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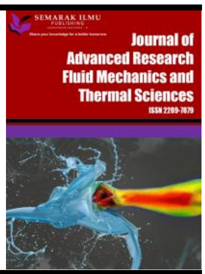

Triple Glazing Performance for Human Thermal Comfort: Systematic Literature Review and Bibliometric Quantitative Analysis

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ABSTRACT

This study investigates the development and performance of triple-glazing technologies in buildings, highlighting the increasing need for human thermal comfort. Despite the popularity of bibliometric analysis in business research, there remains a lack of quantitative analysis and in-depth evaluation specific to glazing technologies. This research employs Systematic Literature Review (SLR) and Bibliometric-Quantitative Analysis (BQA) methods, utilizing the PRISMA framework to select and screen 214 articles. Descriptive analysis and scientometric statistics are conducted using bibliometric software. Key findings reveal trends in thermal comfort, environmental impacts, energy performance, and cost-effectiveness of triple-glazing technologies. The analysis identifies primary challenges, such as managing condensation, balancing insulation with solar gain, and addressing the complexities of installation and initial costs. The research aims to provide a comprehensive understanding of current advancements and the factors influencing the adoption and implementation of triple-glazing technologies, thereby contributing valuable insights to sustainable building practices.

1. Introduction

Enhancing human thermal comfort in building technology has become paramount due to escalating energy prices and stricter environmental regulations [1]. In the United Kingdom alone, approximately 22% of greenhouse gas emissions originate from residential buildings, primarily through domestic heating processes [2]. Implementing measures to bolster home thermal efficiency, such as improved insulation, is crucial for reducing these emissions. Among various strategies, windows and doors are pivotal; typically, they account for 20-25% of heat loss in residences. Enhancing the thermal efficiency of these components not only elevates comfort levels within homes but also diminishes heating costs and carbon emissions.

However, most thermal losses—around 75%—still occur through other building elements like roofs, walls, and floors [3,4]. Addressing these areas through enhanced insulation and draft proofing is equally essential. Such improvements maximize the benefits of high-performance triple-glazed

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windows [5,6]. Against climate change challenges and the push for energy conservation, innovations in building technologies like triple glazing have garnered attention. This study delves into triple-glazing applications within buildings using a systematic literature review and bibliometric quantitative analysis, aiming to uncover recent advancements, persistent challenges, and emerging techniques in the field.

As the world grapples with the escalating challenges of climate change and the imperative to reduce energy consumption, advancements in building technologies have become central to sustainable development [7-9]. Triple glazing, a fenestration solution incorporating three layers of glass with insulating gas spaces, has emerged as a promising technology to enhance the energy efficiency of buildings [8,10,11]. This paper embarks on a comprehensive exploration of triple glazing in buildings through a systematic literature review and bibliometric quantitative analysis. By scrutinizing the current situation, challenges, cutting-edge techniques, and the conception of triple glazing, this study aims to contribute valuable insights to the discourse on sustainable building practices.

1.1 Current Situation and Challenges of Triple Glazing Window Performance

The current state of triple glazing in buildings is marked by a dynamic landscape where technological advancements intersect with challenges in achieving optimal window performance [3,12]. While holding significant promise for improving thermal insulation, triple glazing faces hurdles requiring careful consideration [13,14].

One of the primary challenges lies in the delicate balance between insulation and solar gain [2]. As the number of glass layers increases, there is a potential trade-off between enhanced insulation and increased resistance to solar radiation [4]. This section delves into the intricacies of this challenge, examining how climatic variations and building orientations influence the overall performance of triple-glazing windows [15].

Condensation poses another significant challenge to triple-glazing window performance [3,4]. The temperature differential between the glass layers' inner and outer surfaces can lead to condensation formation, affecting transparency and thermal performance [2]. This challenge necessitates a comprehensive understanding of environmental conditions and materials used to construct triple-glazing units [16]. Strategies to mitigate condensation and enhance overall performance are explored in the literature and will be examined in-depth in subsequent sections [17].

Additionally, the thermal performance of triple-glazing windows is influenced by factors such as the choice of glass coatings, spacer materials, and the type of gas filling the cavities [18-20]. Each of these components plays a critical role in determining the energy efficiency of the windows [21]. Therefore, a nuanced examination of these elements is essential to develop strategies that overcome current challenges and advance triple-glazing technology [22].

Understanding the current situation and challenges requires a comprehensive review of existing literature. This paper will systematically explore peer-reviewed articles, conference papers, and other scholarly works to distil critical insights into the performance hurdles triple glazing faces in diverse environmental contexts.

1.2 Overview of Cutting-edge Triple Glazing Techniques

In response to the challenges posed by conventional triple-glazing systems, ongoing research and innovation have led to the development of cutting-edge techniques designed to optimize triple-glazing performance in buildings [23,24]. This section provides a thorough overview of these techniques, focusing on advancements in materials, coatings, and design strategies that push the boundaries of what triple glazing can achieve.

Innovative glass coatings stand out as a cornerstone in addressing challenges related to solar gain and thermal insulation [13,14,25]. Low-emissivity coatings, for example, have demonstrated the ability to selectively filter and reflect infrared radiation while allowing visible light transmission [14,26]. This enables architects and designers to strike a delicate balance between harnessing natural light and mitigating heat gain, ultimately contributing to improved energy efficiency and occupant comfort [27,28].

Advancements in spacer materials represent another facet of cutting-edge triple-glazing techniques [27,29,30]. Traditional spacers, while effective, can contribute to thermal bridging [31,32]. Recent developments in warm-edge spacers, often composed of materials with lower thermal conductivity, aim to reduce heat transfer and enhance overall insulation [32,33]. Integrating smart technologies, such as dynamic glazing that adapts to changing environmental conditions, adds another layer of sophistication to triple glazing systems, making them more responsive and adaptable to real-time conditions [34-36].

While these cutting-edge techniques hold significant promise, their real-world applicability and effectiveness need thorough investigation [15,33,34]. This paper will critically assess the literature to distil these innovations' practical implications and performance metrics.

1.3 Conception of Triple Glazing

The conception of triple glazing is deeply rooted in the pursuit of energy efficiency, thermal comfort, and sustainability within the built environment [37,38]. Over the years, it has evolved from a simple insulation solution to a multifaceted technology considering various factors, including architectural design, materials science, and environmental impact [39,40].

The historical evolution of triple glazing traces back to the mid-20th century when concerns about energy conservation began to gain prominence [37,41-44]. Initial iterations of triple glazing primarily aimed at enhancing insulation by incorporating an additional glass layer, often filled with air or inert gases. This early conception focused on addressing the challenges of heat loss in colder climates.

As energy efficiency became a critical aspect of building design, triple glazing evolved to meet broader objectives [42,44]. The 1970s and 1980s witnessed increased experimentation with different materials and coatings to balance thermal performance with other considerations, such as solar gain and daylighting [43,45]. This period marked a conceptual shift, recognizing that triple glazing could play a role in passive solar design and overall building aesthetics.

In the 21st century, the conception of triple glazing has expanded further. It is no longer viewed merely as a solution to reduce heat transfer but as a dynamic component of sustainable architecture [46-48]. Concepts like "green building" and "net-zero energy" have propelled the development of triple-glazing systems that contribute not only to energy efficiency but also to the overall environmental impact of buildings [49-51].

The classification of triple glazing involves categorizing different systems based on variations in design, materials, and intended performance [51,52]. This classification is crucial for architects, builders, and researchers to make informed decisions regarding selecting and implementing triple-glazing systems. Moreover, an example of triple glazing is presented in Figure 1 [53].

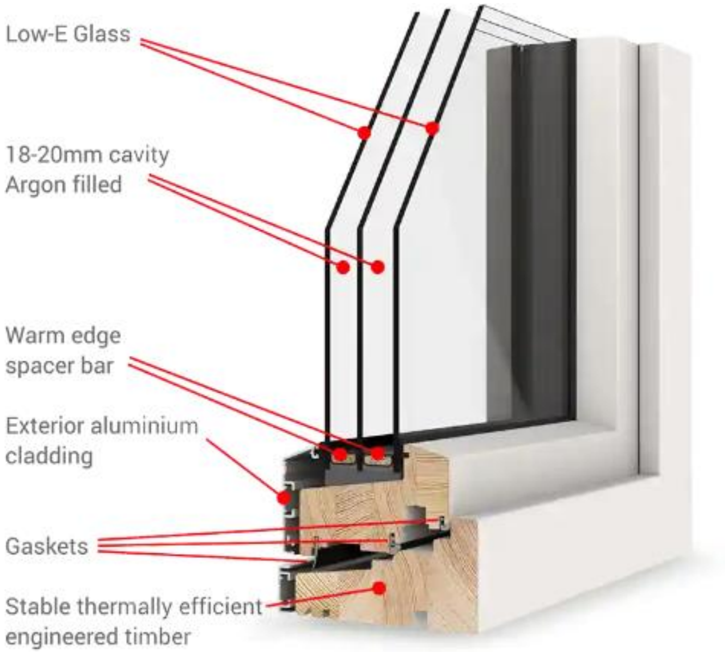

Fig. 1. A schematic diagram of a triple-layer glass

2. Research Methodology

This study employs a mixed-methods systematic review, integrating bibliometric analysis with a systematic literature review to meticulously investigate the development and application of triple-glazing technologies in building environments. This hybrid approach leverages the strengths of both quantitative and qualitative methods [54-56], providing a robust framework for understanding the current landscape and identifying gaps in the literature [53].

2.1 Overview of Mixed-Methods Systematic Review

The mixed-methods systematic review draws upon the benefits of quantitative and qualitative research techniques [57]. This approach enhances the reliability and validity of the research findings and minimizes potential biases by providing a comprehensive overview of the research topic [58]. By integrating different data types and analyses, the study aims to offer a more nuanced understanding of the complex dynamics within triple-glazing technologies [59,60].

