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A REVIEW OF THERMAL COMFORT ASSESSMENT METHODS IN HERITAGE BUILDINGS

Biondy Dwiki Ibnu Wardana[1], Dr. Ir. Erlina Laksmiani Wahjutami[1*] and Nurul Aini[1]
[1]Post-Graduate Student in Magister of Architecture at Merdeka University, Malang, Indonesia
*Corresponding author: erlina.laksmiani@unmer.ac.id

Abstract.

Heritage buildings are architectural structures renowned for their historical, cultural, social, or architectural significance, often preserved due to their association with pivotal historical events, distinctive architectural styles, influential figures, or enduring cultural traditions. Beyond these attributes, heritage buildings are also recognized for their ability to provide effective thermal comfort to its occupants through passive cooling strategies. This capability reflects centuries of learning and adaptation, with these buildings designed to harmonize with their surrounding environment to ensure optimal comfort for their users. The unique thermal characteristics of heritage buildings have garnered significant interest from researchers, prompting numerous studies on their thermal performance. This article reviews journal articles that investigate thermal comfort in heritage buildings globally. The articles were identified through searches on platforms such as Google Scholar, Mendeley, and Publish or Perish, followed by a selection process that resulted in 40 articles being included in the review. The primary aim of this review is to identify the thermal comfort assessment methods commonly employed in research on heritage buildings and to examine the correlation between these methods and the types of studies conducted. By systematically categorizing and analyzing the methodologies used in the reviewed articles, this study offers a comparative evaluation of their relevance and effectiveness in the context of heritage buildings. Moreover, it seeks to understand how different assessment approaches align with specific research objectives and environmental contexts, thereby providing insights into the suitability of each method for various research frameworks. The findings indicate that four primary methods are employed in the reviewed journal articles: literature reviews, physical surveys and measurements, questionnaire surveys, and computer simulations. Among these, physical surveys and measurements are the most frequently used, appearing in 31 articles, followed by computer simulations in 25 articles, questionnaires in 15 articles, and literature reviews in 7 articles. In some cases, these methods are used exclusively, while in others, they are applied simultaneously in the same research.

Keywords: Assessment, Building, Heritage, Method, Thermal Comfort

1. Introduction

1.1. Background

Thermal comfort is defined as the condition of mind in which a person feels satisfied with the thermal environment. According to Fanger (1970), thermal comfort is influenced by six primary factors: air temperature, radiant temperature, humidity, air movement, clothing insulation, and metabolic rate (Fanger, 1970). Organizations such as the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) provide standards for evaluating thermal comfort. ASHRAE Standard 55 specifies that thermal comfort is achieved when environmental conditions meet the expectations of at least 80% of occupants in a given

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space. Similarly, the International Organization for Standardization (ISO 7730) aligns with ASHRAE guidelines, emphasizing the importance of Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) as indicators of comfort levels (ASHRAE-55, 2017). In tropical climates, additional considerations such as natural ventilation and solar radiation significantly influence the achievement of thermal comfort, particularly in buildings designed to maximize passive strategies (Lippsmeier, 1994). Thus, understanding thermal comfort is fundamental in evaluating the performance of buildings, including heritage structures.

The true thermal behavior of building components affects architectural design; this behavior is dependent on exposure effects, orientation, surface features, and the location's climate conditions in addition to the component's steady and periodic thermal characteristics (Noori & Hameed, 2011). This can be seen in heritage buildings which are a learning process over centuries to create a building that is able to adapt to the surrounding environment so that it can provide a sense of comfort to its users. Heritage buildings are defined as structures of historical, cultural, or architectural significance that reflect the values and identities of past civilizations (ICOMOS, 2011). These buildings often incorporate traditional construction methods and materials, which are inherently adapted to local climates and environmental conditions. For instance, many heritage buildings in tropical climates utilize passive design strategies such as natural ventilation, shading, and thermal mass to regulate indoor temperatures and provide thermal comfort (Coch, 1998). The thick walls, high ceilings, and strategic placement of openings in heritage buildings play a critical role in reducing heat gain and enhancing airflow. Studies have shown that these design elements can perform efficiently even without modern HVAC systems, highlighting their potential to meet contemporary thermal comfort standards while preserving their architectural heritage (Martinez-Molina et al., 2022). However, the capability of heritage buildings to provide thermal comfort can be challenged by factors such as climate change, urbanization, and a lack of maintenance, necessitating detailed investigations into their thermal performance.

Numerous studies have explored the architectural and cultural significance of heritage buildings, as well as their adaptation to local environmental conditions. For instance, Yang et al. (2022) evaluated the thermal comfort of historic blocks in Beijing, highlighting the role of microclimate measurements and occupant perceptions (Yang et al., 2022). Similarly, Jin and Zhang (2021) conducted comprehensive assessments of indoor environments in traditional stilt houses in China, emphasizing thermal comfort and natural ventilation (Jin & Zhang, 2021). While these studies provide valuable insights, systematic reviews of thermal comfort research in heritage buildings remain limited. Most existing reviews focus either on the conservation of heritage structures or on broader sustainable building practices, leaving a gap in understanding the specific thermal performance of heritage buildings (Martinez-Molina et al., 2022). This lack of comprehensive reviews on thermal comfort in heritage buildings highlights the need for further research to consolidate findings from various studies and identify key parameters influencing comfort in these structures. A focused review would provide a clearer understanding of the thermal behavior of heritage buildings, their strengths, and areas requiring intervention to align with contemporary comfort standards.

The objective of this review is to identify the thermal comfort assessment methods commonly applied in research articles focused on heritage buildings and to examine the correlation between the chosen assessment methods and the types of studies conducted. This review seeks to systematically categorize and analyze the methodologies utilized across various scholarly articles, providing a comparative evaluation of their relevance and effectiveness in

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heritage contexts. Additionally, the study aims to understand how different assessment approaches align with specific research objectives and environments, thereby offering insights into the suitability of each method for different research frameworks. Through this analysis, the research intends to guide future studies in selecting appropriate assessment techniques to enhance the thermal comfort of heritage buildings.literature review.

1.2. Method

This study is a review aimed at analyzing methods for assessing thermal comfort in indoor and outdoor environments based on existing literature. The research process involves several stages, including article search, selection, and critical analysis of relevant studies. The following steps were taken during the research:

1.2.1. Literature Search

The search for articles was conducted using two major platforms: Google Scholar and Publish or Perish. These platforms were chosen due to their extensive reach and their ability to provide access to a wide range of scholarly journals related to thermal comfort. The keywords used in the search included "thermal comfort," "indoor environment," "outdoor environment," "thermal assessment methods," and other variations relevant to thermal comfort in both indoor and outdoor settings. The search focused on articles published within the last ten years to ensure the relevance of the data analyzed with recent developments in research.

1.2.2. Article Selection

From the initial search, approximately 100 articles relevant to the research topic were identified. The selection process continued by applying specific inclusion and exclusion criteria to filter the most relevant articles:

Inclusion Criteria:

1. Articles that focus on the assessment of thermal comfort in indoor and/or outdoor environments.
2. Articles that provide detailed thermal assessment methods applicable to various building types or environments.
3. Articles that use empirical data or validated simulation models.

4. Exclusion Criteria:
5. Articles not relevant to the topic of thermal comfort or lacking specific assessment methods.
6. Articles with restricted access that could not be fully analyzed.

After the selection process, 40 journal articles that met the criteria were chosen as the main focus of this review.

