generations.

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Authors' Contributions

All authors have contributed to the final manuscript. The contribution of all authors: conceptualization, methodology, formal analysis, writing original draft preparation, writing review, and editing. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

All authors have no conflict of interest related to this study.

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