2.2 Detailed Steps in the Research Methodology
2.2.1 Bibliometric analysis

The performance analysis phase uses bibliometric software to analyse the data extracted from a large corpus of literature [61]. This involves examining citation patterns, publication frequencies, and the impact of different research contributions within the field [62,63]. The performance analysis helps identify key authors, institutions, and countries that are significant contributors to the research area, providing insights into the core themes and trends that dominate the field [64,65].

Science mapping is conducted to visualize the relationships and networks between various research areas, authors, and publications [66,67]. This phase utilizes tools such as VOSviewer and CiteSpace to create network maps highlighting researchers' interconnections and collaborative patterns [68]. The maps also help identify emerging trends and the evolution of themes over time, offering a visual representation of the scientific landscape [69].

Network analysis delves deeper into the bibliometric data, exploring the structural and dynamic aspects of the literature [70]. It examines how different themes are interrelated and identifies research clusters that represent significant study areas [71]. This analysis is crucial for understanding how different research topics are interconnected and influence each other, providing a comprehensive view of the field's development [72].

2.2.2 Systematic Literature Review (SLR)

This study implements a rigorous selection and screening process following the PRISMA guidelines. Initially, a broad search uses predefined keywords to gather relevant articles from databases such as Scopus [73]. This initial pool of literature is then screened based on titles and abstracts to exclude irrelevant studies, with the remaining articles undergoing a full-text review to ensure they meet the inclusion criteria [74].

Data extraction involves detailed reading and coding of the selected articles to collect data on study characteristics, methodologies, findings, and conclusions [75,76]. This data is synthesized to identify patterns, themes, and gaps in previous literature [56]. The synthesis highlights the current state of research and provides insights into the effectiveness and challenges of triple-glazing technologies.

To ensure the credibility and reliability of the findings, a quality assessment is conducted on all included studies. This assessment evaluates the methodological rigor, transparency of reporting, and potential biases in the studies. The quality assessment helps refine the final selection of articles and ensures that the conclusions are based on high-quality evidence. All the detailed steps are plotted in Figure 2.

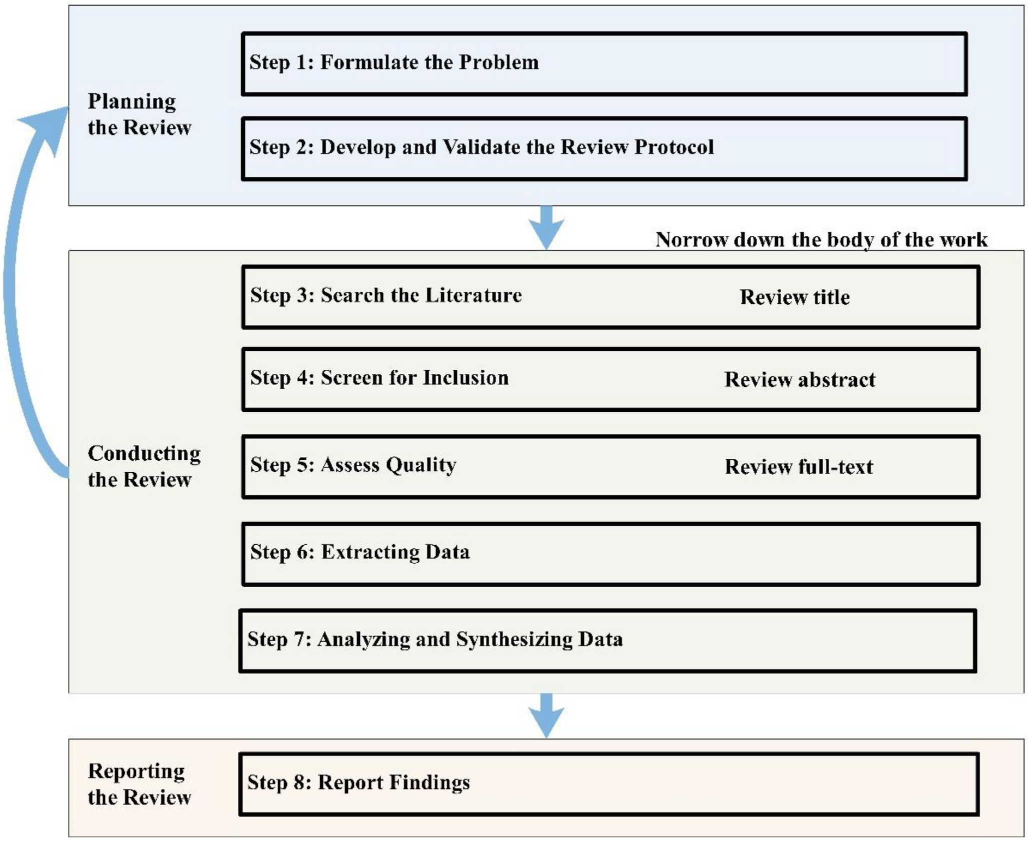

Fig. 2. Framework of systematic literature review

2.3 Data Collection Strategy

The data collection involves a systematic search of electronic databases using a combination of keywords related to triple glazing, thermal comfort, and energy efficiency. The search strategy is designed to be comprehensive, incorporating both broad and specific terms to capture a wide range of studies. The databases searched include major platforms like Scopus and Web of Science, which are known for their extensive scientific and technical literature coverage.

The inclusion criteria specify that studies must be peer-reviewed articles or conference papers focusing on triple glazing and its applications in buildings. Exclusion criteria remove studies that are not in English, are not peer-reviewed, or do not directly address the research questions. This selective approach ensures that the review focuses on relevant and high-quality studies.

2.4 Analytical Framework

The study's analytical framework is designed to evaluate the literature findings systematically. It involves categorizing the data into thematic areas such as technological innovations, performance metrics, and application challenges. This framework facilitates a structured literature analysis and identifies systematic trends and key drivers in the research on triple-glazing technologies.

2.5 Ethical Considerations

Given the nature of this systematic review, the primary ethical consideration involves properly citing and acknowledging the data sources. The study adheres to ethical standards in scholarly publishing by ensuring that all sources are accurately quoted and permissions are obtained for any copyrighted material used in the review.

3. Data Collection for the Literature

3.1 Literature Search Strategy

3.1.1 Defining search terms and keywords

The first step in the data collection process involves developing a robust set of search terms and keywords. These terms are carefully selected to cover all potential variants and combinations relevant to triple-glazing technologies and their applications in improving building energy efficiency. Keywords such as "triple glazing," "thermal insulation windows," "energy-efficient buildings," and "sustainable construction materials" are combined with broader terms like "building technology" and "green building standards" to ensure comprehensive coverage, as Table 1 shows.

Table 1
Keywords and literature search results

String	Results
TITLE-ABS-KEY ("Thermal comfort" OR "Thermal satisfaction" OR "Thermal wellness" OR "Thermal well-being" OR "Comfortable warmth" OR "Pleasant temperature" OR "Optimal thermal environment" OR "Thermal harmony" OR "Thermal balance" OR "Thermal contentment" OR "Thermal coziness" OR "Comfortable climate" OR "Three-layer glazing" OR "Triple-pane windows" OR "Triple-pane glazing" OR "Three-fold glazing" OR "Triple-insulated windows" OR "Three-sheet glazing" OR "Triply glazed windows" OR "Triple-layered glazing" OR "Three-times glazed" OR "Triple-coated windows" OR "Three-cased glazing" OR "Triple-paned windows" OR "Three-tiered glazing" OR "Triple-glass windows" AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (SUBJAREA, "Social Sciences," "Engineering," and "Arts and Humanities.")) AND (LIMIT-TO (LANGUAGE, "English")) Manual screening based on the results of searching*	214

*Note: the Scopus research was conducted in May 2024.

3.1.2 Selection of databases and sources

The literature search spans several academic databases renowned for their extensive scientific and engineering research repositories. Primary databases include Scopus, Web of Science, and Google Scholar. These platforms are chosen for their comprehensive coverage, credibility, and accessibility of peer-reviewed articles, conference papers, and technical reports. Additionally, industry reports, white papers, and standards documents from organizations such as the International Energy Agency (IEA) and the Green Building Council are reviewed to incorporate practical insights and current industry practices.

3.2 Data Extraction Process
3.2.1 Initial search and data retrieval

An initial query is conducted across the selected databases using the defined search terms. This query is structured using Boolean operators to refine the search results and enhance the relevance of the retrieved documents. The initial search results are exported into bibliographic management software such as Zotero, which assists in organizing and screening the literature for further review.

3.2.2 Screening and eligibility checks

The retrieved articles undergo a two-stage screening process. The first stage involves a review of titles and abstracts to filter out studies that do not directly pertain to the scope of triple glazing in building applications. The second stage includes a full-text review where articles are assessed against a detailed set of inclusion criteria. These criteria ensure the studies are relevant and recent and provide significant insights into the research questions.

3.3 Application of inclusion and exclusion criteria

The inclusion criteria for the literature are defined as follows:

i. Peer-reviewed articles published within the last 20 years.
ii. Studies focus on applying, performing, or evaluating triple-glazing technologies.
iii. Articles that provide empirical data, case studies, or detailed reviews of existing technologies and their applications.

iv. Studies published in English.
v. Exclusion criteria include:
vi. Non-peer-reviewed sources such as blogs, non-academic publications, and informal reports.
vii. Studies that do not provide specific insights into triple glazing but focus on general building technologies.
viii. Duplicate studies or previous versions of updated research works.
ix. Articles not accessible in full-text format.

3.4 Quality Assessment
3.4.1 Assessment criteria

To ensure the high quality and relevance of the selected studies, a rigorous quality assessment is performed based on several criteria:
i. Methodological rigor: Studies must display a transparent and reproducible research methodology.
ii. Relevance to the research questions: Articles must directly contribute to answering the research questions posed in this study.
iii. Impact and citation metrics: High citation counts can indicate the influence and recognition of the research within the academic community.

3.4.2 Tools and techniques for assessment

Tools such as VOSviewer and CiteSpace are used to perform citation analysis, helping to identify highly influential works and key research clusters. This bibliometric approach supplements the manual quality assessment by objectively measuring the research impact.