2. Research Locations

In this article, 40 journal articles about thermal comfort in heritage buildings from 2016 to 2023 are reviewed and analyzed. Each journal article contains different research of thermal comfort in different type of buildings and countries. The studies in these journal articles were conducted across 23 countries, spanning various regions around the world, including East Asia, West Asia, Western Europe, Southern Europe, North Africa, East Africa, North America, and South America. These countries include China, Egypt, Spain, Saudi Arabia, India, Italy,

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Sweden, Algeria, Argentina, Cyprus, France, Indonesia, Iran, Jordan, Malaysia, Mexico, Poland, Portugal, South Korea, Tanzania, Turkey, the USA, and one study reviewing articles across multiple countries (Martínez-Molina et al., 2016). The number of journal articles varies by country, with the highest number found in China with 6 journal articles (He & Isa, 2024; Jin & Zhang, 2021; Xiaohui et al., 2019; Yang et al., 2022; J. Zhang et al., 2023; Q. Zhang et al., 2021), followed by 5 in Egypt (Ahmad et al., 2021; Alsaid et al., 2023; Ibrahim et al., 2021; Khalil et al., 2018; Taher et al., 2019) dan Spain (Blázquez et al., 2019; Caro & Sendra, 2021; Martinez-Molina et al., 2018; Onecha & Dotor, 2021; Sáez-Pérez et al., 2023), 3 in Saudi Arabia (Al-Sakkaf et al., 2021; Alwetaishi, 2022; Mohamed et al., 2019), 2 in India (Kushwah et al., 2020; Verma et al., 2022), Italy (Balocco & Colaianni, 2018; Palka Bayard de Volo et al., 2023), and Sweden (Abdul Hamid et al., 2020; Bakhtiari et al., 2020), and 1 journal article each from Algeria (Khledj & Bencheikh, 2021), Argentina & France (Requena-Ruiz, 2016), Cyprus (Thravalou et al., 2018), Indonesia (Prabowo, 2020), Iran (Mangeli et al., 2023), Jordan (Zoubi & Almalkawi Amal Th., 2019), Malaysia (Yusoff & Ja'afar, 2019), Mexico (Murillo et al., 2021), Poland (Fedorczak-Cisak et al., 2022), Portugal (Gomes et al., 2021), South Korea (Jo et al., 2023), Tanzania (Liu et al., 2022), Turkey (Diler et al., 2021), and USA (Martinez-Molina et al., 2022). The diversity in research locations within these journal articles offers a detailed perspective on the variations in research methods employed in places with different climate conditions.

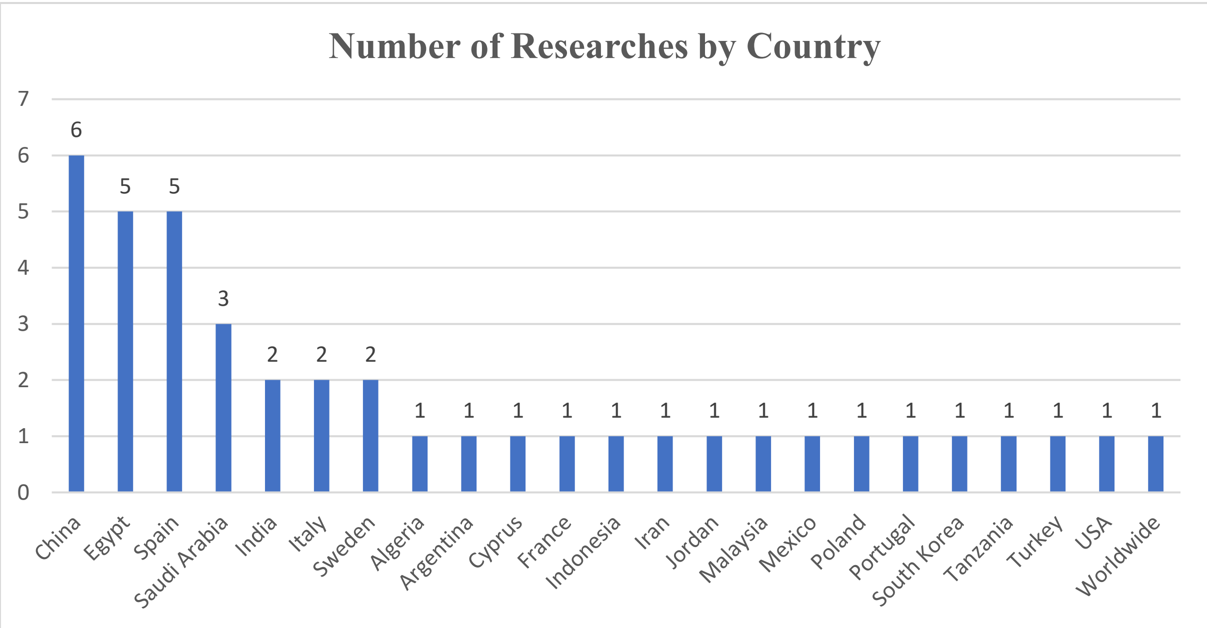

Figure 1. Number of researches by country

3. Type of Building Researched

The review also reveal a diversity in the types of building objects studied. Building variations are based on function, consisting of 17 residential buildings, followed by 5 religious buildings, 4 educational buildings, 4 villas, 3 office buildings, 2 palaces, 2 monumental buildings, 2 hospital buildings, and 1 museum, as well as one journal article that examines various building types. Furthermore, the number of objects in each building type can be further broken down by

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the country of study location. Of the 17 residential buildings, there are 5 in China, 3 in Egypt, 2 in Spain, and one each in India, Cyprus, Jordan, Mexico, and Tanzania. Among the 5 educational buildings, there is one each in Indonesia, Malaysia, Spain, Turkey, and the USA. Four educational buildings are located in Egypt, Italy, Algeria, and South Korea, with one building in each country. The four villas are situated in Egypt, Argentina, France, and Poland. The two palaces are in Saudi Arabia, two monumental buildings are in China and India, two hospital buildings are in Spain and Portugal, and one museum is located in Spain. Each building type studied in the reviewed journal articles has unique characteristics, adding further depth to the article review results in this paper.

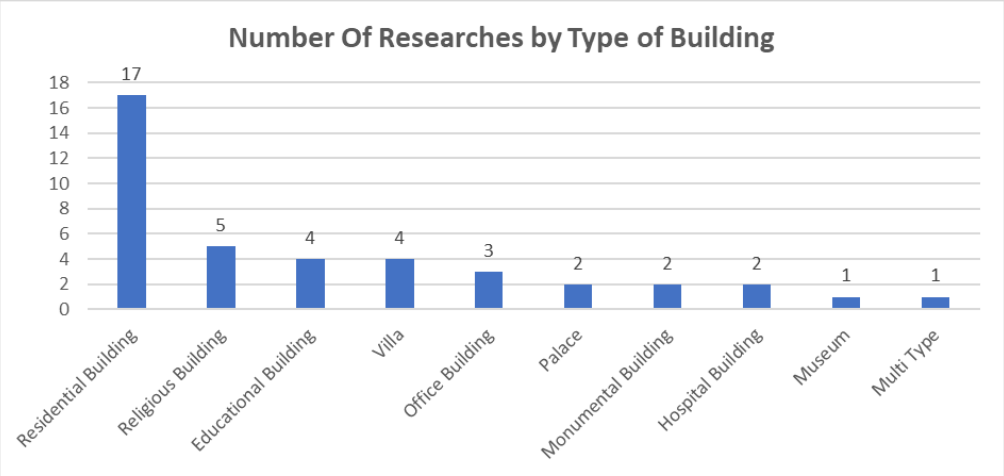

Figure 2. Number of researches by type of building.

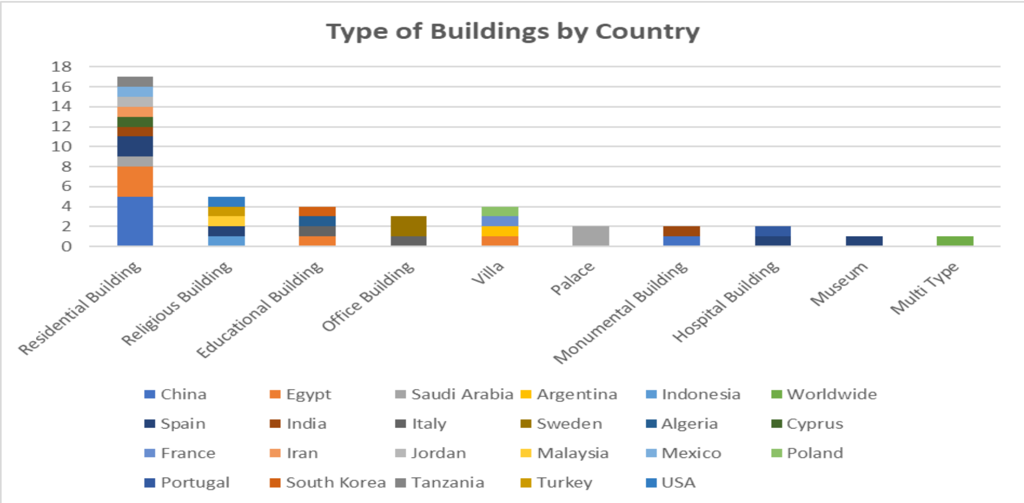

Figure 3. Type of building by country.

