

BIBLIOMETRIC ANALYSIS OF THERMAL COMFORT AND ENVIRONMENTAL QUALITY: A FRAMEWORK FOR SUSTAINABLE CONSTRUCTION

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ABSTRACT:

Thermal comfort and environmental quality in buildings are critical factors in achieving Sustainable Development Goals related to health, energy efficiency, and sustainable constructions. The present paper aims to establish a scientific framework for sustainable construction, focusing both on the thermal comfort and indoor/outdoor quality of the air. With the average person spending 87% of their day indoors, understanding thermal comfort, defined as the subjective experience of a satisfactory thermal environment, is essential. Two primary models, the stable model and the adaptive model, are employed to analyze thermal comfort, accounting for various factors such as ambient temperature, air circulation, and individual differences. This study uses bibliometric analysis and scientific mapping to evaluate 14,179 articles from the Web of Science database indexed in the last 4 years (2020/2024). Current findings indicate a significant interest in this topic, with China and the USA leading in research output. The study reveals a strong focus on improving thermal comfort through innovative materials, mixed-mode ventilation, and vegetation integration in urban environments. Additionally, there is a notable emphasis on the air quality's influence on human health. Present analysis underscores the international collaboration implications, highlighting strong links between major research countries. This comprehensive bibliometric study provides insightful observations about the field's prospects and existing trends, highlighting the necessity of ongoing research and interdisciplinary collaboration to enhance thermal comfort and environmental quality in sustainable construction.

1. INTRODUCTION

As a means to attain Sustainable Development Goals (SDGs) 3, 7, and 11, which deal with topics like "optimal health and well-being," "clean and affordable energy," and "sustainable urban areas and communities," thermal comfort, defined as the subjective experience of being in an environment that meets one's thermal comfort needs, is an important step in the right direction (Djongyang, Tchinda and Njomo, 2010). Approximately eighty-seven percent of the day is spent inside by the average individual (Klepeis et al., 2001). This has led to an increase in studies examining the topic of thermal comfort within structures, where "a state of mind that reflects contentment regarding the temperature of the surrounding environment" is defined (Anon., 2024).

The two methods most often utilized for researching and analyzing thermal comfort are the adaptative and stable models. In line with Fanger's theory, the stationary model accounts for the way human body and its surroundings regulate temperature. The model assumes constant air conditioning aspects throughout the research and uses an equation for individual and environmental factors to determine thermal comfort, which is known as the

predicted average vote (PMV). When subjected to specific permutations of specified indoor thermal environment variables, this index estimates and expresses the mean score on a standardized scale for numerous individuals' thermal sensation votes (Arballo et al., 2016).

When one feels neither too hot/cold, they can be considered as being thermally comfortable. Several variables affect this perception, including radiant temperature, ambient temperature, air circulation, humidity, and individual differences (such as metabolic rate and clothing thermal resistance). Common thermal comfort models (such as O. Fanger's from the 1960s) use these variables to assess how pleased a building's occupants will be as a whole (Fanger, 1967).

Both the highest and lowest temperatures expected to be comfortable are part of the comfort zone, which includes the neutrality/comfort line. A suitable limit is often between 80 and 90% acceptance, which indicates a temperature range optimal for human comfort, with 2-3 °C on each side of the ideal comfort line. For very hot and dry conditions, the comfort zone threshold can be calculated by adding 2 °C on each side where fans are present. In order to determine the comfort zone threshold for each

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component in humid environments, adding 1 °C is feasible (Soebarto and Bennetts, 2014). Everything has to be thought of in order for buildings and Heating, Ventilation, and Air Conditioning (HVAC) systems to be precisely designed for providing thermal comfort and run efficiently. Unfortunately, building designers frequently fail to consider or implement them properly. Standardized design input values are more typically seen as global values than as recommendations for usage in particular contexts. When calculating thermal comfort, only a few variables with uncertainty are considered at the operational level (d'Ambrosio Alfano et al., 2014).

Among the many aspects of an indoor environment's quality are optimal temperature, acoustic comfort, lighting quality and the quality of the air. Examining these elements is highly pertinent, as individuals dedicate a significant percentage of their day to enclosed structures (Gani, Zamberi and Teni, 2018). There are many variables that affect a building's energy consumption, including the building envelope, exterior and interior boundary conditions, system efficiency, and installed appliances. To optimize energy efficiency, it is essential to implement design solutions based on these factors. Key elements to consider include local climate, architectural form, construction materials, thermal performance of the building enclosure, exterior and interior temperatures, equipment efficacy, occupancy patterns, and occupant behavior (Latha, Patil and Kini, 2022).