3.5 Data Synthesis and Analysis
3.5.1 Coding and categorization

Data extraction involves detailed coding and categorization once the final literature set is determined. Information regarding research methodologies, findings, geographical focus, and technological innovations is systematically extracted and categorized to facilitate comparative analysis.

3.5.2 Thematic analysis

A thematic analysis is conducted to identify and synthesize common themes, trends, and gaps in the literature. This analysis helps us understand the evolution of triple-glazing technologies over time and their impact on building thermal comfort.

3.5.3 Cross-validation and reliability checks

To enhance the reliability of the findings, cross-validation is performed where possible, comparing data points across multiple studies. This process helps confirm the consistency and accuracy of the reported results.

3.6 Ethical Considerations and Copyright Compliance

Throughout the data collection process, ethical considerations are rigorously maintained. Proper attribution is given to all sources, and copyright laws are respected, ensuring that all materials used are appropriately licensed or fall within fair use parameters.

3.7 Limitations of the Data Collection Process

While efforts are made to ensure comprehensive and unbiased data collection, limitations include potential publication bias, where only studies with positive findings are published. Additionally, excluding non-English articles might omit relevant international research that could contribute valuable insights into the field. To do that, the whole PRISMA is presented in Figure 3.

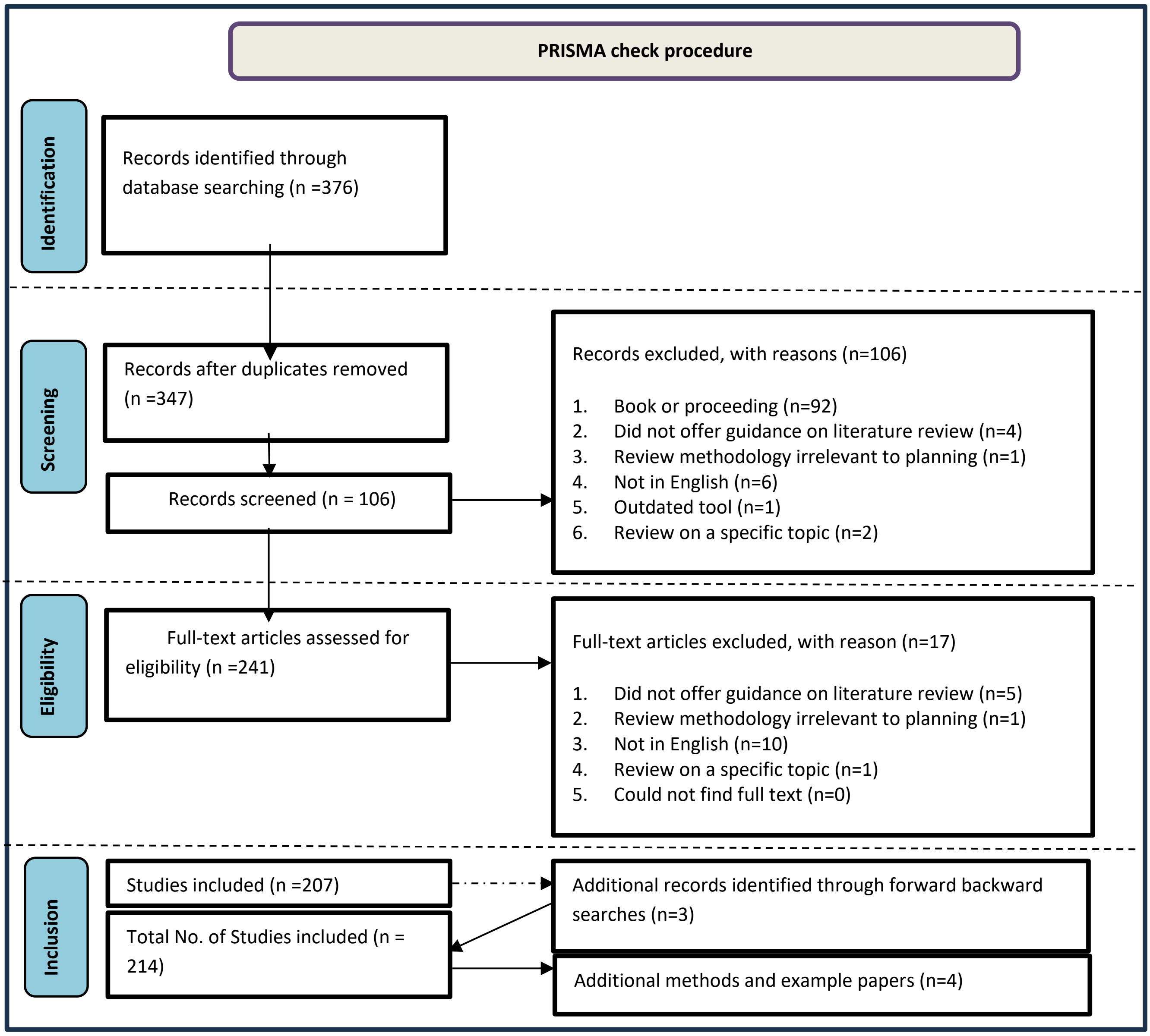

Fig. 3. PRISMA check procedure

4. Literature Descriptive Analysis and Scientometric Statistics

In the preceding section, the procedure for data gathering and selection was detailed. The current section collects and reviews literature data, followed by statistical analysis [69]. It presents a descriptive analysis of the gathered data. Utilizing statistical and mathematical methods, descriptive literature analysis can produce quantitative data from extensive historical literature [77]. The analysis results can be graphically represented through visual knowledge mapping and knowledge structure analysis.

Conducting a descriptive literature study involves two primary steps: exterior feature analysis and content analysis [63]. Exterior feature analysis, which examines growth trends, impact, and author distribution by region, relates to trends in academic fields, leading researchers, and regional development. Content analysis employs visualization techniques such as co-occurrence analysis, cluster analysis, and strategic coordinate analysis to illustrate changes in research popularity and knowledge structure systems over time [78-80]. This section covers descriptive analysis, while systematic analysis will be discussed in the following section. The analysis in this section will utilize the following software tools.

4.1 The First Step of Bibliometric Analysis: Performance Analysis

This section details the step-by-step process of performance analysis, the initial phase of bibliometric assessment. As the starting procedure of bibliometric evaluation, it employs objective data generated from specific tools and software to uncover metrics related to publications, citations, and combined citation-publication metrics.

4.1.1 Overview of main information regarding thermal comfort with glazing

The selected 214 articles on thermal comfort with glazing can be extensively analysed using the visualization software RStudio. After extracting and importing data from various databases into RStudio, this powerful software generates a comprehensive overview of the primary information and the annual scientific production related to thermal comfort in glazing areas. Figure 4 presents the main information overview.

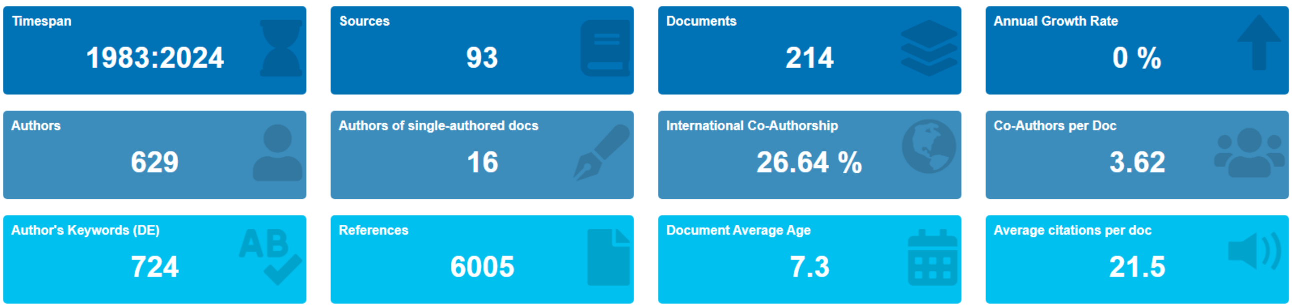

Fig. 4. Overview of the leading information regarding thermal comfort with glazing

The data extracted from Rstudio covers a substantial timespan from 1983 to 2024, incorporating insights from 214 documents from 93 journals, books, and other scholarly materials. The documents exhibit an average age of 7.3 years, suggesting a relatively recent and contemporary focus on the subject matter. The citation landscape is robust, with an average of 21.5 citations per document, underscoring the scholarly impact and relevance of the literature. The comprehensive analysis extends to 440 Keywords Plus (ID) and 724 Author's Keywords (DE), providing a nuanced understanding of the terminology and conceptual framework employed in the research landscape. The 629 authors involved in the study reflect a collaborative effort, with 16 single-authored documents and an average of 3.62 co-authors per document. The international co-authorship rate of 26.64% highlights a global perspective in the scholarly discourse on triple glazing in buildings. Document types include 203 articles, one combined with a book chapter, and five articles, each classified as early access and proceedings paper, showcasing the diverse nature of the literature. With a total of 6005 references, the study is well-grounded in existing knowledge, drawing on a broad spectrum of sources. This bibliometric analysis provides a comprehensive overview of the research landscape surrounding triple glazing in buildings, emphasizing its global, collaborative, and well-cited nature while underlining the contemporary focus and breadth of the existing literature.

4.1.2 Annual scientific publications

The dataset on annual scientific publications, spanning from 1994 to 2024, reveals distinct phases in research trends concerning window performance for human thermal comfort. These phases are delineated into three major stages, each characterized by unique traits and developments within the field, as detailed in Figure 5. Each stage represents a specific period with observable patterns and shifts in the focus of research activities.