4. Type of Researches

After identifying the research locations and building types, the types of research were also identified to understand their correlation with the research methods used in these journal articles. Four types of research were identified: evaluative research, experimental research,

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article review, and comparative research. Evaluative research is the most frequently conducted type in these journal articles, accounting for 23 out of 40 articles. In evaluative research, the thermal comfort of the research objects is measured to determine whether the existing building conditions can provide good thermal comfort within the space. The results of this research can also serve as recommendations for strategies to improve thermal comfort in the building. The next research type is experimental research, covering 9 out of 40 articles. In experimental research, in addition to evaluating thermal comfort, strategies to enhance thermal comfort, such as retrofitting or vegetation patterns, are also applied to the research object through model simulations, resulting in concrete solutions for improving thermal comfort. The next type of research identified in this paper is comparative research, which includes 6 out of 40 articles. Comparative research is conducted to compare the thermal comfort performance of heritage buildings with modern buildings. Research is also conducted to compare two architectural works with similar building types. The last type of research is research review. This type of research is conducted by reviewing existing research journal articles. Generally, this research is carried out on large geographic areas where direct measurement is not feasible, such as a 2023 study examining the thermal comfort of rural homes across China (J. Zhang et al., 2023), and a 2016 study investigating thermal comfort in historic buildings worldwide (Martínez-Molina et al., 2016). The correlation of these four types of research with the research methods used in the reviewed articles will be further examined to draw conclusions regarding the appropriate methods to be applied based on the type of thermal comfort research on historic buildings to be conducted.

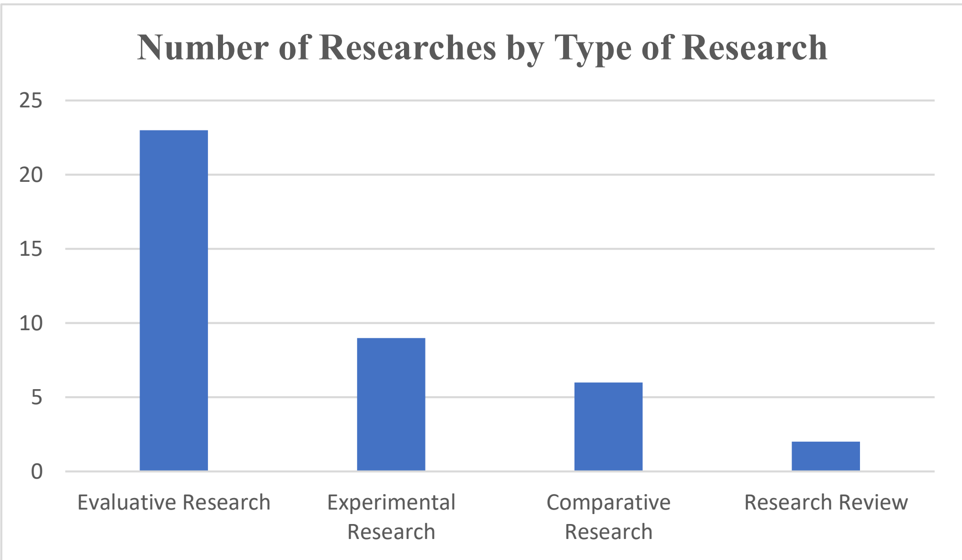

Figure 4. Number of researches by type of research.

5. Research Methods

In general, 4 methods of thermal comfort assessment used in 40 articles that we reviewed. The 4 methods are literature studies, physical surveys and measurements, questionnaire surveys, and computer simulations. The review shows that physical survey and measurement is the most used method in these journal articles where 31 articles use this method, followed by computer simulation with 25 articles, questionnaire with 15 articles, and literature review with

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7 articles. Some of these methods used exclusively or simultaneously with other methods in one research.

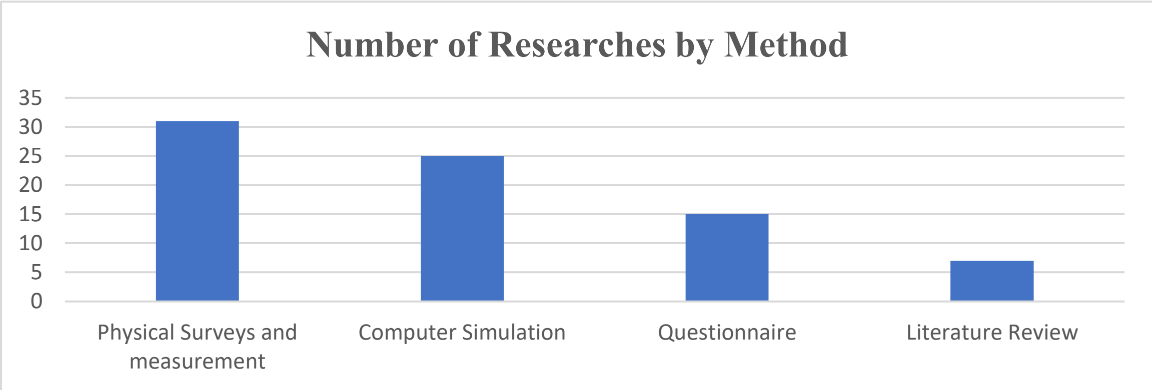

Figure 5. Number of researches by method.

5.1. Literature Review

The literature review method is a systematic approach to collecting, analyzing, and synthesizing existing research on a particular topic. This method is used in research that has objects with a wide scope, making it impossible to make direct observations. Literature review is a critical research methodology that synthesizes existing knowledge, identifies gaps, and provides a structured approach to understanding a specific research area (Snyder, 2019). It is essential for advancing academic research and theory development.

In total, there are 7 articles that used this method for their research. Based on the types of buildings studied, there are three studies focusing on residential buildings that utilize this method, followed by studies on religious buildings, villas, and palaces, with one study each. Furthermore, this method has been applied in research conducted in six countries, including two studies in China and one study each in Egypt, Saudi Arabia, Argentina, Indonesia, and globally. The review findings also indicate that this method has been employed in experimental research, evaluative research, and research reviews, with two articles for each type of research, and one article in comparative research. These findings highlight the versatility and broad applicability of this method across diverse building types, geographical contexts, and research approaches.

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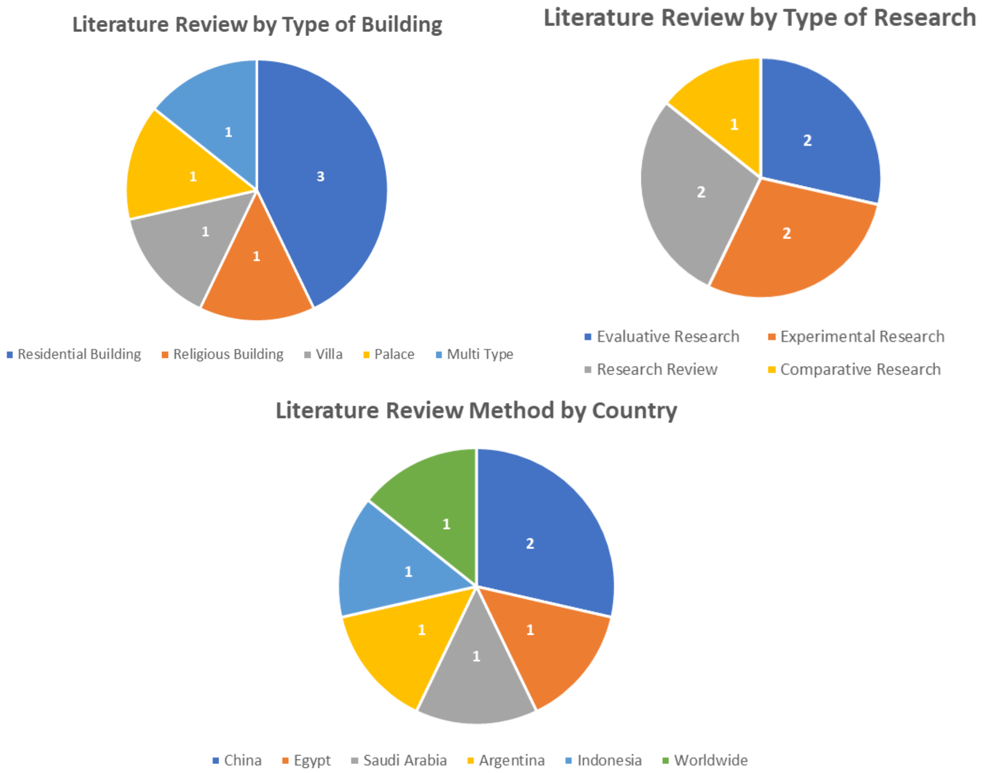

Figure 6. Literature review by type of building, type of research, and country.