Numerous studies have thoroughly investigated the effect that building occupants have on energy efficiency (Bungau et al., 2023). Individuals desire staying in a nice, comfortable place where they can work and relax; thus, there's a correlation between their actions and how much energy a building use. Along with other factors like the quality of the inner space atmosphere, lighting quality, and acoustic quality, thermal comfort is a major determinant of inhabitants' satisfaction regarding their indoor environment. To create buildings that improve the health of residents while decreasing energy usage, it's critical to comprehend the complex interactions between environmental/individual elements that affect thermal comfort (Mahdavi et al., 2021).

Important public initiatives that hasten the shift from traditional to sustainable, low-energy construction practices include energy requirements and building labeling. Buildings in the US have reduced their energy use by 25% after implementing Energy Star accreditation, which has been acknowledged by the real estate market (Zhang, Li and Ma, 2022).

The rising quantity of both original and review articles on the topic of indoor thermal comfort attests to the widespread interest in this topic among scientists around the world. A variety of enclosed places, including homes, public utility buildings, and even automobiles, were used for the testing. Spending time in public utility buildings, such as schools and offices, can be more challenging than in private residences when it comes to managing their indoor climate. Public utility buildings are especially interesting from the standpoint of energy usage since they are utilized for extended periods. Building design first focuses on the building's system, then it establishes the building's envelope and architectural features. Next, it designs the HVAC systems to meet these requirements, achieve thermal comfort, and ensure energy efficiency and performance standards. This structured approach ensures that the building's characteristics guide the HVAC design. This essential consideration should be prioritized in both

newly constructed and energy-retrofitted buildings (Cholewa et al., 2022).

Findings from the academic literature indicate that:

- (1) It is important that the model used to estimate thermal comfort takes demographic factors like age, gender, and socioeconomic status into account.
- (2) The benefits of mixed-mode ventilation, which combines mechanical and natural methods, include reduced energy consumption and enhanced thermal comfort; however, the control systems for this type of ventilation need additional investigation.
- (3) Significantly reducing ventilation requirements while preserving indoor thermal comfort may be achieved through optimizing aspects that influence the design of the passive building, including window positioning, the ratios between windows and walls, and solar protection installations.
- (4) Further research is required for examining the topic regarding thermal comfort in educational institutions throughout the hot season.
- (5) More investigational research is required to completely comprehend the indoor air quality (IAQ) of university buildings, especially regarding aerosol pollutants caused by bacteria and fungi, for providing a clearer evaluation of the constructed surroundings (Jia et al., 2021).

As a result of individual preferences and environmental factors, people in various parts of the building may experience vastly different temperatures. The thermal preferences of inhabitants can differ even when subjected to the same environmental temperature. Occupant satisfaction and energy consumption are very different. Moreover, thermal storage structures in buildings can greatly affect both energy usage and thermal comfort (Musiał, Lichołai and Katunský, 2023). Maintaining a comfortable temperature and achieving significant energy savings without heating and ventilation systems can be achieved using phase change materials with latent heat storage capacity. (Momeni and Fartaj, 2023).

Adjusting the air conditioning system according to thermal comfort was found as being one of the main points of most investigations. As expected, the ideal control variable to employ as a thermostat setpoint is indoor temperature; however, it was not always certain if this meant operating temperature or air temperature. When it comes to control, there are a variety of ways to determine control settings. Some use simple expert rules, while others use more advanced modeling techniques like predictive model control and machine learning. Approximately two-thirds of the analyzed studies included optimization phases carried out using one of the numerous approaches available in the scientific literature. Research on novel control systems is mostly limited to the simulation level (Grassi et al., 2022).

Current paper considered laying out a scientific framework for sustainable construction that would be simple to understand and use by everyone involved, including architects, designers, authorities, beneficiaries, and investors. The framework targets topics like indoor/outdoor environment quality, thermal comfort, constructions etc.

The research concept emerged from the acknowledgement that rising global temperatures are linked to a range of negative health outcomes, such as increased heat-related illnesses (rash, exhaustion, heatstroke, cramps), worsening air quality, the spread of vector-borne diseases, and greater risks from extreme weather events. Therefore, effective strategies are needed to improve thermal comfort, targeting both indoor/outdoor air quality (IAQ/OAQ). The current work's goal was to evaluate the topic's development potential in this engineering subfield using bibliometric evaluation and scientific mapping analysis. The research focuses on identifying and analyzing bibliographic resources covering thermal comfort subject, specifically examining indoor/outdoor environments' quality. The relevance of this topic in the academic literature frame included in the Web of Science (WoS) database is evaluated using a predefined algorithm.

