# SUSTAINABLE ARCHITECTURE RESEARCH TRENDS: A BIBLIOMETRIC ANALYSIS FOCUSING ON BUILDING FAÇADE DESIGN WITH THE INFLUENCE OF THERMAL COMFORT

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## ABSTRACT

*Buildings account for a significant portion of global energy use, making facade design a critical component in efforts to achieve sustainable architecture. In tropical climates, challenges such as high solar radiation, temperature, and humidity increase the demand for innovative facade strategies that improve thermal comfort and energy efficiency. Proven strategies such as shading devices, roof overhangs, and natural ventilation have demonstrated effectiveness in reducing indoor heat gain and increasing occupant comfort. This study aims to analyze current research trends in sustainable architecture with a focus on building facade design and its impact on thermal comfort. Bibliometric analysis was carried out using Scopus-indexed publications from 2016 to 2025, with keywords related to building design, thermal comfort, and facade efficiency. VOSViewer software was used to map keyword networks, visualize publication trends, and identify dominant themes and research clusters. The analysis includes 51 relevant publications and reveals a growing interest in facade-related energy research over the last decade. The majority of research is focused on engineering, energy, and environmental science, with global contributions from China, the United States, and Italy. Keyword clustering identified three core research themes: architectural design strategies, building envelope technologies, and thermal comfort performance. Despite a growing body of research, this study highlights a gap in facade design research specifically adapted to tropical climates, where humidity and solar radiation issues require more context-sensitive solutions. These findings underscore the need for more localized and multidisciplinary research, as well as the integration of adaptive and intelligent façade systems. This research contributes to the knowledge base by identifying research patterns and gaps, offering a foundation for future investigations into facade innovations that support energy-efficient and thermally comfortable buildings in diverse climate contexts.*

***Keywords:*** *Bibliometric, Façade Design, Thermal Comfort, Energy Efficiency*

## INTRODUCTION

In recent decades, sustainable architecture has become a major focus in efforts to reduce building energy consumption and its impact on the environment. One of the key elements in sustainable architecture is facade design, which plays an important role in improving the energy efficiency and thermal comfort of buildings. In tropical environments, the main challenges in facade design are dealing with high temperatures, high humidity, and strong sunlight intensity throughout the year (Hendrik & Tualaka, 2023). Therefore, an optimal facade design approach must be able to maximize natural lighting and cross ventilation while reducing excess heat to create comfortable thermal conditions inside the building. Several facade design strategies that have been proven effective in increasing energy efficiency and thermal comfort include the use of shading, overhangs, and the application of natural ventilation (Nasution & Rambe, 2024). With an appropriate design, the facade can function as an adaptive element that not only saves energy but also enhances the well-being of occupants by regulating indoor temperature and air quality. Various studies have been conducted to explore innovations in facade design that can improve building energy efficiency in line with increasing attention to sustainability issues. Research conducted by Ekele Thompson Ochedi and Ahmad Taki (2022) discusses the development of a framework for energy-efficient residential building design in Nigeria, with a focus on improving indoor thermal comfort and reducing energy consumption (Thompson & Taki, 2022). This study used mixed methods, including interviews with architects and residents, observational surveys of 22 existing buildings, and simulations of the thermal performance of three types of residential buildings. The research results show that building design, especially the facade and building envelope elements, plays an important role in energy efficiency and can help design professionals and policymakers create more sustainable buildings.

Meanwhile, research conducted by Ayah Mohamed Ramadan (2022) focused on building envelope optimization techniques to increase energy efficiency in office buildings in Egypt by using energy simulation through *Design Builder* And *Energy Plus*; this study compared various building envelope designs and found that the application of layered building envelopes as well *double green skin façade* can reduce energy consumption by up to 80% and reduce $CO_2$ emissions, thereby increasing indoor thermal comfort (Ramadan, 2022).