5.1.1. Literature Review Method Usage in Articles

The journal article that used this method is “Thermal Comfort Investigation of Rural Houses in China: A Review” (J. Zhang et al., 2023). In this research, the researchers conducted a comprehensive search of relevant papers using three main databases: Google Scholar, Web of Science, and China National Knowledge Infrastructure (CNKI). They used specific keywords related to thermal comfort in rural houses to gather relevant publications. The initial list of papers was screened based on the research topic, and the selected papers were stored in a research database. By using this method, the researcher categorizing and reviewing the literature based on climate zones and thermal comfort approaches. The researchers analyzed the similarities and differences among the studies and identified common themes and findings. They also examined the limitations of existing thermal comfort standards and the influence of other factors, such as wind speed, humidity, and building construction, on thermal comfort research in rural areas. The method allowed the researchers to summarize the state of thermal comfort field investigations in rural houses in China, identify research gaps, and provide recommendations for further research in this area. Another research that used this method is “Effect of Thermal Insulation on Building Thermal Comfort and Energy Consumption in Egypt” (Morsy et al., 2018). In this research, the researchers conducted a literature review to gather information on thermal comfort models, energy consumption, and thermal insulation materials. This step helped them understand the existing knowledge and theories related to the topic.

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5.2. Physical Surveys and Measurments

The Physical Survey & Measurement method is a technique involving the direct collection of data from a platform anchored to the surface. This approach provides accurate and reliable data, supporting a wide range of applications in architectural research, particularly in thermal assessment studies. A total of 31 articles have utilized this method in their research. Regarding the types of buildings examined, 14 studies focused on residential buildings, followed by 5 studies on religious buildings, 3 on villas, 2 each on educational buildings and hospitals, and 1 study each on palaces, monumental buildings, and museums. Geographically, this method has been applied in research conducted across 21 countries, including five studies in Spain, three in Egypt, two each in China, Saudi Arabia, India, and Sweden, and one study each in Argentina, Indonesia, Italy, Algeria, Cyprus, Iran, Jordan, Malaysia, Mexico, Poland, Portugal, South Korea, Tanzania, Turkey, and the United States. The review also reveals that this method has been predominantly employed in evaluative research, with 20 articles, followed by comparative research with 6 articles, and experimental research with 5 articles. These findings emphasize the widespread adoption and adaptability of the Physical Survey & Measurement method in addressing diverse research needs across various building types and global contexts.

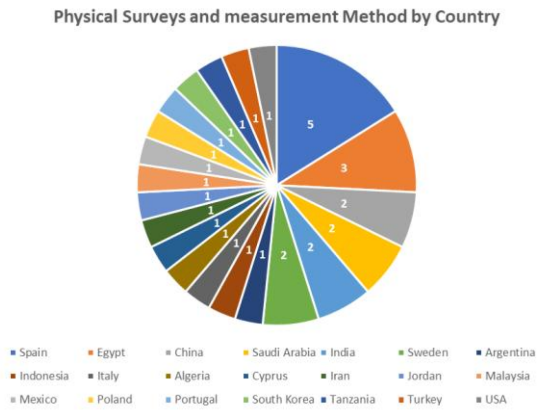
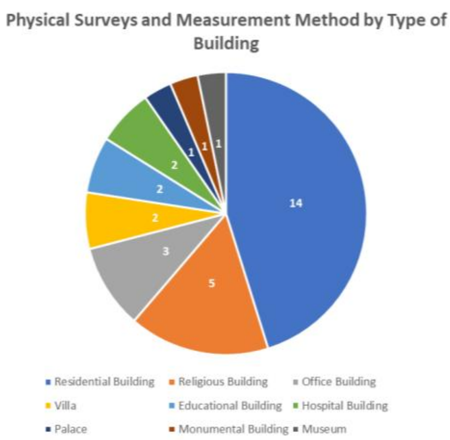


Figure 7. Physical survey and measurement method by country.



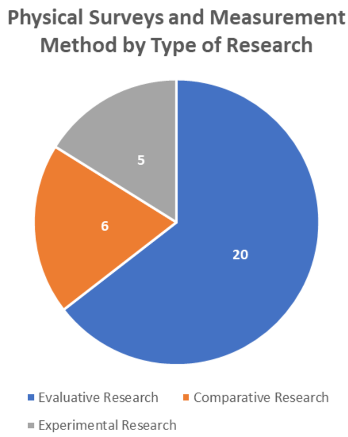


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Figure 8. Physical survey and measurement method by type of building and type of research.

5.2.1. Stages of the Site Survey and Measurement Method

There are two stages involved in applying this method in research. These stages are critical steps that must be undertaken to ensure the collection of accurate and detailed data, thereby enhancing the reliability and accountability of the research findings. Moreover, these stages contribute to the novelty of the research, enabling it to make a significant contribution to the field of architecture, particularly in the context of thermal comfort in heritage buildings. The stages to be carried out are data selection planning and field measurements.

1. **Data Collection Planning**
   - Selection of Monitoring Sites: Identifying representative rooms or areas within the heritage building that reflect typical conditions for assessment.
   - Environmental Monitoring Setup: Placing data loggers or other instruments to capture critical variables, such as temperature, humidity, and airflow, at specific intervals and heights to avoid direct sunlight interference. Additionally, an outdoor weather station may be installed to collect simultaneous outdoor data to adjust for seasonal variations.
2. **Field Measurements**
   - Instrument Calibration and Data Logging: Deploying calibrated instruments (e.g., temperature and humidity sensors, anemometers) to record real-time indoor environmental parameters.
   - Weather Data Collection: Using on-site weather stations to gather outdoor parameters like wind speed, temperature, and pressure, which are critical in calibrating energy models and assessing how outdoor conditions impact indoor comfort levels.

Furthermore, in studies utilizing the site survey and measurement method, several key variables influencing thermal comfort are examined to assess the thermal comfort conditions of the buildings under investigation. These variables include:

1. **Thermal comfort parameters**
   Indoor temperature, relative humidity, and CO2 levels.
2. **Energy efficiency indicators**:
   Energy use patterns and insulation effectiveness.
3. **Occupant comfort metrics**
   Predicted Mean Vote (PMV) and actual feedback on comfort satisfaction.
4. **Environmental performance factors**
   Airflow, light exposure, and acoustic quality

5.2.2. Site Survey and Measurement Method Usage in Articles

The first article that applied this method for its research is “An Appraisal of Vernacular Architecture of Bikaner: Climatic Responsiveness and Thermal Comfort of Havelis” (Verma et al., 2022), The researchers conducted a physical survey of the study area to identify contextual issues and settings, specifically focusing on vernacular havelis and old houses in Bikaner. The survey aimed to understand the typology, architectural style, construction techniques, and

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materials used in these traditional buildings. To evaluate the climatic responsiveness and thermal comfort of the vernacular havelis and contemporary houses, the researchers measured temperature, relative humidity, mean radiant temperature (MRT), and air velocity outside the buildings and in different indoor spaces. These measurements were taken every three hours during extreme climatic conditions, specifically on June 21st and 22nd, and December 21st. The study reveals that the vernacular haveli (VH1), with its heavy construction, small openings, and central courtyard, offers superior thermal comfort compared to the contemporary house (CH1), as evidenced by lower predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) values, indicating enhanced occupant comfort in both summer and winter conditions.