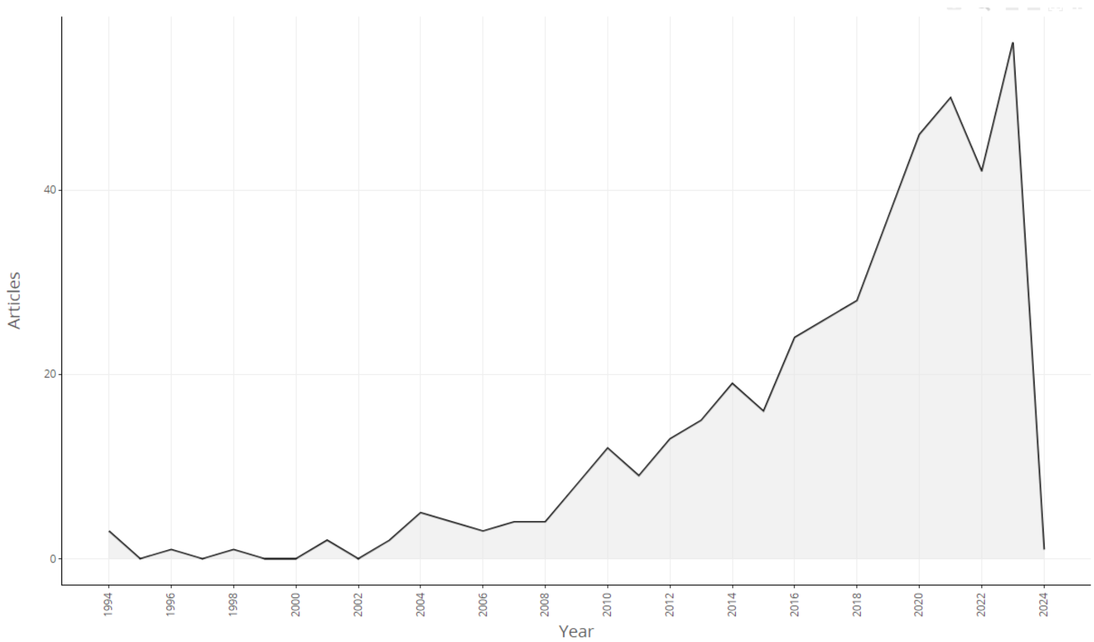

Fig. 5. Number of publications from 1994 to January 2024

Stage 1 (1994-1996): Emergence and early exploration

The initial stage is marked by sporadic interest, with minimal publications from 1994 to 1996. Researchers begin exploring the concept of triple glazing in buildings, laying the groundwork for future investigations.

Stage 2 (1997-2016): Incremental growth and maturation

From the late 1990s to the mid-2010s, there is a notable uptick in publications, reflecting increased awareness and a more focused exploration of triple glazing. This stage signifies incremental growth, with researchers delving into technical, economic, and environmental aspects, leading to the field's maturation.

Stage 3 (2017-2024): Prolific engagement and potential transition

The latter part of the analysed period witnesses a surge in scholarly activity, reaching its peak in 2018 and 2021. This stage suggests a culmination of cumulative knowledge and a heightened level of engagement. However, the slight decline in publications from 2022 to 2024 may indicate a potential transition or stabilization as researchers reassess priorities or focus on consolidating existing knowledge.

4.1.3 Three-field plot analysis

The three-field plot analysis facilitates understanding the interrelations among three distinct dimensions: journal sources, authors, and countries [81]. This method visualizes the connections within the dataset by examining the relationships between these variables. As shown in Figure 6, the arrangement from left to right represents journals (SO), authors (AU), and countries (AU_CO), respectively. RStudio creates relational maps where the thickness of the lines between items reflects the strength of their relationships, with thicker lines indicating stronger connections [82]. The size of each label denotes the frequency of terms within the relevant publications, and larger bars indicate more significant numbers of references, keyword occurrences, and author contributions. Distinct colors in the visualization delineate different thematic clusters.

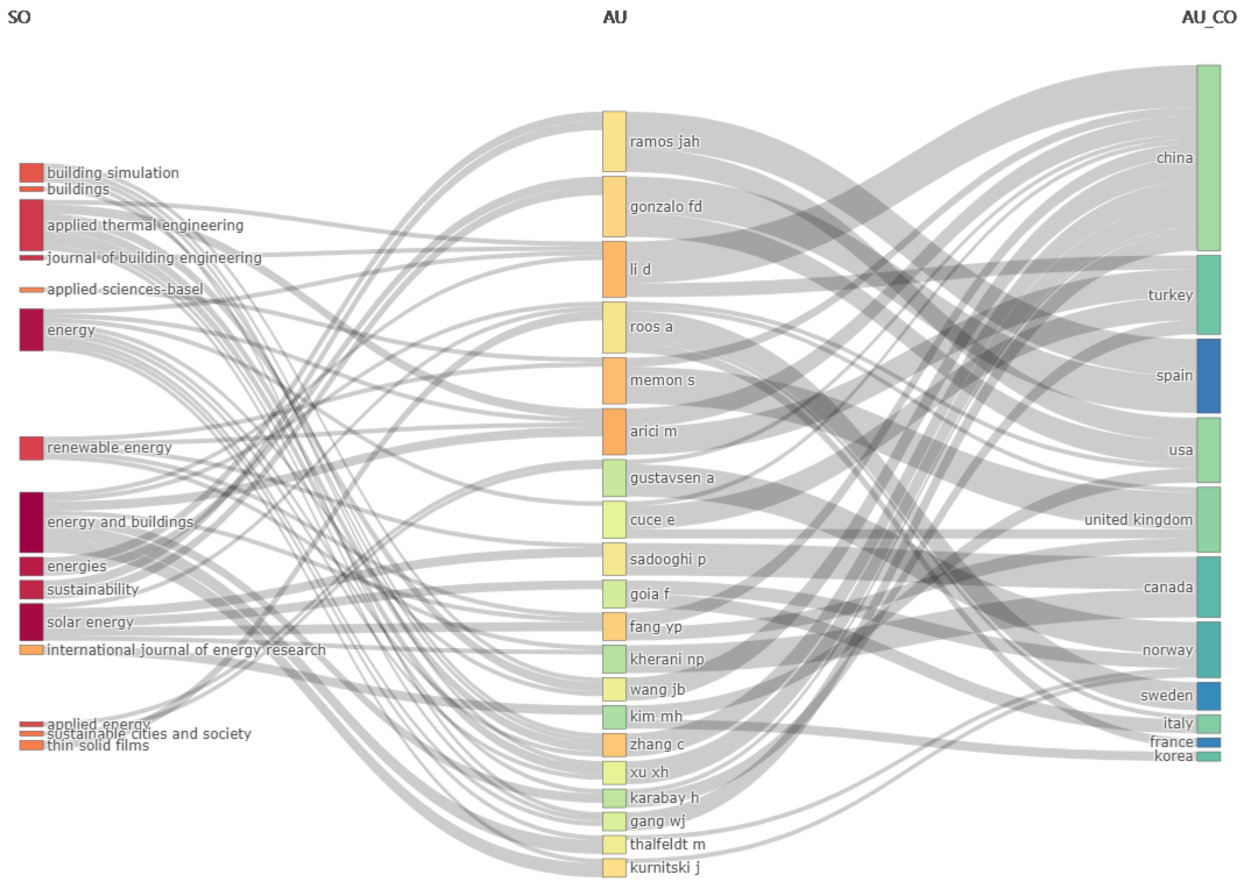

Fig. 6. Three-Field Plot analysis

In Figure 6, 15 journals are featured, with 'Energy and Buildings' (SO=13) and 'Applied Thermal Engineering' (SO=11) having the highest number of publications, followed by 'Energy' (SO=9). Twenty authors contributed to 28 'Energy and Buildings studies,' with 'Building Simulation' accounting for eleven. Prominent among these authors are Ramos, J. (AU=13), Gonzalo, F. (AU=13), and Li, D. (AU=12), who have the highest number of publications. Regarding the country variable, China (AU_CO=40), Turkey (AU_CO=17), Spain (AU_CO=16), the USA (AU_CO=14), and the UK (AU_CO=14) are identified as the most connected, demonstrating significant scholarly output in this research area.

4.1.4 Analysis of key sources and highly cited works

Figure 7 illustrates an exhaustive review of the most pertinent literature concerning thermal comfort in glazing systems, covering an analysis of 278 articles from various academic journals. This comprehensive examination underscores the global scope and foundational texts shaping this field of study.