2. MATERIALS AND METHODS

Bibliometric analysis studies are beneficial in gaining an overview of a topic. When carrying out this study, the international WoS database was used, which includes a large number and varied types of publications, that are essential for a comprehensive analysis. The use of a Topic Search (TS) ensured a comprehensive and detailed examination of the subject, as this model searches for key terms in the abstract, keywords field, and title. The following search algorithm was applied: TS= ("Indoor environmental quality" OR "Indoor air quality satisfaction" OR "Olfactory comfort" OR "Indoor climate auditing" OR "Indoor air quality" OR "Indoor climate" OR "Outdoor environmental quality" OR "Outdoor air quality" OR "HVAC systems" OR "Outdoor climate" OR "Thermal comfort"), which led to the identification of 14179 relevant articles, written in English and published in the last 5 years (2020-2024).

The identified articles were classified into 194 categories, of which "Construction Building Technology" and "Civil Engineering" had the largest number of articles, with 5102 and 3906 articles classified. For analyzing the 14179 articles written in English, from the period 2020-2024, the VOSviewer version 1.6.20 was used (Anon., 2022). This program facilitates the analysis of a large volume of documents and the observation of various bibliometric markers, such as word co-occurrence networks and collaborative relationships between countries or authors. Figure 1 shows a Treemap type diagram of the categories with a significant number of classified documents.

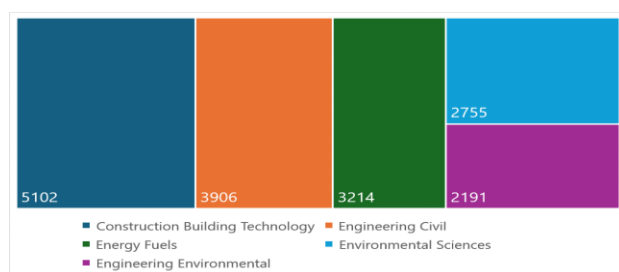


Figure 1. A Treemap type diagram displaying the categories in which there is a significant number of classified publications

The data required for this analysis were extracted from the WoS database via the native export function of the web interface. The chosen format was "tab delimited text file", compatible with the VOSviewer program. In order to ensure obtaining all the relevant data, the "full record and cited references" option was selected in

the "record content" section. For obtaining the most up-to-date image of the scientific environment in this field, only articles published in the last five years were selected. From this data, information such as the most prolific countries and journals were extracted, and specific charts generated using VOSviewer.

3. RESULTS

3.1 Findings from academic information resources based on searches guided by Boolean operators

In the first stage of the design and application of the research methodology, the evaluations were carried out following three main terms in the evaluation: IAQ, OAQ, thermal comfort. The association between these in the specialized literature was analyzed with the help of three basic Boolean operators: AND, OR and NOT.

Although the number of studies on each term is relatively large, publications evaluating the associations between them are significantly fewer (Figure 2). It should be noted that this research topic is of increased interest to researchers, additional research and validations are still needed for obtaining thermal comfort by increasing IAQ/OAQ.

Scientific and technological progress, together with a greater orientation towards sustainability, have contributed to the growing amount of research papers in this field. Integrating sustainability into thermal comfort or air quality investigations emphasizes a real importance of finding green solutions that simultaneously improve indoor and outdoor environmental conditions.

Current research not only reflects an increased academic interest, but also responds to practical needs for improving thermal comfort by increasing air quality, an achievable objective if continuous research and interdisciplinary collaborations are carried out and new principles are implemented. Our outcomes are offering valuable insights and potential solutions that can contribute significantly to achieving improved thermal comfort and air quality.

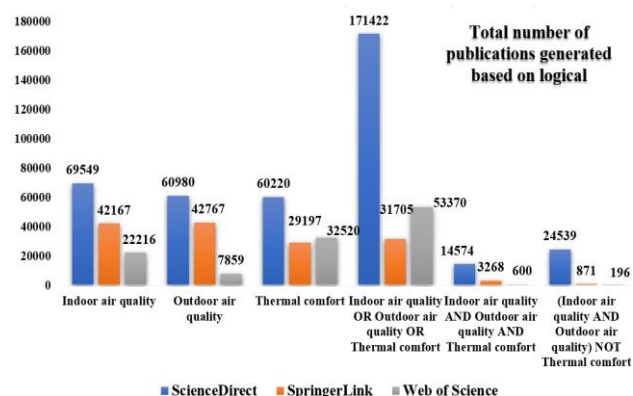


Figure 2. Publications on indoor/outdoor air quality and thermal comfort identified in international databases using logical operators

3.2 Detailed bibliometric evaluation and scientific mapping in the field of thermal comfort and indoor and outdoor environment quality

Between 2020 and 2024, a total of 99 countries published different types of articles in the researched field. China is the most prolific country, producing over 30.29% articles in this field. The USA ranks second with 12.72% of all published articles. From the perspective of average citations per article, the USA stands out, with 12.06 citations/article, followed by England with 11.14 and Italy with 11.45 citations/article. Table 1 presents the top countries in this field (TLS representing the total link strength is an amount assigned by VOSviewer that indicates the degree of collaboration between items).