Apart from that, research conducted by Abed Al-Waheed Hawila, Abdelatif Merabtine, Nadège Troussier, and Rachid Bennacer (2019) in the journal *Building and Environment* discusses the optimization of glass facade design to increase thermal comfort in buildings using a combination of dynamic simulation and metamodelling, this study applies the method *Design of Experiments (DoE)* and a desirability function to analyze the parameters that most influence thermal comfort, as well as develop a glass facade design optimization model. The research results show that optimized glass facade design can improve thermal comfort and reduce energy consumption, highlighting the importance of building envelope design in achieving energy efficiency and occupant comfort (Hawila et al., 2019).

Other research conducted by Miren Juaristi, Roel Loonen, Francesco Isaia, Tomás Gómez-Acebo, and Aurora Monge-Barrio (2020) in the journal *Sustainable Cities and Society* introduces a new methodological approach in dynamic climate analysis to support the early stages of opaque adaptive facade design (*Adaptive Opaque Façade*) (Juaristi et al., 2020). The so-called method of *Dynamic Climate Analysis (DCA)* allows architects and facade engineers to identify the most appropriate adaptive facade response from the early stages of design without the need for complex building simulations. By analyzing climate data to detect changing weather patterns and assessing the potential thermal behavior of facades, DCA can help optimize adaptive facade designs by utilizing environmental resources and reducing building energy requirements without relying on specific technological solutions.

From these various studies, it can be concluded that innovation in building facade design, whether through the application of layered building envelopes, optimized glass facades, or adaptive facades based on dynamic climate analysis, has an important role in increasing energy efficiency and creating a more sustainable built environment.

Bibliometric research on facade design has been carried out, such as Bhote and Chauhan (2025) discuss how optimizing building facade design can save energy, especially in the hotel sector, by analyzing thousands of studies and highlighting the importance of climate responsive technology (Bhote & Chauhan, 2025). Research from Avinç (2024) reviews research trends on nature-imitating (biomimetic) building facade design for energy efficiency and shows its contribution to architectural innovation through adaptive and sustainable solutions (Avinç, 2024). Apart from that, research from Blanco and Convertino (2023) analyzed trends in green facade research since 1999, which shows that the use of vegetation in buildings is increasingly in demand because of its benefits for thermal efficiency, urban design, and sustainability (Blanco & Convertino, 2023). This research found a gap in the exploration of facade design, which focuses on the influence of thermal comfort, which has not yet been widely researched, so there is potential for investigation using bibliometric methods and VOSViewer for visualization.

Bibliometric analysis is an effective method to identify publication patterns, dominant research topics, and research gaps that have not been explored much (Peginusa et al., 2024). This method is also used to map research trends in sustainable architecture by highlighting the keywords of building, material, façade, and thermal (Pramesti et al., 2021). The study analyzed 859 publication documents from 1976 to 2020 using Scopus and VOSViewer to identify key research clusters, such as energy, façade technology, measurement, thermal, and climate. The results show that research on facades and building materials is still dominated by European countries, while research in tropical countries is still limited, thus opening future research for further exploration in facing the challenge of high humidity for sustainable buildings. The aim of this research is to study trends and gaps in sustainable architecture research. This research will reveal publication patterns, main keywords, a collaboration between researchers, and the development of future research in this field through bibliometric analysis based on Scopus data.

## THEORY / RESEARCH METHODS

This study investigates research trends on "building facade design and its influence on thermal comfort in sustainable architecture" using "bibliometric analysis." Bibliometric analysis is highly preferred because it can describe the main themes in a particular research field, the relationships between authors, and scientific publication patterns (Donthu et al., 2021). "Bibliometric analysis on building façade design and thermal comfort in sustainable architecture reveals key research themes, with dominant clusters in energy, façade technology, and thermal performance. Pramesti et al. (2021) highlight the need for further studies in tropical climates due to unique humidity challenges." (Pramesti et al., 2021). This method allows for the analysis of research distribution based on the year of publication, journal, and contributing institution. It also allows researchers to determine prominent authors and institutions, identify major keywords and thematic relationships, and discover citation patterns and research impact. This study uses a "quantitative" approach with bibliometric data processing and network visualization with VOSViewer.