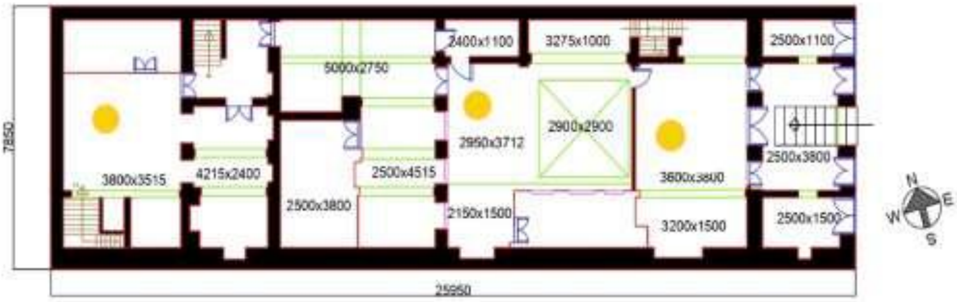

Figure 9. Floor Plan of Vernacular Haveli (source: Verma et al., 2022)

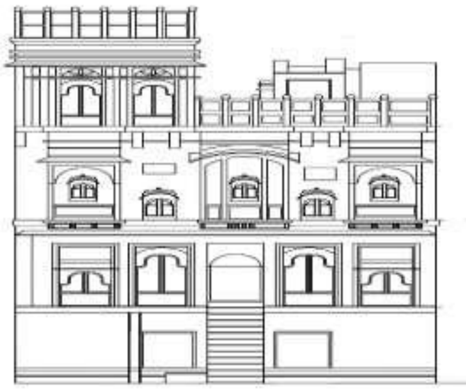

Figure 10. Elevation of Vernacular Haveli (source: Verma et al., 2022)

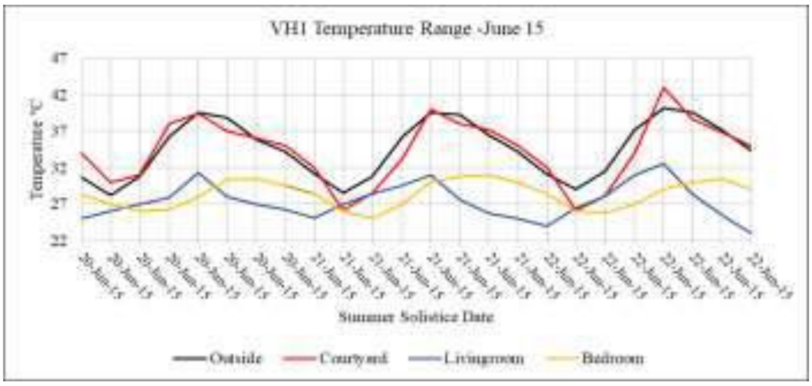

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Figure 11. Summer Temperature Profile of Vernacular Haveli VH1

(source: Verma et al., 2022)

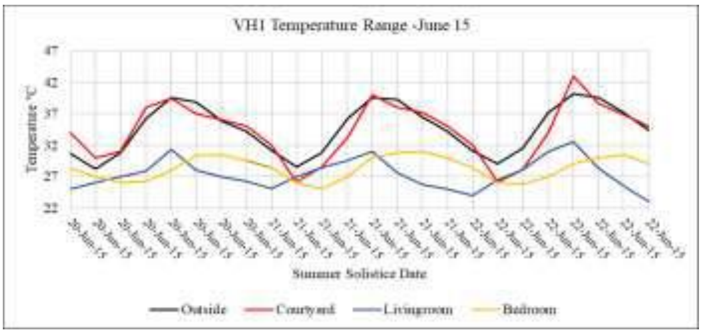

Figure 12. Relative Humidity Profile of all spaces of Vernacular Haveli VH1 in summer

(source: Verma et al., 2022)

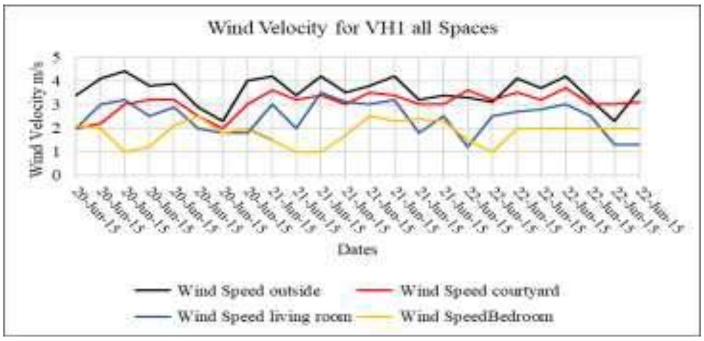

Figure 13. Wind velocity in different spaces in Vernacular Haveli VH1

(source: Verma et al., 2022)

The next research is “Thermal Comfort Assessment of the Beijing Historical Town Blocks: Analysis of Indices and Applications” (Yang et al., 2022). In this research, real-time microclimate measurement was conducted to assess thermal comfort in the Beijing Historical Town Blocks. The researchers used portable weather stations, specifically the Kestrel5500 portable weather station and the TES1333R solar radiation meter, to collect data on various microclimate parameters such as air temperature, relative humidity, wind direction, wind speed, solar radiation, altitude, and atmospheric pressure. These measurements were taken continuously for a period of 7 hours during a typical Beijing summer day from 9:00 to 16:00. The measurement points were evenly set in the selected streets of the historical blocks, covering urban buildings on both sides of the streets and the associated communal spaces. The weather stations were placed 1.5 meters above the ground to ensure accurate measurements. The data was recorded at 5-minute intervals to generate a comprehensive dataset. To avoid interference from other heat sources like cars and air conditioners, the weather stations were positioned in a way that minimized such disturbances. Additionally, the researchers recorded the official broadcasts from the meteorological station on the measurement days to provide reference data for comparison. This real-time microclimate measurement method allowed the researchers to

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gather objective data on the microclimate conditions in the historical blocks, which was crucial for evaluating thermal comfort in the outdoor environment.

5.3. Questionaire Surveys

The questionnaire method is a widely used research tool that involves collecting data through a structured set of questions. This method is particularly effective in gathering information from a large number of respondents, allowing researchers to analyze trends and patterns in the data. The questionnaire method serves as a vital tool in research for collecting structured data, enabling researchers to gain insights into specific issues, such as human perception of thermal comfort inside a heritage building. The findings from the questionnaires in this study underscore the importance of comprehensive data collection and user involvement in the design process.

A total of 15 studies have applied this method in their research. In terms of building types, 8 studies concentrated on residential buildings, followed by 2 studies each on office buildings and villas, and 1 study each on religious buildings, educational buildings, and museums. Geographically, this method has been utilized in research conducted across 11 countries, with 3 studies in China, 2 studies each in Spain and Sweden, and 1 study each in Saudi Arabia, Argentina, Algeria, Iran, Mexico, Poland, Tanzania, and the United States. The review further highlights that this method has been predominantly employed in evaluative research, accounting for 14 articles, with 1 article dedicated to comparative research. These findings underscore the method's relevance and adaptability in investigating thermal comfort across diverse building types and global regions.