Country	Articles	Citations	Average citations / article	TLS
China	4295	42779	9.96	1749
USA	1804	21751	12.06	1418
England	928	10337	11.14	1169
Italy	807	9243	11.45	704
South	662	5117	7.73	290

Table 1. The top five countries in the evaluated field according to the number of publications provided

During the same interval, 1643 journals had at least one publication that matched the search algorithm. The top publication in this time interval is Building and Environment, with 1518 (10.71%) articles. It also has the highest impact factor (IF) of the top five, with a value of 7.4, indicating that the published articles are a valuable benchmark in the scientific community. In second place is Energy and Buildings with 903 (6.37%) items and a significant IF of 6.7. Regarding the number of citations per article, all the previously mentioned journals stand out, except that, in this case, Energy and Buildings ranks first. Table 2 presents the list of the top publications in the researched domain (P representing the number of publications; C, citation count; Avg C, average citations/document; IF, impact factor; Pub, publisher; E, Elsevier; M, Multidisciplinary Digital Publishing Institute).

Journal	P	C	Avg C	IF 2023	Pub
Building and Environment	1518	19351	12.75	7.4	E
Energy and Buildings	903	11692	12.95	6.7	E
Journal of Building Engineering	618	6473	10.47	6.4	E
Sustainability	587	3475	5.92	3.9	M
Energies	541	3028	5.6	3.2	M

Table 2. The 5 most prolific journals regarding the publications in the evaluated field

In the case of the international collaborations map between 2020 and 2024 for the evaluated field (Figure 3), the colors represent the cluster to which the country represented in the bubble belongs. Countries in the same cluster tend to collaborate more frequently. There is a clear correlation between a country's issued articles and the diameter of the bubble, and between the level of cooperation between two nations and the width of the lines linking them.

Figure 3 illustrates only the countries that have published at least 50 articles, grouped into three clusters:

- the red cluster, led by China, including 30 countries;
- the green cluster, led by Italy, including 23 countries, mostly European;
- the blue cluster, led by Spain, including 5 countries.

The strongest collaborative relationships are seen between China and the US, China and England, China and Japan, and China and Singapore. When it comes to the relations between countries in different clusters, the collaborations between Italy and Spain, the USA and Germany, and China and Denmark stand out.

The figure reveals that China is at the center of a broad network of international collaborations, with strong ties to both Western and Asian countries.

The connections between different clusters show the interdependence of international research efforts and highlight significant cross-cluster collaborations.

In the term co-occurrence network map (Figure 4), the diameter of the bubbles is corresponding to the term occurrences, and bubbles color indicates the cluster to which the term belongs. Terms located in the same cluster tend to have higher co-occurrence. The width of the lines linking the two terms correlates with the number of co-occurrences of those words. Only terms that had a minimum of 50 occurrences are represented. Among them are:

- "urban heat island" (256 occurrences, average citations 16.27);
- "outdoor thermal comfort" (580 occurrences, average citations 11.68);
- "city" (288 occurrences, average citation 12.79);
- "phase change materials" (165 occurrences, average citations 15.81);
- "management" (337 occurrences, average citations 13.61).

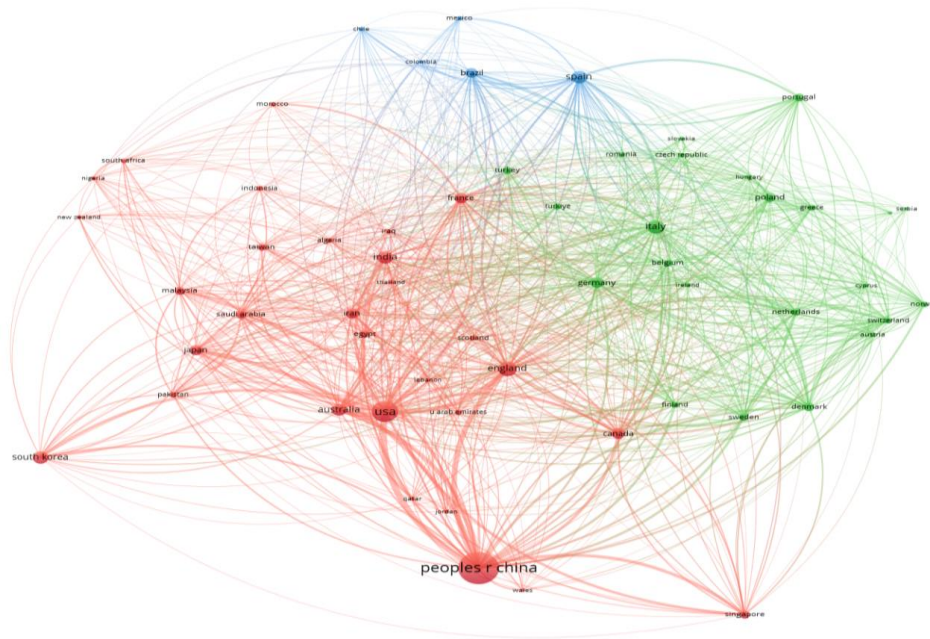
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Figure 4. The map of high occurrence terms for the evaluated domain.