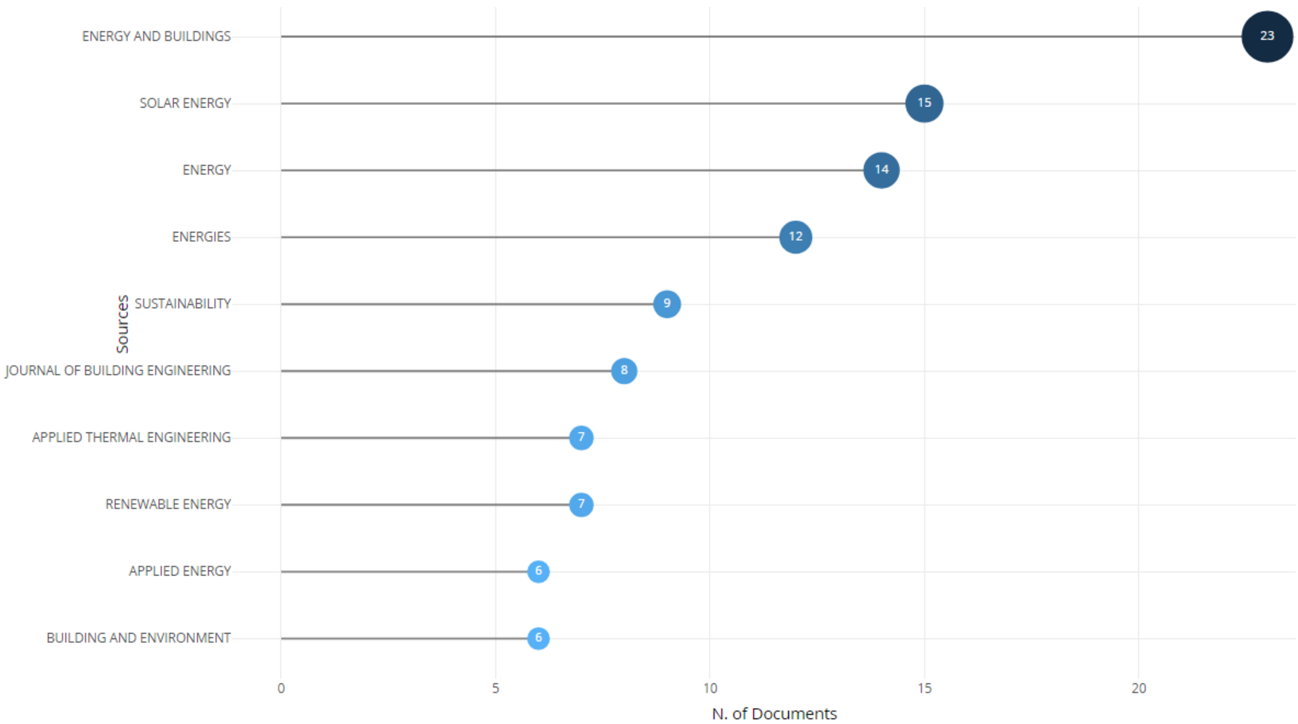

Fig. 7. Most relevant sources for thermal comfort with glazing area

The Most Relevant Sources data extracted from Rstudio for the systematic literature review and bibliometric quantitative analysis of "Triple glazing in buildings" reveals key journals and publications that have significantly contributed to the scholarly discourse. The leading source is the journal "Energy and Buildings," with 23 publications, underscoring its pivotal role in housing a substantial body of research on the topic. Following closely is "Solar Energy" and "Energy," with 15 and 14 publications, respectively, indicating the intersection of triple-glazing research with solar and general energy domains. "Energies" and "Sustainability" also contribute 12 and 9 publications, emphasizing the broader context of sustainable energy solutions. The "Journal of Building Engineering" and "Applied Thermal Engineering" are notable platforms with 8 and 7 publications, respectively, highlighting their significance in disseminating research findings in building engineering and thermal aspects. Other vital journals such as "Renewable Energy," "Applied Energy," and "Building and Environment" each contribute a substantial number of publications, showcasing a diverse array of sources influencing the discourse.

Interestingly, "Noise Control Engineering Journal" and "Journal of Raman Spectroscopy" suggest considering acoustic and spectroscopic aspects in the study of triple glazing. Moreover, "Sustainable Cities and Society" underscores a commitment to exploring the societal implications of energy-efficient building solutions. The data also includes contributions from materials science journals like "Thin Solid Films" and "Solar Energy Materials and Solar Cells," showcasing an interdisciplinary perspective. Overall, this analysis of Most Relevant Sources provides a nuanced understanding of the diverse range of journals shaping the discourse on triple glazing in buildings, emphasizing the interdisciplinary nature of the research and its intersection with fields such as energy, sustainability, engineering, and materials science. Additionally, trend topics extracted from selected author's keywords for this area are plotted in Figure 8.

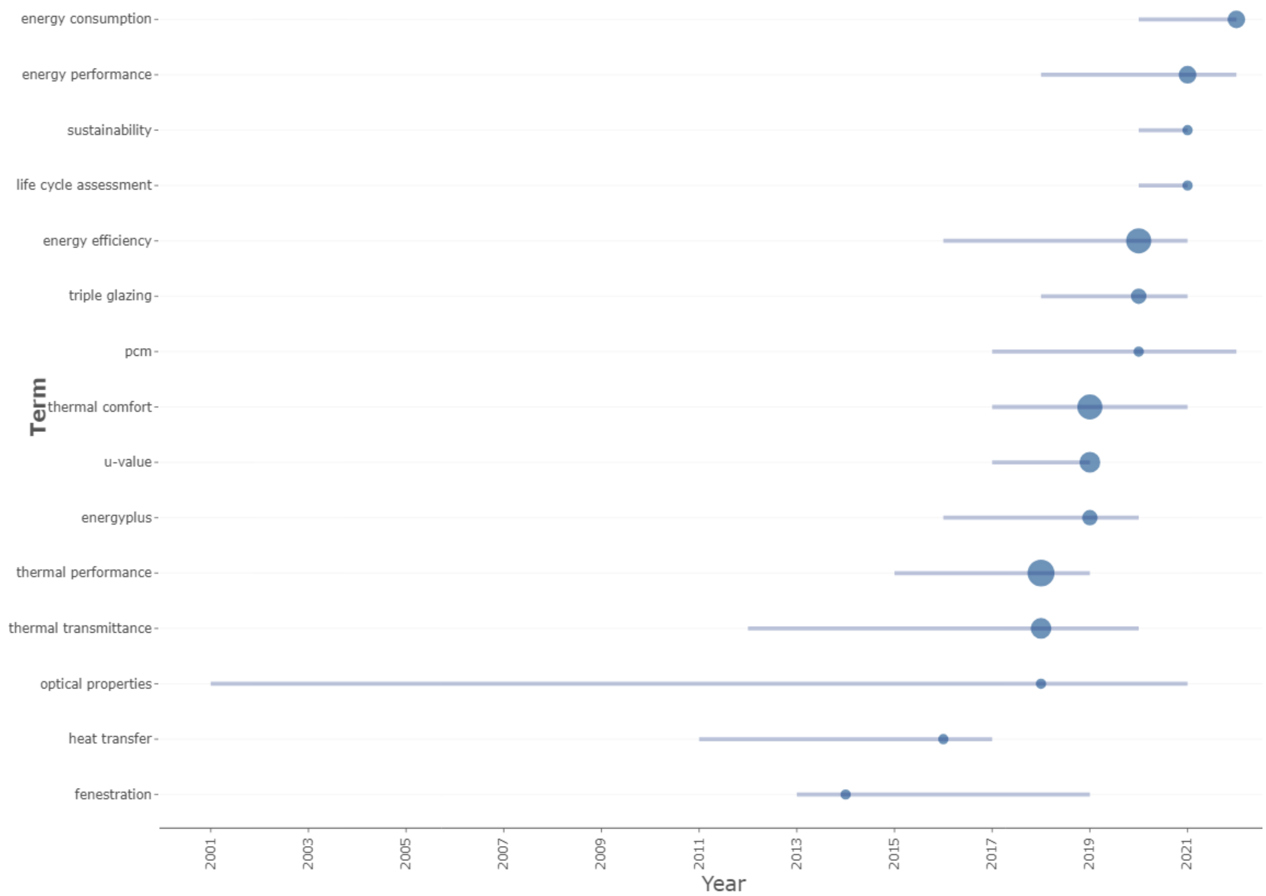

Fig. 8. Current trending topics within the thermal comfort domain related to glazing

4.2 Second Step of Bibliometric Analysis - Science Mapping

Following the initial performance analysis, the second step in our bibliometric investigation is science mapping. This analysis delves into the intricate connections between different scholarly works, facilitating a deeper understanding of the relationships within the corpus of literature.

This phase employs several analytic techniques to map the relationships among publications:

i. Co-authorship Analysis: This method assesses the intensity of collaboration by examining the number of joint publications.
ii. Co-occurrence Analysis: It explores how frequently specific terms appear across the literature, providing insight into thematic connections.
iii. Citation Analysis: This approach evaluates the influence of studies by counting the frequency of citations amongst them.
iv. Bibliographic Coupling: Here, the focus is on the common references between documents to determine relatedness.
v. Co-citation Analysis: This technique measures the strength of relationships based on how frequently articles are cited together [77,80,83-86].

Despite its critical importance, the research on thermal comfort in glazing systems is relatively underrepresented, with only 214 pertinent articles identified through a comprehensive database search. These articles contributed 1081 keywords. Using the VOSviewer software for visualization, keywords occurring at least five times were further analysed, narrowing the focus to 61. The relational strength of these keywords was meticulously quantified, identifying the most significant terms based on their link strength within the network. The findings from this co-occurrence analysis are detailed in Figure 9, highlighting key focus areas and their interconnections within the field.

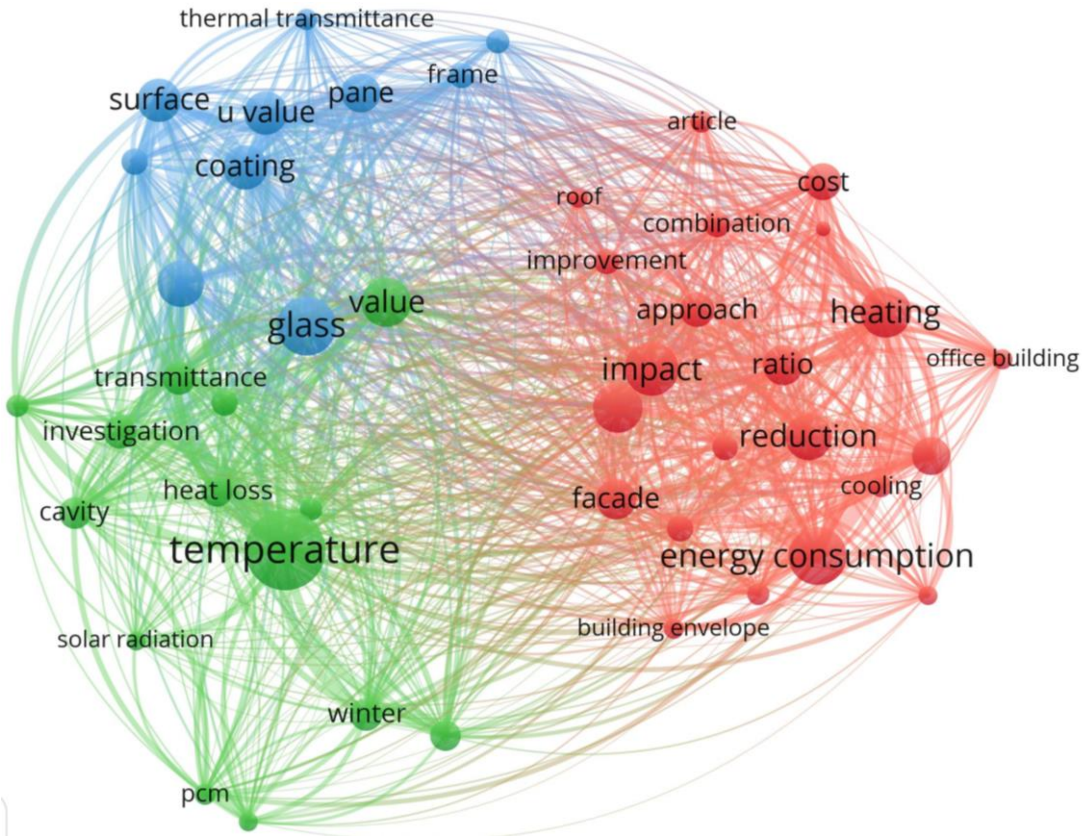

Fig. 9. Co-occurrence network of keywords of thermal comfort with glazing

The visual representation provided by the map file illustrates the co-occurrence networks of keywords about thermal comfort in glazing systems. Analysed using the VOSviewer software, the map clusters keywords by their similarities. In this visualization, the proximity between nodes, the size of each node, and the node colour correspond to the relational strength, frequency of occurrence, and keyword clusters, respectively. This arrangement facilitates understanding the key themes and their interrelations within the field [77,84].