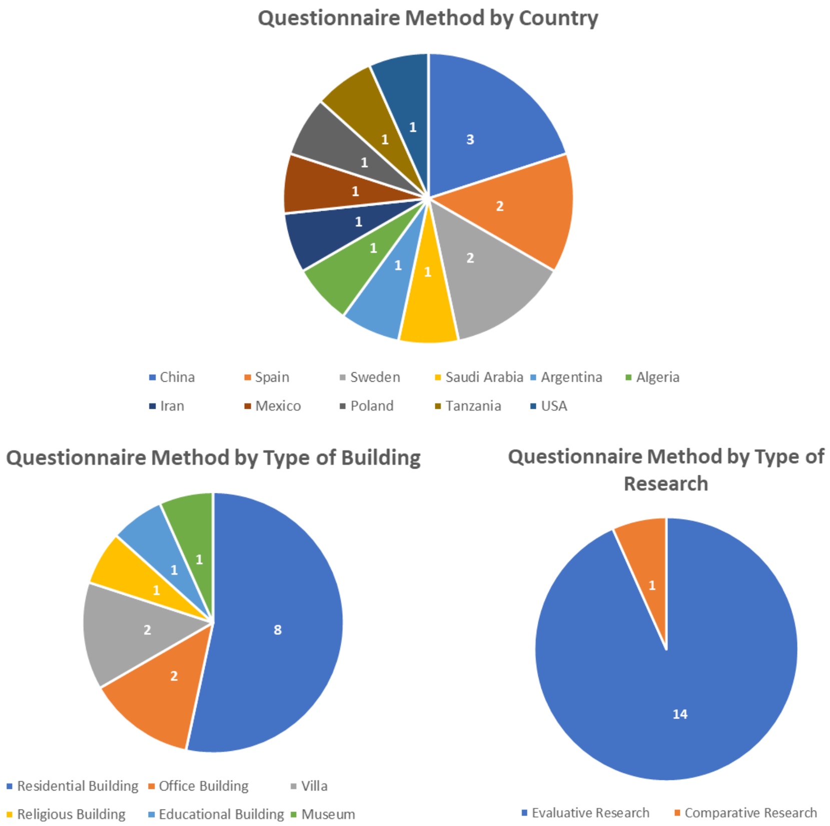

Figure 14. Questionnaire method by type of building, type of research, and country.

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5.3.1. Stages of the Questionnaire Method

This method involves two crucial stages that are fundamental to obtaining accurate and comprehensive data, thereby bolstering the reliability and credibility of the research outcomes. These stages also enhance the research's originality, allowing it to make a meaningful contribution to the architectural field, particularly in the study of thermal comfort in heritage structures. Based on the reviewed research articles, the stages undertaken in this method are design and development, data collection, and data analysis.

1. **Design and Development**

The questionnaire is created to capture specific aspects of occupants' perceptions, such as thermal comfort, satisfaction with lighting and ventilation, and overall indoor environmental quality. Questions are designed to align with recognized standards, such as the ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) standards, to ensure data consistency and reliability.

2. **Data Collection**

Questionnaires are distributed to a representative sample of occupants at different times and settings. The survey may also use software platforms (e.g., Questionnaire Star) to gather responses, which enables efficient data analysis and management.

3. **Data Analysis**

Responses are statistically analyzed to determine patterns and trends in occupants' comfort perceptions. This analysis helps identify discrepancies between perceived comfort and objective environmental measurements, such as temperature, humidity, and air velocity, which are critical for assessing indoor conditions.

5.3.2. Variables Measured Using the Questionnaire Method

We can identify the variables measured using the questionnaire method based on the studies presented in the reviewed journal articles.The first research that use questionnaire method is “Thermal Comfort Assessment of the Beijing Historical Town Blocks: Analysis of Indices and Applications” (Yang et al., 2022). The research utilized questionnaire surveys as a method to obtain subjective evaluations of thermal comfort from the public. The surveys were conducted synchronously with the real-time microclimate measurements. The questionnaires were designed systematically and consisted of two parts. The first part collected basic parameter information about the respondents, including gender, age, height, weight, clothing, ongoing activity, and location of the survey. The second part focused on the respondents' subjective feelings of thermal comfort. It included the following sensitivity votes: thermal sensitivity vote (TSV), thermal comfort vote (TCV), humidity sensitivity vote (HSV), wind speed sensitivity vote (WSV), and solar radiation sensitivity vote (RSV). The TSV had seven levels ranging from hot to cold, the TCV had five levels ranging from very comfortable to very uncomfortable, and the HSV, WSV, and RSV each had five levels representing different degrees of sensitivity. The questionnaires were distributed to the respondents during the measurement period, and the average time for completing each questionnaire was 3-5 minutes. A total of 1091 effective feedback sheets were obtained. The data from the questionnaires were then analyzed and used in conjunction with the objective measurement data to evaluate the thermal comfort of the historical town blocks. The next research is “Comprehensive assessment of thermal comfort and indoor environment of traditional historic stilt house, a case of dong minority dwelling,

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China" (Jin & Zhang, 2021). The questionnaire survey was conducted using the Questionnaire Star software. It was divided into two parts: satisfaction with traditional space utilization and satisfaction with thermal comfort, natural ventilation, natural lighting, sound insulation, indoor air quality, and other factors of the living space. A total of 472 questionnaires were distributed, with 469 valid responses. In a research that taken place in the Museu de la Història de València in Spain, qualitative data was gathered through questionnaires distributed to visitors. These questionnaires aimed to assess visitors' satisfaction with the thermal environment, specifically focusing on their Thermal Sensation Vote (TSV). This combination of data collection methods provided a holistic view of how indoor conditions impacted visitor comfort (Martinez-Molina et al., 2018). Based on the review above, variables observed in the questionnaire method include:

1. **Thermal Comfort**: Questions assess temperature preferences, perception of warmth or coolness, and overall comfort with current thermal conditions using Thermal Sensation Vote (TSV) and Thermal Comfort Vote (TCV) index
2. **Ventilation and Air Quality**: Respondents rate their satisfaction with air movement and freshness, which contributes to perceived indoor air quality using Wind Comfort Vote (WCV) index.
3. **Lighting**: Questions about natural and artificial lighting evaluate if lighting levels meet occupant needs.
4. **Acoustic Comfort**: Satisfaction with noise levels is also evaluated, especially in environments where noise control is challenging
5. **Humidity Sensation Vote (HSV)**: Measures occupants' perceptions of humidity, ranging from "dry" to "humid," which affects the overall thermal comfort.
6. **Radiant Sensation Vote (RSV)**: Represents occupants' sensations of warmth or cold due to radiant sources, often from walls, floors, or other surfaces in the building.

5.4. Computer Simulations

Computer simulation methodology refers to the structured approach used by computer architects to model and analyze the performance of processor designs and enhancements. computer simulation methodology is a critical framework that guides computer architects in effectively modeling and analyzing processor designs. By incorporating statistical rigor and a structured process, architects can improve the accuracy and reliability of their simulation results, ultimately leading to better design decisions.

There are 25 articles that use this method in their research. The application of the computer simulation method can be analyzed based on its distribution across countries, building types, and research types. By country, Egypt leads with the highest usage (5 studies), followed by Spain (4), and China and Saudi Arabia (3 each). Several other countries, including Italy, Sweden, Argentina, Algeria, Cyprus, Jordan, Portugal, South Korea, and Turkey, show limited usage with only 1 or 2 studies each. When analyzed by building type, the method is predominantly applied to residential buildings, accounting for 10 studies. Educational buildings follow with 4 studies, while office buildings, villas, religious buildings, and hospital buildings each represent 2 studies. Palaces and monumental buildings account for 1 study each, showing a lower focus on these building categories. Regarding the type of research, evaluative research emerges as the most common, with 12 studies utilizing computer simulation to assess various

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parameters. Experimental research follows closely with 9 studies, while comparative research is less prevalent, representing only 4 studies. This breakdown highlights the versatile application of computer simulation methods across diverse geographical locations, building types, and research approaches, reflecting its critical role in evaluating and improving thermal performance and comfort in the built environment.