highlights the importance of optimizing indoor environments to enhance occupant comfort while also considering energy conservation measures. Research in this area often explores the use of innovative building materials, advanced HVAC systems, and smart home technologies to achieve these goals.

The green cluster, with 55 terms, addresses outdoor temperature and related topics. Key terms here include "urban heat island", "urban microclimate", "climate-change", "thermal sensation", "heat-stress", "adaptation", "strategies", "outdoor thermal

comfort", "overheating", "hot", "radiation", "physiological equivalent temperature" and "vegetation." This cluster underscores the challenges and solutions associated with managing outdoor thermal environments, particularly in urban areas. The urban heat islands impact which arises because of higher temperatures in densely built environments, is a significant concern. Research in this cluster often focuses on strategies such as urban greening, the use of reflective building materials, and the implementation of cool roofs or pavements for mitigating heat and improving outdoor comfort. The relationship between outdoor thermal conditions and public health, as well as the socio-economic implications of climate adaptation measures, are also critical areas of investigation.

The blue cluster, consisting of 51 terms, focuses on IAQ and its impact on the health of people. Prominent terms in this cluster include "indoor air quality," "health," "pollutants," "air pollution," "humidity," "risk," "occupants," "emissions," "volatile organic compounds" and "ventilation." This cluster highlights the importance of maintaining high IAQ to ensure the well-being of building occupants. Research in this domain addresses the identification and mitigation of indoor pollutants (volatile organic compounds (VOCs), biological contaminants – mold and bacteria, or particulate matter). Effective ventilation systems, air purification technologies, and the use of low-emission building materials are common strategies explored to enhance IAQ. Additionally, this cluster often investigates the health outcomes associated with poor IAQ, including respiratory issues, allergies, and other chronic conditions.

Terms with high co-occurrence across these clusters indicate the interconnected nature of these topics. For instance, "exposure" is frequently linked with "indoor air quality," reflecting the direct effect of air-contained pollutants on occupants. Similarly, "thermal comfort" co-occurs with "performance," "buildings," "optimization," and "design," indicating the multidisciplinary approach required to achieve thermal comfort through building operation or design. Overall, the co-occurrence network reveals the multifaceted character of environmental quality and thermal comfort investigations. It emphasizes the need for a holistic approach that considers both indoor and outdoor environments and integrates strategies across building design, urban planning, and public health. This comprehensive understanding is crucial for developing sustainable construction practices that enhance both occupant comfort and environmental performance. The overall co-occurrence network is presented in Figure 5.

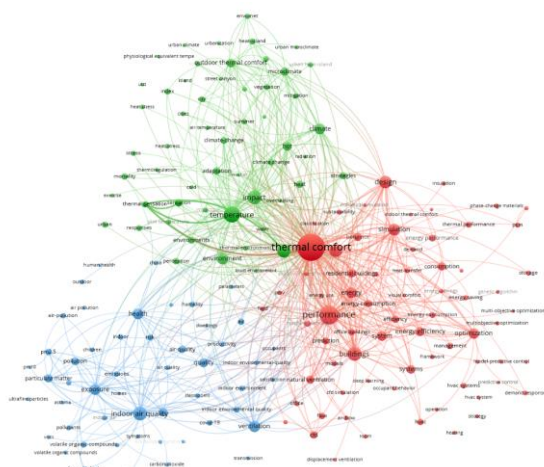


Figure 5. The co-occurrence network map of the terms

Based on the search algorithm applied, two 'hot papers' were identified according to WoS, meaning that they gathered significant citations in January and February 2024, raising their status in the top 0.1% of papers in the academic field Environment/Ecology (i.e., paper entitled 'Urban heat islands and their effects on thermal comfort in the US: New York and New Jersey') (Yin et al., 2023), and the second in the field of Engineering (i.e., paper entitled 'A review on buildings energy information: Trends, end-uses, fuels and drivers') (González-Torres et al., 2022).