The Co-occurrence network of keywords derived from VOSviewer for "Triple glazing in buildings" provides a comprehensive overview of the thematic structure and interrelationships within the research field. The keywords are grouped into three distinctive clusters, each shedding light on key aspects of the topic. Cluster 1 predominantly centres around building design and energy-related concepts, encompassing terms such as "building envelope," "case study," "comparison," and "energy consumption." This cluster reflects a holistic exploration of energy-efficient building design approaches and the impact of triple glazing. Cluster 2 delves into the thermal performance and material aspects of triple glazing, featuring keywords like "cavity," "heat loss," "investigation," "measurement," and "solar radiation." The emphasis on these terms suggests a nuanced investigation into the materials, thermal dynamics, and performance metrics associated with triple glazing. Cluster 3 revolves around the technology and components of triple glazing systems, as indicated by keywords like "coating," "frame," "glass," "heat transfer," "surface," and "u value." This cluster underscores the technological intricacies of triple glazing, emphasizing the importance of coatings, frames, and thermal transmittance in achieving optimal performance. The co-occurrence of "PCM" (phase change material) within Cluster 2 suggests an interest in innovative materials for thermal regulation. Overall, the interconnectedness of keywords across clusters signifies a multidisciplinary approach, where building design, thermal dynamics, and technological components collectively contribute to the systematic understanding of triple glazing in buildings. Additionally, "comparison" and "investigation" act as integrative themes, bridging various clusters and emphasizing the prevalence of analytical and comparative methodologies within the scholarly discourse. This network analysis provides a nuanced lens to comprehend the multifaceted dimensions of triple-glazing research, highlighting the intersections of building design, thermal performance, and technological advancements in the quest for energy-efficient and sustainable building solutions.

4.3 Third Step of Bibliometric Analysis - Network Analysis

The final component of the bibliometric analysis involves network analysis, which augments the outcomes of earlier analytical techniques in bibliometric research, aligning with the methodologies proposed by Donthu *et al.,* [59]. This phase employs three distinct approaches, network metrics, clustering, and visualization, to enhance the understanding of the dataset.

4.3.1 Cluster analysis

While preliminary observations of the visualized networks might reveal noticeable clusters, CiteSpace offers a more rigorous method for detecting and delineating these clusters through its advanced clustering capabilities [59,80,87].

Using CiteSpace, a cluster analysis was performed to elucidate the core themes and prominent research areas within the field, spanning from 1994 to 2024 with annual increments [88]. The study employed the log-likelihood ratio (LLR) to label the clusters shown in Figure 10. The high modularity Q value of 0.789 indicates effective clustering, characterized by dense interconnections within clusters and fewer connections between them. The substantial mean silhouette value of 0.9066 further attests to the homogeneity within these clusters. This analysis highlights that while the volume of research on thermal comfort is limited, the existing literature is closely interconnected and focuses on overlapping issues within the field. Nevertheless, vast areas remain underexplored, meriting deeper investigation.

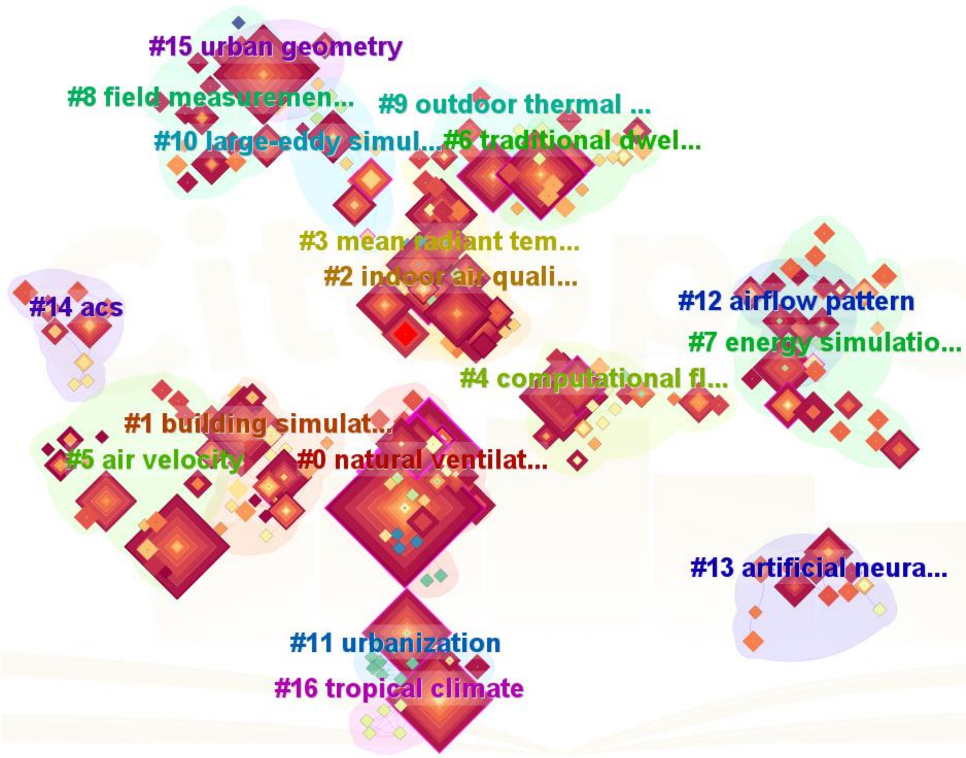

Fig. 10. Keywords cluster analysis visualization

The cluster analysis generated from Citespace for the systematic literature review and bibliometric quantitative analysis of "Triple glazing in buildings" reveals a diverse landscape of interconnected research themes within the broader context of building design, energy efficiency, and environmental quality. Cluster 1 centres around the core concepts of building design, comfort, and thermal environments, with keywords such as "buildings," "comfort," "natural ventilation," and "thermal comfort." This cluster underscores the significance of creating energy-efficient and comfortable indoor spaces. Cluster 2 delves into specific aspects related to thermal performance, including "heat loss," "heat transfer," and "temperature." Including "cavity" and "PCM" suggests exploring innovative materials and technologies to enhance thermal dynamics. Cluster 3 focuses on technology and performance, featuring terms like "coating," "frame," "glass," and "u value," emphasizing the technological intricacies of triple glazing systems. Notably, the cluster analysis extends beyond the immediate scope of triple glazing, encompassing broader environmental considerations such as "urban heat island," "outdoor thermal comfort," and "air quality" in Cluster 4. This cluster suggests an interdisciplinary approach, acknowledging the interplay between building technologies and the larger urban and environmental context. Including keywords related to numerical simulations, models, and air quality dispersion in Clusters 2 and 3 highlights the role of advanced modelling techniques in understanding the performance of triple glazing.

Additionally, Clusters 7, 9, and 12 suggest connections to human behavior, health, and mitigation strategies, indicating a holistic approach that considers the broader societal and environmental implications of triple glazing. Overall, this cluster analysis paints a comprehensive picture of the multifaceted dimensions explored in the literature on triple glazing, ranging from building design and technology to environmental quality, health considerations, and urban microclimates. The interconnectedness of these thematic clusters signifies a rich and integrated research landscape, emphasizing the importance of a holistic approach in advancing knowledge and innovation in the field of triple glazing in buildings.

The Citespace cluster analysis for "Triple glazing in buildings" reveals thematic clusters encompassing building design, thermal dynamics, technology, and broader environmental concerns. Interdisciplinary in nature, it incorporates advanced modelling techniques and explores the societal implications of triple glazing, succinctly offering a holistic perspective on the subject. Apart from that, Figure 11 unveils the iteration of keywords by timeline.