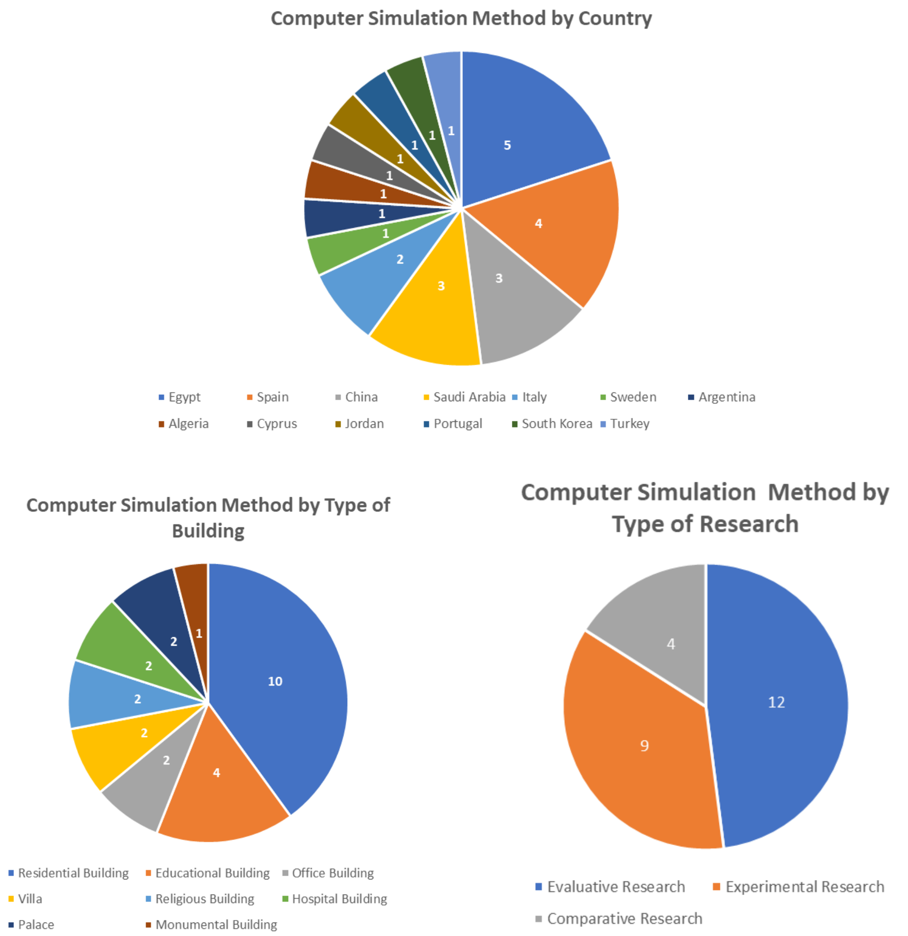

Figure 15. Computer simulation method by type of building, type of research, and country.

5.4.1. Stages of the Computer Simulation Method

The process of computer simulation in heritage building studies involves a systematic integration of empirical data and advanced computational tools. Each step in the methodology is crucial to ensuring accurate representation of environmental conditions and reliable simulation outcomes. Key steps include:

1. **Data Collection**: Empirical measurements of environmental variables (e.g., temperature, humidity) are taken using sensors or monitoring devices. For instance, in "Thermal Comfort Assessment of Stone Historic Religious Buildings in a Hot and

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Humid Climate During Cooling Season," microclimate data were gathered using wireless devices and questionnaires (Martinez-Molina et al., 2022).

2. **Model Development**: The building's physical properties (materials, geometry, ventilation) are modeled using computational tools. The article "Are the Dwellings of Historic Mediterranean Cities Cold in Winter?" emphasizes the use of detailed physical and thermal modeling to simulate environmental responses (Caro & Sendra, 2021).
3. **Simulation Execution**: Computational tools such as Computational Fluid Dynamics (CFD) or energy modeling software like EnergyPlus are utilized. Simulations assess heat distribution, airflow, and humidity under varying environmental scenarios. D'Agostino et al.'s work on Italian cathedrals used CFD models validated against field data.
4. **Result Validation**: Simulated outcomes are cross-referenced with measured data to ensure accuracy, as described in "Modelling of reversible plant system operations in a cultural heritage school building for indoor thermal comfort" (Balocco & Colaianni, 2018).

These steps form a comprehensive framework for studying thermal comfort in heritage buildings. The integration of field measurements and computer simulations ensures that results are both precise and practical, contributing to the development of sustainable preservation strategies while accommodating the needs of occupants and stakeholders.

5.4.2. Types of Computer Simulations Used

Different types of computer simulations cater to the unique requirements of heritage buildings, from evaluating thermal comfort to optimizing energy performance. These simulations leverage a variety of specialized tools and models to provide detailed insights into the indoor environmental quality of historic structures. The main types include:

1. **Energy Performance Simulation**: Tools like EnergyPlus or TRNSYS are used to evaluate heating and cooling demands. These are applied in studies like "Impact of a Retrofitting Project on Thermal Comfort and Energy Efficiency of a Historic School in Miliana, Algeria" (Khledj & Bencheikh, 2021).
2. **Thermal Comfort Models**: Fanger's Predicted Mean Vote (PMV) model and adaptive comfort methods are commonly integrated.
3. **Computational Fluid Dynamics (CFD)**: Simulations analyze airflow patterns and ventilation.

These simulation types collectively provide a robust toolkit for addressing thermal comfort and energy performance in heritage buildings. Each type offers unique capabilities that, when combined with empirical data, ensure a holistic understanding of environmental dynamics in complex historic settings.

5.4.3. Applications Across Research Fields

The integration of computer simulations and field measurements has enabled researchers to address various challenges in heritage building studies. These applications span multiple research fields, underscoring the versatility and significance of simulation methodologies. Key applications include:

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1. **Heritage Building Preservation**: Simulations help maintain artifact conservation conditions, as in "Thermal comfort assessment of stone historic religious buildings in a hot and humid climate during cooling season. A case study" (Martinez-Molina et al., 2022).
2. **Energy Efficiency Retrofitting**: Studies aim to reduce energy use while preserving heritage value, as discussed in "Adaptive approach-based assessment of a heritage residential complex in southern Spain for improving comfort and energy efficiency through passive strategies: A study based on a monitored flat" (Blázquez et al., 2019).
3. **Indoor Comfort in Religious Structures**: Analysis focuses on high-volume spaces with unique thermal dynamics, e.g., "Simulation Method to Assess Thermal Comfort in Historical Buildings with High-Volume Interior Spaces" (Martinez-Molina et al., 2022).

The applications of computer simulations in heritage building research are diverse and impactful. They not only address pressing conservation and sustainability concerns but also provide actionable insights for future interventions, ensuring that historic structures remain functional and relevant in contemporary contexts.

6. Dicussion – Combination of Methods

In the reviewed research articles, the methodological approaches vary significantly, reflecting the diverse needs and objectives of each study. Some studies employ a single method, focusing on either empirical measurements, subjective evaluations, computational simulations, or literature reviews, depending on the research goals and available resources. However, many researchers combine two or more methods to achieve a more comprehensive analysis and reliable findings. Combining methods such as **Physical Survey and Measurement (PSM)**, **Questionnaire (Q)**, **Computer Simulation (CS)**, and **Literature Review (LR)** enables researchers to address complex problems from multiple perspectives. For example, integrating real-world measurements with subjective evaluations or predictive simulations allows for a holistic understanding of research phenomena. This sub-section provides a detailed explanation of the various methodological combinations observed in the reviewed studies, including their purpose, significance, and contributions to advancing scientific knowledge in the respective fields.

6.1. Physical Survey and Measurement & Computer Simulation

The combination of **Physical Survey and Measurement (PSM)** and **Computer Simulation (CS)** emerges as the most frequently employed research methodology, with a total of 12 studies. This high number indicates that researchers often rely on both empirical field data and simulated computational results to evaluate and validate their findings.

6.1.1. Significance of the Combination

By integrating PSM and CS, researchers can cross-validate measured and simulated data, ensuring accuracy and reliability. For instance, measured on-site data serve as baseline input for simulations (Blázquez et al., 2019), while simulation results allow for testing various scenarios that may not be feasible to replicate physically (Blázquez et al., 2019).

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6.1.2. Example Application

One study analyzed the thermal performance of the Royal Hospital of Granada through a combination of field measurements and energy simulations. Direct temperature data from two rooms, collected during summer and winter, were used to calibrate a simulation model in EnergyPlus. The results revealed that room orientation and construction elements, such as thick masonry walls, play a pivotal role in thermal comfort, demonstrating the effectiveness of integrating real-world data with simulations to evaluate heritage buildings (Blázquez et al., 2019). Another study examines the thermal comfort of the Ulu Mosque by utilizing field measurements of temperature and humidity levels alongside computational simulations. Data collected on-site were incorporated into simulation software to assess how the mosque's design and materials influence thermal conditions. The combined approach enabled an in-depth understanding of passive cooling mechanisms and provided recommendations for enhancing comfort without compromising the building's historical integrity.