Figure 6 shows a way of splitting the most numerous WoS publications, complying with the implemented algorithm according to the most frequently addressed SDGs. Most publications target SDG number 13 (i.e., Climate action with 9767 publications), followed by SDG 11 (i.e., Sustainable Cities and Communities with 4110 publications) and SDG 3 (i.e., Good Health and Well Being with 3333 publications). Also, represented with over 1300 publications, is SDG number 7 (i.e., Affordable and Clean Energy), followed by groups with less than 250 publications for a given SDG.

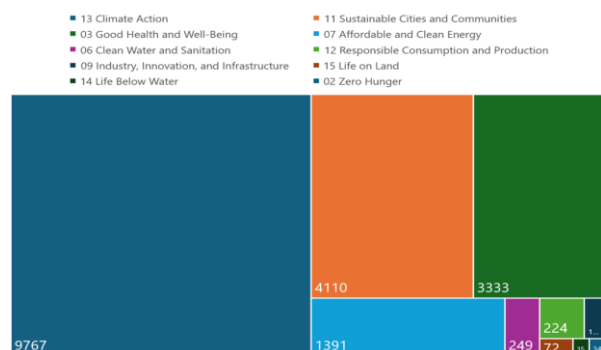


Figure 6. Number of publications targeting a specific SDG

Figure 7 shows the most prolific authors per topical generated search based on the algorithm used in WoS. The digits represent the number of publications/each author. In regard to the number of publications of the most prolific authors based on the search algorithm, the first place is occupied by Zhang, H. with 95 publications, tied with Zhang, Y., and followed by Wang, Y. with 85 publications and Kim, J. with 82.

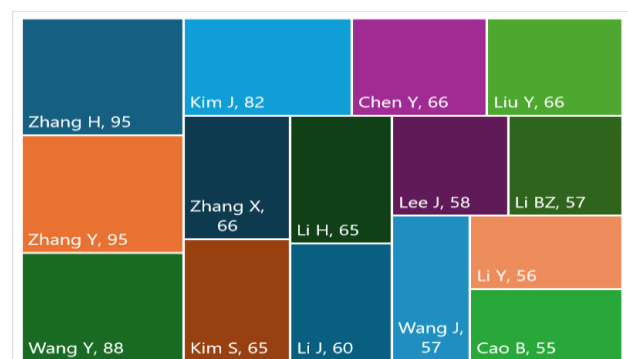


Figure 7. The most prolific 15 authors for the evaluated topic

Figure 8 shows the affiliation with department of the most prolific authors. In terms of departmental and university affiliations, Tsinghua University School of Architecture leads the ranking with 223 publications by authors affiliated here, followed by the Building Science and Technology department of the same

university with 165. European universities such as the Technical University of Denmark with 114 publications, and University College London Bartlett, Faculty of the Built Environment with 115 publications also stand out.



Figure 8. The affiliations with department of the most prolific authors in the evaluated field

Differences based on the algorithm are also noticeable at the level of chosen publishers, where Elsevier leads the top with 7210 publications, followed by MDPI with 3167 publications, and Springer Nature with 1065. These high numbers are also based on the significant number of journals indexed in these wide coverage databases. Figure 9 depicts top 15 publishers targeting papers from the evaluated field.

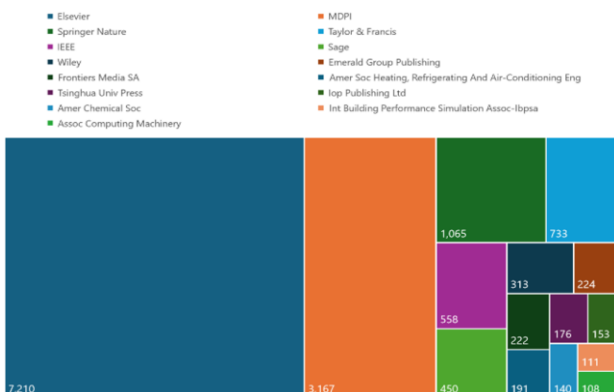


Figure 9. The most prolific publishers for the evaluated field

4. DISCUSSIONS

The bibliometric analysis reveals insightful trends and underscores the significance of researching in IAQ/OAQ, thermal comfort, their interplay, also considering the broader framework of sustainable building practices. The results indicate a growing global interest in these areas, driven by the need to align with SDGs 3, 7, and 11, which advocate for optimal health and well-being, clean and affordable energy, and sustainable urban areas and communities. This discussion will delve deeper into these trends, the implications of the findings, and the critical areas that demand further research.