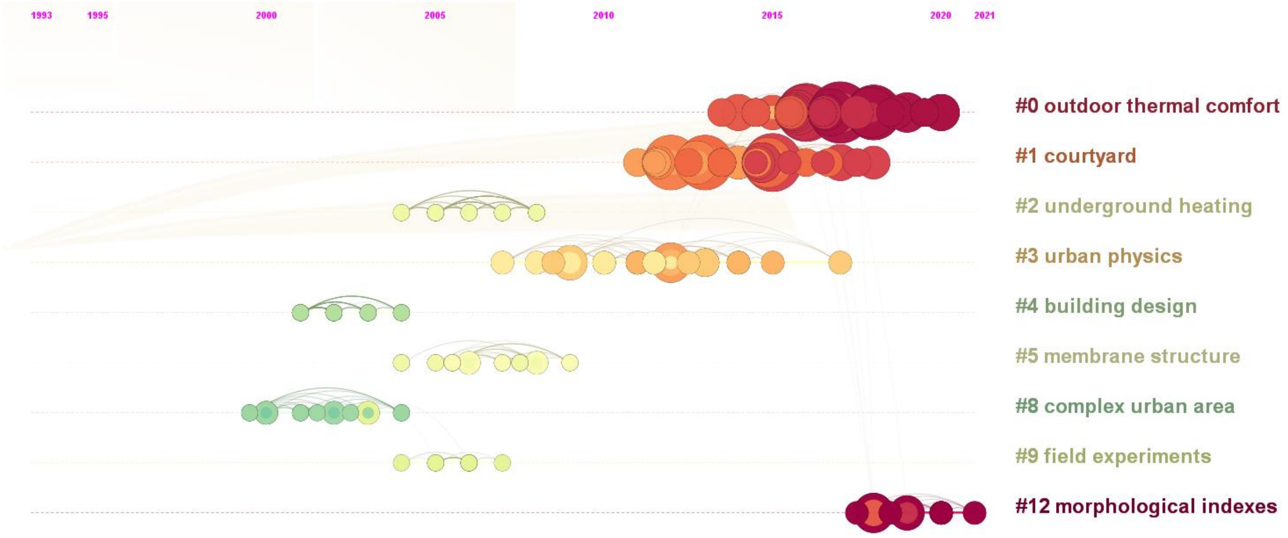

Fig. 11. Iteration of keywords by time zone

4.3.2 Citation burst analysis and interpretation

The Citation burst analysis conducted via CiteSpace identifies keywords that have demonstrated significant increases in frequency over a designated timeframe, indicative of emerging trends or rapidly developing areas within the field. This analysis captured 25 keywords that exhibited pronounced bursts of citations, as depicted in Figure 12. This method highlights the dynamically evolving topics that are garnering increasing scholarly attention.

The data reveals the top 25 keywords with the strongest citation bursts identified through Citespace analysis. Notable bursts include "air quality" with a peak strength from 2005 to 2012, suggesting a sustained scholarly interest in this aspect over the specified period. "Computational fluid dynamics" and "ventilation system" exhibited intense bursts in 2012, indicating a concentrated surge in research attention. "Prediction" experiences a peak burst from 2013 to 2014, reflecting heightened interest in predictive modelling. Keywords such as "microclimate modelling," "urban microclimate," and "green roofs" showcase notable bursts, indicating dynamic and evolving trends in environmental and climatic studies within the specified timeframe.

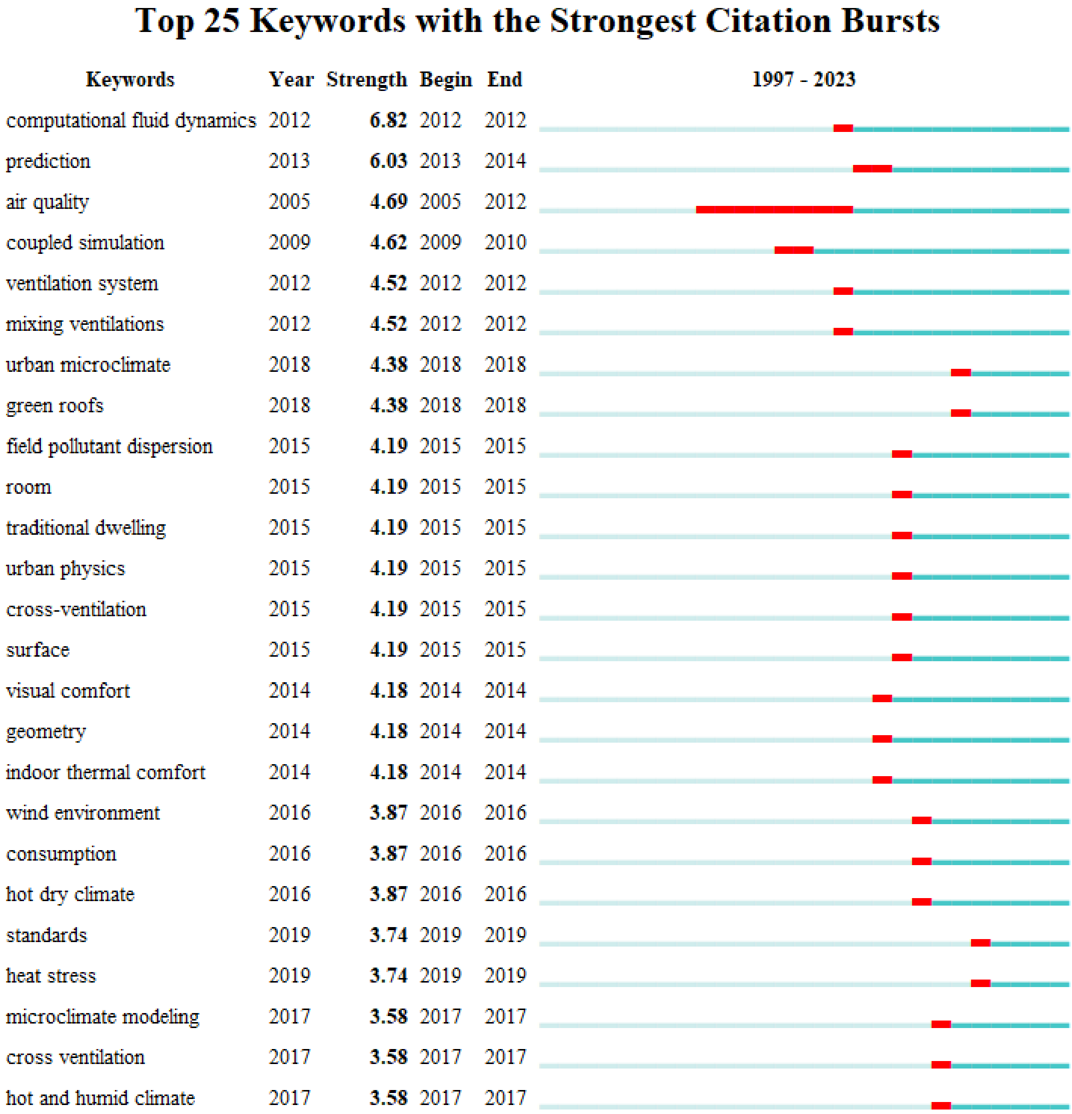

Fig. 12. Top 25 keywords with the highest Citation burst in the literature

5. Systematic Analysis of Triple Glazing Systems from Literature

In this section, the study advances into a detailed discussion grounded on the systematic literature review and the bibliometric quantitative evaluation of triple-glazing technologies in building construction. This section uses a SWOT analysis framework to dissect the strengths, weaknesses, opportunities, and threats relevant to implementing triple glazing within architectural designs. The objective is to crystallize crucial insights, pinpoint prevailing research voids, and present an integrated perspective on the accumulated knowledge surrounding this technology.

By methodically analysing the attributes and limitations of triple glazing systems, alongside the potential enhancements and challenges they face, this assessment aims to contribute to a more nuanced understanding of the field. The comprehensive analysis is designed to support stakeholders in making informed decisions and fostering innovations in building technology that aligns with sustainable development goals.

5.1 Strengths of Triple Glazing Systems on Buildings

Strengths encompass the positive attributes and advantages associated with triple glazing in buildings. Identifying and understanding these strengths is essential for recognizing the potential benefits that triple glazing can offer to architectural design and energy efficiency.

One of the undeniable strengths of triple glazing is its superior thermal performance [89,90]. The additional glass layer, combined with gas-filled cavities and advanced coatings, significantly reduces heat transfer, enhancing the insulation properties of buildings [91]. This strength is particularly crucial in regions with extreme climates, where efficient insulation can contribute to substantial energy savings [92].

Triple glazing contributes to improved energy efficiency in buildings by minimizing heat loss and reducing the reliance on heating and cooling systems [3,93]. This strength aligns with global efforts to create sustainable and environmentally friendly structures, ultimately lowering the carbon footprint associated with building operations [94].

Triple glazing balances energy efficiency and occupant comfort by allowing ample natural light into buildings while mitigating glare and excessive solar heat gain [95,96]. This strength positively impacts the overall well-being of occupants, creating a comfortable and well-lit indoor environment [97,98].

With a growing emphasis on sustainable building practices, triple glazing aligns with environmental goals by enhancing energy performance and reducing the need for artificial heating and cooling [90,99]. This strength positions triple glazing as a valuable component in green building initiatives [100-103].

5.2 Weaknesses of Triple Glazing Systems on Buildings

Weaknesses encompass the challenges and limitations associated with triple glazing. Understanding these weaknesses is crucial for addressing potential drawbacks and optimizing the technology for various architectural contexts [82,94,104].

One notable weakness of triple glazing is the propensity for condensation to form between glass layers [16,105]. This issue can compromise visibility and thermal performance [106,107]. Managing condensation remains challenging, especially in climates with varying temperatures and humidity [108].

The additional glass layer and gas-filled cavities contribute to the weight of triple-glazing units [95,109,110]. This can pose challenges during installation and may require adjustments to building structures [48,111,112]. Moreover, the complexity of installation can increase costs and limit its applicability in certain construction scenarios [113,114].

While the long-term energy savings are evident, the initial cost of triple-glazing systems can be higher than that of conventional double-glazing [115]. This financial barrier may hinder widespread adoption, particularly in tight-budget projects [33,116].

Achieving an optimal balance between thermal insulation and solar gain can be challenging [11,27]. In some cases, the benefits of reduced heat loss may be offset by increased solar heat gain, especially in warmer climates [117,118]. This requires careful consideration and customization based on specific environmental conditions [119].

5.3 Opportunities of Triple Glazing Systems on Buildings

Opportunities represent potential areas for growth, improvement, and innovation in the realm of triple glazing in buildings. Identifying these opportunities allows researchers, designers, and industry professionals to chart paths for future developments and advancements.

The ongoing advancements in materials science and technology present an opportunity for innovative solutions to address weaknesses such as condensation issues and weight considerations [24,26]. New coatings, spacer materials, and smart technologies can contribute to enhancing the overall performance of triple glazing [120].