6.2. Physical Survey and Measurement & Questionnaire

The second most common combination, used in 8 studies, is **Physical Survey and Measurement (PSM)** and **Questionnaire (Q)**. This approach bridges objective field measurements with subjective human responses, allowing for a more holistic understanding of phenomena such as thermal comfort.

6.2.1. Significance of the Combination

While PSM provides objective physical measurements, questionnaires capture the subjective dimension of comfort, satisfaction, or perception. Combining these methods ensures that research accounts for both measurable data and human-centric responses, offering richer insights.

6.2.2. Example Application

In assessing thermal comfort in a heritage building, researchers might measure indoor air temperature and humidity (PSM) while distributing questionnaires to occupants or visitors to record their comfort perceptions. The comparison between subjective comfort levels and measured conditions can identify gaps and inform necessary improvements.

6.3. Physical Survey and Measurement, Questionnaire, & Computer Simulation

This combination, found in 5 studies, integrates **Physical Survey and Measurement (PSM)**, **Questionnaire (Q)**, and **Computer Simulation (CS)**. By incorporating these three methods, researchers achieve an extensive, multi-perspective analysis of complex research questions.

6.3.1. Significance of the Combination

This combination is powerful because it blends objective field measurements with subjective input while leveraging computational simulations to test hypotheses or predict outcomes. Such a comprehensive methodology enhances the depth and applicability of research findings.

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6.3.2. Example Application

In evaluating indoor environmental quality, researchers might measure temperature, air quality, and light levels (PSM), collect occupant feedback on comfort and satisfaction (Q), and simulate potential design improvements using software tools (CS). This approach ensures both current conditions and proposed solutions are well-documented.

6.4. Computer Simulation (Standalone)

Interestingly, **Computer Simulation (CS)** alone is used in 5 studies. This indicates a reliance on computational methods to predict outcomes or analyze systems without real-world measurements or subjective inputs.

6.4.1. Advantages of CS

CS allows researchers to model scenarios under controlled and varied conditions, saving time and resources compared to extensive field measurements. It is particularly valuable in theoretical or preliminary studies.

6.4.2. Limitations of CS

While simulations are efficient, their accuracy depends on input data and assumptions. Without validation from real-world measurements (PSM) or user feedback (Q), simulation results may not fully reflect actual conditions.

6.5. Physical Survey and Measurement (Standalone)

Three studies solely use **Physical Survey and Measurement (PSM)**. This method remains fundamental for obtaining accurate, real-world data, particularly in fields like building science, environmental monitoring, and engineering.

6.5.1. Strengths of PSM

PSM provides concrete, reliable data that form the foundation of empirical research. It is especially useful when the focus is on physical parameters such as thermal performance, air movement, or energy consumption.

6.5.2. Limitations of PSM

Relying solely on PSM may overlook subjective aspects or the potential for predictive modeling, which are addressed by Q and CS, respectively.

6.6. Literature Review (Standalone and Combinations)

Literature Review (LR), both standalone (2 studies) and in combination with other methods, highlights the importance of reviewing existing research as part of the scientific process.

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6.6.1. Standalone LR (2 Studies)

These studies rely exclusively on reviewing published research to synthesize findings, identify gaps, and develop theoretical frameworks. While efficient, standalone LR lacks new empirical data.

6.6.2. LR in Combination

The review shows combinations of **LR & Q**, **LR & CS**, and **LR, PSM, Q, & CS** with minimal occurrences (1 study each). Integrating LR with other methods strengthens research by ensuring it is grounded in prior knowledge while generating new data or insights.

6.6.3. 7. LR, PSM, Q, & CS Combination

The most comprehensive methodology, combining **LR, PSM, Q, and CS**, is used in only one study. In a research that comparing historical houses designed by Le Corbusier and André Wogenscky employs a comprehensive methodology combining literature review, physical survey and measurements, questionnaires, and computer simulations to evaluate thermal comfort in modernist architectural works. Archival research and historical documentation contextualize thermal design within its cultural and technical framework, while field measurements and occupant surveys provide empirical and qualitative data on environmental performance and sensory experiences. Advanced simulation tools like EnergyPlus and CFD validate and enhance these findings, offering quantitative insights into heat transfer, airflow, and the effectiveness of passive design strategies (Requena-Ruiz, 2016). This integrated approach bridges historical and modern perspectives, providing a holistic understanding of thermal comfort and its relevance to both heritage conservation and contemporary adaptation.

In summary, the reviewed studies showcase a diverse range of methodological approaches, with many leveraging combinations of Physical Survey and Measurement (PSM), Questionnaire (Q), Computer Simulation (CS), and Literature Review (LR) to address complex research questions. These integrative methodologies enhance the depth, reliability, and applicability of findings by combining empirical data, subjective insights, and predictive modeling. While standalone methods have their merits, the synergy of multiple approaches often provides a more comprehensive understanding, particularly in studies involving heritage conservation, thermal comfort, and environmental performance. This highlights the importance of tailoring methodologies to the specific objectives and challenges of each research endeavor.

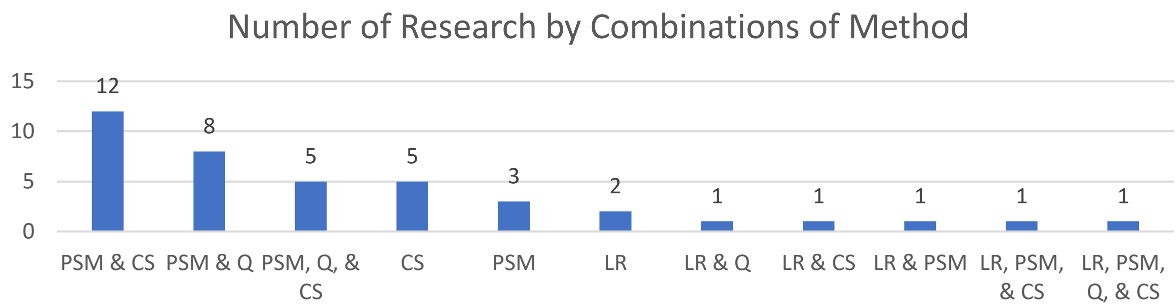

Figure 16. Combination of methods.

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7. Conclusion

The review of thermal comfort assessment methods in heritage buildings underscores the diversity and adaptability of methodologies employed to address the unique challenges of evaluating and optimizing thermal conditions in these structures. Four primary methods—literature reviews, physical surveys and measurements, questionnaires, and computer simulations—serve as the foundation for research in this field. Among these, physical surveys and measurements are the most frequently utilized, emphasizing their critical role in capturing accurate empirical data on environmental conditions. However, the standalone use of any single method, while valuable, often provides limited perspectives, highlighting the increasing preference for combining methodologies to achieve more comprehensive and reliable findings.

The integration of multiple approaches, such as combining physical surveys and measurements with computer simulations or questionnaires, has proven particularly effective. This mixed-method approach enables researchers to analyze thermal comfort from both objective and subjective perspectives. For instance, empirical data on temperature, humidity, and airflow can be cross-referenced with computational models to simulate environmental performance under various scenarios. Simultaneously, questionnaires capture the occupants' perceptions and satisfaction levels, providing insights into the human experience of thermal comfort. Such combinations allow for holistic evaluations that are not only precise but also contextually relevant to the occupants' needs.

These methodologies have been successfully applied across a wide range of heritage building types, including residential buildings, religious structures, museums, and educational facilities, in diverse climatic conditions worldwide. The findings from these studies highlight the potential of integrating traditional passive design strategies, such as natural ventilation and thermal mass, with modern analytical tools to enhance the sustainability and functionality of heritage buildings.

Looking ahead, future research should prioritize refining these methodologies, focusing on more seamless integration of empirical measurements, computational modeling, and user-centric assessments. Such advancements will be instrumental in developing adaptive strategies that balance the preservation of historical and cultural significance with the contemporary demands for comfort, energy efficiency, and sustainability in heritage structures.

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