The geographic distribution of publications indicates that the topic of air quality or thermal comfort is of global interest, with China leading in the number of publications. This prominence reflects China's rapid urbanization, industrial growth, and increasing focus on sustainable building practices to mitigate environmental impacts. The high number of publications from

China (30.29%) suggests robust research activities, supported by significant investments in sustainable technologies and policies.

The United States of America, ranking second, also shows a high average citation per article (12.06), indicating the impactful nature of its research. This might be attributed to the country's advanced research infrastructure and strong emphasis on sustainability in building practices, supported by programs like Energy Star (Boyd, Dutrow and Tunnessen, 2008), which promotes energy efficiency in buildings.

England and Italy, while publishing fewer articles, demonstrate strong international collaboration (high TLS). This suggests that researchers in these countries are well-integrated into the global scientific community, facilitating the exchange of knowledge and innovative practices. Such collaborations are essential for tackling complex global challenges related to thermal comfort and air quality, as they bring diverse perspectives and expertise together.

The term co-occurrence map highlights three primary clusters of research:

a) Thermal Comfort in Residential Buildings (Red Cluster): This cluster focuses on optimizing thermal comfort in residential buildings, a critical aspect given that individuals spend approximately 87% of their time indoors. Research in this area often involves studying the interaction of various factors like insulation, energy efficiency, HVAC systems, and building materials. The goal is to create environments that maintain comfortable temperatures with minimal energy consumption, thereby contributing to SDG 7;

b) Outdoor Temperature and Related Topics (Green Cluster): This cluster addresses issues related to outdoor thermal environments, including the effects of both climate change / urban heat islands. Research often is related to the urban planning strategies, such as increasing vegetation, using reflective materials, and enhancing urban design to mitigate excessive heat in cities. These efforts align with SDG 11, which seeks to create sustainable, safe, resilient, and inclusive cities;

c) Indoor Air Quality and Health (Blue Cluster): The importance of IAQ on human health is emphasized by the blue cluster. This includes identifying and/or mitigating pollutants like VOCs, particulate matter, and biological contaminants. Enhancing IAQ is crucial for ensuring occupants' health and well-being, aligning with SDG 3. Research in this area often explores advanced ventilation systems, air purification technologies, and the use of low-emission materials.

Achieving thermal comfort in buildings involves several challenges. Firstly, the design/operation of HVAC systems must be optimized to maintain comfort while minimizing energy consumption. However, building designers often overlook detailed considerations of thermal comfort, relying on generalized design inputs rather than context-specific data. This can lead to suboptimal indoor environments and higher energy use. Furthermore, many elements affect thermal comfort: radiant/surrounding temperature, humidity, air flow, and individual characteristics – clothing insulation, metabolic rate, etc.). Accurate modeling and assessment of these factors are necessary to create comfortable indoor environments (Enescu, 2017). The comfort zone, typically defined by a temperature range with 80-90% acceptance, varies depending on conditions

like humidity and the presence of ventilators. Adjusting these parameters for different climates and building types is essential for achieving optimal comfort (Li, Sun and Chen, 2023).

Building energy usage is significantly impacted by thermal comfort. Various factors (building shape/size, external weather conditions, system efficiency, and occupant behavior) influence energy use. Maintaining thermal comfort often requires substantial energy for heating and cooling, highlighting the need for energy-efficient building designs and systems (Yang, Yan, and Lam, 2014).

Studies show that occupants' behavior plays a crucial role in energy consumption. People adjust their environment to achieve comfort, which can lead to increased use of HVAC systems. Therefore, understanding and influencing occupant behavior is key to reducing energy use while maintaining comfort (Chen et al., 2021; Zhang and Calautit, 2022; Xu et al., 2023).. Implementing mixed-mode ventilation, which combines mechanical and natural ventilation, can also reduce energy consumption while enhancing thermal comfort (Peng et al., 2022). Beyond thermal comfort, indoor environmental quality encompasses factors like acoustic comfort, lighting quality, and air quality. These elements are interrelated and collectively influence occupants' satisfaction and health (Khovalyg et al., 2020). For instance, poor IAQ can lead to health issues, affecting comfort and productivity. Improving indoor environmental quality requires a holistic approach that considers all these factors (Bungau et al., 2024). Advanced building materials, efficient HVAC systems, and smart building technologies can help create healthier and more comfortable indoor environments. Continuous monitoring and adaptive control systems can also ensure optimal conditions are maintained (Halhouli Merabet et al., 2021).