The diversity of climatic conditions presents an opportunity for tailoring triple-glazing solutions to specific climate zones [32,118,121]. Customizing coatings, gas fillings, and other components based on regional characteristics can optimize the technology's performance in various environments [29,122].

As sustainable building practices gain momentum, there is an opportunity to integrate triple glazing seamlessly into holistic, sustainable design strategies [118,123]. This involves considering triple glazing not as a standalone technology but as an integral part of a comprehensive approach to energy-efficient and environmentally friendly architecture [124].

Opportunities arise through government incentives and regulations that promote energy-efficient building technologies [125]. Increased support, subsidies, or regulatory frameworks encouraging the adoption of triple glazing can drive its integration into mainstream construction practices [126,127].

5.4 Threats of Triple Glazing Systems on Buildings

Threats encompass external factors that may pose challenges or obstacles to the widespread adoption and success of triple glazing in buildings [20]. Recognizing these threats is essential for developing strategies to mitigate risks and enhance the resilience of triple-glazing technology.

The existence and continual development of alternative energy-efficient technologies, such as dynamic glazing or advanced insulation materials, threaten the market penetration of triple glazing [110,123,128]. Competition from alternative solutions may impact the widespread adoption of triple glazing [129].

The rapid pace of technological innovation can lead to the obsolescence of existing triple-glazing systems [130]. This threat emphasizes the importance of continuous research and development to stay ahead of emerging technologies and maintain the relevance of triple glazing in the architectural landscape [89].

Resistance from the market, including builders, architects, and consumers, can threaten the adoption of triple glazing [130]. Concerns about initial costs, perceived complexities, or the technology's effectiveness may hinder its acceptance in the mainstream market [118,131].

A lack of consistent industry standards and triple-glazing regulations can threaten its quality control and performance consistency [132,133]. Standardization is crucial to ensuring that triple glazing meets established benchmarks for energy efficiency and durability [108,129].

5.5 Synthesis and Implications

The SWOT analysis provides a comprehensive understanding of the current state of triple glazing in buildings. The identified strengths, weaknesses, opportunities, and threats present a roadmap for future research, development, and implementation strategies.

To capitalize on the strengths of triple glazing, research efforts should continue to address weaknesses such as condensation management and weight considerations. Technological innovations, including advancements in coatings and spacer materials, offer opportunities for improvement. Moreover, customization based on climate zones and integration with sustainable design practices can further enhance the value proposition of triple glazing.

Mitigating threats involves staying abreast of competing technologies, ensuring continuous research and development, and actively engaging with industry stakeholders to address market resistance. Establishing consistent industry standards and leveraging government incentives can help overcome challenges and foster a conducive environment for the widespread adoption of triple glazing.

In conclusion, the systematic literature review, bibliometric quantitative analysis, and SWOT analysis provide a robust foundation for understanding the current landscape of triple glazing in architecture, as shown in Table 2. The findings and insights from this analysis contribute valuable knowledge to the ongoing discourse on energy-efficient building technologies, paving the way for future research directions and practical implementations in sustainable architecture.

Table 2
The summary of the triple glazing in architecture SWOT analysis

Dimension	Summary
Strength	(i) Superior thermal performance and insulation, reducing heat transfer. (ii) Enhanced energy efficiency, minimizing the need for artificial heating and cooling. (iii) Improved occupant comfort through balanced daylighting and glare reduction.
Opportunities	(i) Technological innovations in materials and design for better performance. (ii) Customize specific climate zones to optimize efficiency. (iii) Integration with sustainable design practices and supportive government incentives for adoption.
Weakness	(i) Potential for condensation between glass layers. (ii) Increased weight and complexity of installation, possibly requiring structural adjustments. (iii) Higher initial costs compared to conventional glazing options.
Threats	(i) Competition from other energy-efficient technologies. (ii) Risk of rapid obsolescence due to fast-paced technological advancements. (iii) Market resistance due to cost, complexity, or scepticism about effectiveness.
Future directions	(i) Pursue further research into new materials and technologies to address current weaknesses. (ii) Develop standards and regulations to facilitate broader adoption and integration into sustainable design. (iii) Explore interdisciplinary approaches to enhance thermal comfort and energy efficiency.

6. Discussion of Findings and Limitations

This study extensively evaluated existing research concerning the thermal performance of glazing systems, aiming to delineate the evolution and critical factors shaping this study area. The subsequent synthesis of findings sheds light on the current body of knowledge's integral benefits and inherent shortcomings.

To summarize the developments and significant factors that have influenced the development of the literature on thermal comfort with glazing systems, this research set out to conduct a comprehensive analysis of that literature. The findings include a discussion of the benefits and drawbacks of the research gap. Conducting a review of the literature and trend analysis, this section will highlight and expound on the field's limitations and suggest a few promising areas for more study.

i. While comprehensive, the study's reliance on major academic databases introduces inherent limitations due to excluding global databases not covered in the analysis. The selection of research material, predominantly from English-language sources, presents a bias that may overlook significant contributions in other languages. This limitation is crucial, as it narrows the scope of the review to a subset of available research, potentially skewing the results.

   While English remains the dominant language for academic publications, leading to a reasonable assumption of comprehensive coverage, this approach does not account for the richness of research published in other languages, which could offer valuable insights and perspectives on triple glazing in buildings.

   The discussion thus underscores the importance of expanding research methodologies to include a more comprehensive array of databases and languages. This expansion would enrich the analysis and provide a more global perspective on the advancements, challenges, and opportunities associated with triple-glazing technology in the context of sustainable building practices.

ii. The quest for thermal comfort through triple glazing intersects with the realms of building thermal engineering, physics, and materials science, forming a complex, interdisciplinary system. Despite the wealth of theoretical analyses, there is a noticeable gap in empirical research—case studies and real-world testing are scarce, limiting the ability to validate theoretical models and conclusions. This shortfall partly stems from the limited range of available thermal comfort solutions tailored to triple glazing.

   Integrating innovative glazing materials and dynamic technologies promises to revolutionize the domain of glazing thermal preferences. This evolution is not just accelerating the development within the field but is also fostering cross-disciplinary collaboration. It paves the way for more personalized models of thermal comfort that can be scaled up to larger urban projects, including smart cities and Transit-Oriented Developments (TOD).

   The expansion into new materials and technologies broadens the scope of triple-glazing applications, blurring the lines between disciplines. This trend underscores the necessity for multidisciplinary cooperation, pushing the boundaries of traditional research frameworks to accommodate the complexity of human thermal comfort perceptions within the built environment.

iii. Challenges of Interoperability and BIM Integration in Triple Glazing Systems

The development and Optimization of triple glazing systems through Building Information Modeling (BIM) face significant hurdles due to the absence of a globally recognized standard for project interoperability and information sharing. This fragmentation is evident in the plethora of standards and formats currently utilized, such as IFC, DWG, SOSI, LandXML, and QUADRI, ranging from open file formats accessible by various software to proprietary formats restricted to specific applications. This diversity leads to potential data loss during format conversions, posing challenges for effectively leveraging BIM in enhancing glazing systems' performance.

The need for a unified, universally accepted BIM standard tailored to the specific needs of thermal comfort in buildings is increasingly critical. Such a standard would facilitate seamless data exchange and integration, enabling more effective testing and operation and improving triple-glazing systems.

Addressing these interoperability challenges is essential for advancing the role of triple glazing in achieving energy-efficient and occupant-friendly buildings, calling for concerted efforts among industry stakeholders to establish and adopt comprehensive guidelines that align with the evolving demands of sustainable architecture.

iv. Advancements and Challenges in Glazing Material Development

This study provides an overview of the trends and factors influencing window performance for human thermal comfort, identifying a gap in the investigation of drivers or barriers to glazing material development. To bridge this gap, a combination of qualitative and quantitative analyses is proposed to understand these influencing factors. This approach includes quantitative rankings and impact comparisons to evaluate the adoption and implementation of cutting-edge glazing materials. Additionally, the paper suggests developing a framework for the typical glazing system selection process to effectively address adoption and implementation challenges.

Future research also emphasizes the need to analyse the market for advanced glazing materials, particularly how these materials affect individual thermal perception. This analysis should differentiate between materials at the research-development stage and those already in production. Although not covered in this research, such an investigation is crucial for developing a comprehensive framework or prototype that will aid in the systematic selection and implementation of innovative glazing materials, further enhancing the field of thermal comfort and energy efficiency in buildings.

v. Technological Integration in Window Design for Enhanced Thermal Comfort

The findings highlight a shift towards incorporating advanced technologies into window design, with smart glass, dynamic shading systems, and sensor-driven ventilation as crucial innovations. These technologies promise to significantly improve thermal comfort by giving occupants more control over their indoor environments. However, realizing their full potential is contingent upon overcoming initial investment and ongoing maintenance hurdles. Addressing these challenges is crucial for facilitating their broader adoption and maximizing their impact on building design and occupant well-being.

7. Conclusion

This study has systematically reviewed and analysed the literature on triple glazing in buildings, highlighting its significant potential for improving thermal performance and energy efficiency. The findings from the comprehensive analysis reveal that triple glazing offers substantial benefits, including enhanced insulation, reduced energy consumption, and improved thermal comfort. However, the implementation of triple glazing is not without challenges. Issues such as condensation, weight, and initial costs remain significant barriers that need to be addressed through ongoing research and innovation.

The bibliometric-quantitative analysis provides valuable insights into the development trends, influencing factors, and innovative techniques in triple glazing. This study emphasizes the importance of integrating advanced materials and intelligent technologies to overcome existing challenges and optimize the performance of triple-glazing systems. Furthermore, it underscores the need for tailored solutions that consider climatic variations and building orientations to maximize the benefits of triple glazing.

In conclusion, while triple glazing presents a promising solution for enhancing building energy efficiency and occupant comfort, its widespread adoption requires addressing the current limitations and leveraging technological advancements. Future research should focus on developing more efficient, cost-effective glazing solutions and comprehensive strategies to mitigate the identified challenges. By doing so, triple glazing can significantly contribute to sustainable building practices and energy conservation and environmental sustainability goals.

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