Several areas require further research for enhancing building energy efficiency and thermal comfort. These include:

- a) Demographic Factors: Research should consider demographic variables like age, gender, and socioeconomic status, as these can influence thermal comfort perceptions and needs;
- b) Mixed-Mode Ventilation: More studies are needed to optimize mixed-mode ventilation systems, ensuring they effectively balance energy use and thermal comfort;
- c) Passive Building Design: Investigating passive design elements like window placement, wall-to-window ratios, and solar protection can reduce ventilation needs while maintaining comfort;
- d) Educational Institutions: More research is required on thermal comfort in educational buildings, particularly during hot seasons, to improve learning environments;
- e) Indoor Air Quality: Further studies on IAQ in various building types, including universities, are needed to understand and mitigate pollutant impacts;
- f) Advanced Control Systems: Developing and testing advanced HVAC control systems, including predictive modeling and machine learning, can improve energy efficiency or comfort.

Moreover, the implementation of technology transfer principles in the context of improving thermal comfort and indoor

environmental quality involves a systematic approach to disseminating knowledge, innovations, and best practices from research institutions to industry stakeholders, policymakers, and the public (Hellwig et al., 2019; Craiut et al., 2022).

Technology transfer's first step is to disseminate research findings, technological innovations, and best practices through publications in scientific journals, presentations at conferences, and reports (Alkhazaleh, Mykoniatis and Alahmer, 2022). Researchers publish their findings in peer-reviewed journals, which serve as a repository of knowledge accessible for all scientific community or practitioners alike (Ross-Hellauer et al., 2020). For instance, studies on innovative materials, smart HVAC systems, and urban greening strategies are published to share insights and evidence of their effectiveness (Hui et al. 2023; Peiris et al., 2023). Technology transfer thrives on collaborative partnerships between government entities, non-profit organizations, industry partners, and research institutions (Mikkonen et al., 2018). Collaborations encourage the sharing of knowledge, resources, and ideas necessary for translating research into practical applications. Industry partners provide insights into market needs and constraints, while researchers contribute scientific rigor and innovation. Government agencies often play a role in funding research projects and facilitating regulatory approvals for new technologies (Craiut et al., 2022).

Demonstrating the practical application of technologies in real-world settings is crucial for showcasing their benefits and building confidence among potential users. Demonstration projects involve implementing innovative technologies in pilot buildings or urban areas, where their performance can be monitored and evaluated. For instance, a smart HVAC system might be installed in a commercial office building to showcase reduced energy use and enhanced IAQ (Jia et al., 2019). Demonstration projects serve as living laboratories that validate technologies and provide valuable data for scaling up implementation. Technology transfer is facilitated by supportive regulations and rewards that promote the use of sustainable construction technology. Governments may offer financial incentives, tax credits, or grants to offset the initial costs of implementing energy-efficient technologies or green building practices. Policies such as building codes and standards also play a crucial role in mandating minimum performance requirements and fostering a market for innovative technologies that improve thermal comfort and indoor environmental quality (Corsi et al., 2020; Hafez et al., 2023).

Furthermore, for supporting a transition to sustainable building practices, policies and public initiatives are essential. Programs like Energy Star in the US have demonstrated significant energy savings and can act as examples for other regions. Building labeling and/or energy requirements can drive the use of designs and technology that save energy. In practice, designing buildings for thermal comfort and energy efficiency requires integrating various strategies, from passive design elements to advanced HVAC systems. Continuous education and collaboration among architects, engineers, and policymakers are crucial for implementing best practices and achieving sustainable development goals (Boyd, Dutrow and Tunnessen, 2008).

The selected method of analysis in this research study imposes certain constraints. The study exclusively included English-language documents; consequently, papers that may be of excellent quality and influence but were written in a different language were excluded. The primary constraint of this

investigation is the inability to manually verify each paper that was incorporated into the analysis for preventing the inclusion of incorrect results. The integration of artificial intelligence software to differentiate between papers that are relevant and false positives is the most probable solution for overcoming this final flaw in the near term.

5. CONCLUSIONS

The bibliometric study carried out on the IAQ and thermal comfort in buildings revealed a notable rise in attention from scientists within the last half decade, based on this topic. China and the US lead global research, publishing the largest number of articles in the field. The analysis also highlighted the importance of international collaboration, with strong links between China, the US, England and other European countries, demonstrating a global approach to these challenges.

Current research focuses on improving thermal control both inside construction and urban outdoor environment by using innovative materials and the integration of vegetation. At the same time, there is increased interest in studying IAQ and its resulting effects regarding human health, reflecting an increased concern for creating healthier and more sustainable living and working environments.

The complex interplay between individual preferences, environmental factors, and building design necessitates a holistic approach to achieving thermal comfort and energy efficiency. The use of phase change materials, advanced control systems, and innovative building technologies offers promising avenues for future research and practical application. As the global focus on sustainability and climate resilience intensifies, continued interdisciplinary collaboration and knowledge sharing will be essential to advancing the field and meeting the evolving needs of building occupants and the environment.

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