To ensure the relevance and quality of the documents analyzed, the research data filtering process uses a number of exclusion criteria. Publications in 2016–2025 were limited to focus on recent research. To reflect the various elements that contribute to facade design and thermal comfort, selected areas of study include engineering, energy, environment, social sciences, arts and culture, materials science, and combined. To maintain the credibility of the data, preprint or unreviewed publications were not included. Additionally, considering academic standards for high-quality journals, only publications in English were used. Eligible documents were exported in CSV format and analyzed using VOSViewer for visualization and bibliometric mapping after applying these criteria.

**Table 1.** Data Exclusion

| Criteria | Limitation | Information | Result of Document |
|---|---|---|---|
| Keyword | Thermal, Comfort, Building, Façade, Design, Efficient | Search keywords according to the selected theme | 74 |
| Year | 2016-2024 | Data recency is less than 10 years | 74 |
| Subject Area | - Engineering<br>- Energy<br>- Environmental Science<br>- Social Science<br>- Art and Humanities | Subject filtration of research data according to the chosen theme | 46 |
| Publication Stage | Final | Only research that has been published can be used as data in this research | 45 |

| Criteria | Limitation | Information | Result of Document |
|---|---|---|---|
| Language | English | So that it is easy to understand in accordance with the international language | 45 |

The data used in this research was obtained from the Scopus database, which everyone can access. It only includes journal articles that are freely accessible, meaning each article in the journal can be examined in its entirety without sacrificing a subscription. Of the initial 74 documents, systematic screening was performed based on topic relevance and full access availability; as a result, the final 51 documents were studied. Although the data collection date, March 18, 2025, may seem like a date in the future, it is true because the data was collected on that day.

## RESULTS AND DISCUSSION

### Publication: Year, Subject, Publisher & Country

Based on annual trends, 51 publications from the period 2016–2024 were selected for analysis. Using the Scopus analysis program, graphs and diagrams show annual publication trends, subject area involvement, the most active Chinese countries, and the publishers who contributed most to this research keyword. The results of the analysis show that publications have increased significantly since 2016 as a result of increased attention to thermal efficiency in the design of building facades. Although research on this subject was limited at first, in recent years, there has been a significant increase. The highest publications published in a particular year, such as 2018 or 2021 (refer to Figure 1). The analysis shows that the engineering research category has the most publications, followed by energy, materials, and environment. The analysis results show that journals discussing sustainable architecture, energy efficiency, and facade design have the highest number of publications. The dominance of these fields also reflects the multidisciplinary approach used in facade design research to improve thermal comfort and energy efficiency. (see Figure 2) Some of the journals that are most active in publishing related research are the Journal of Building, Buildings, Lecture Notes in Civil Engineering, Energy and Buildings, A Be Architecture, and The Built Environment (see Table 2). Most research results are published in English, indicating that this research has international scope and is widely accepted in the scientific community. Overall, the trend of publications on this subject has increased significantly in the last ten years.

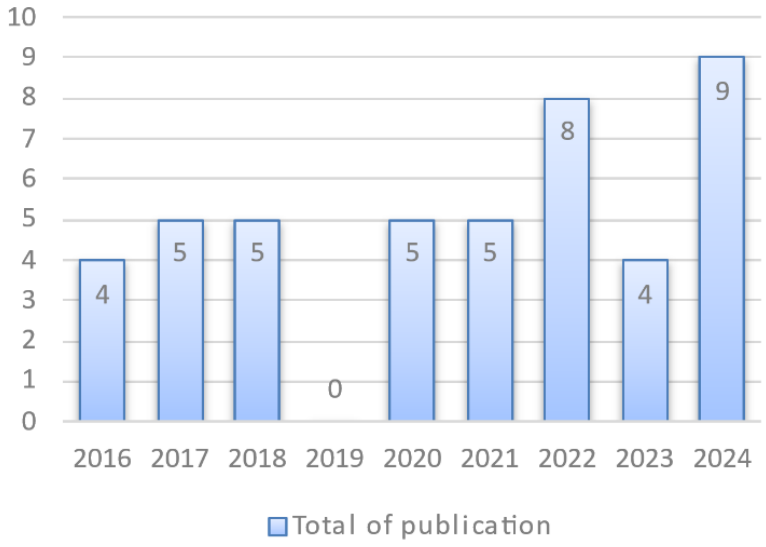


**Figure 1**. Document by Year

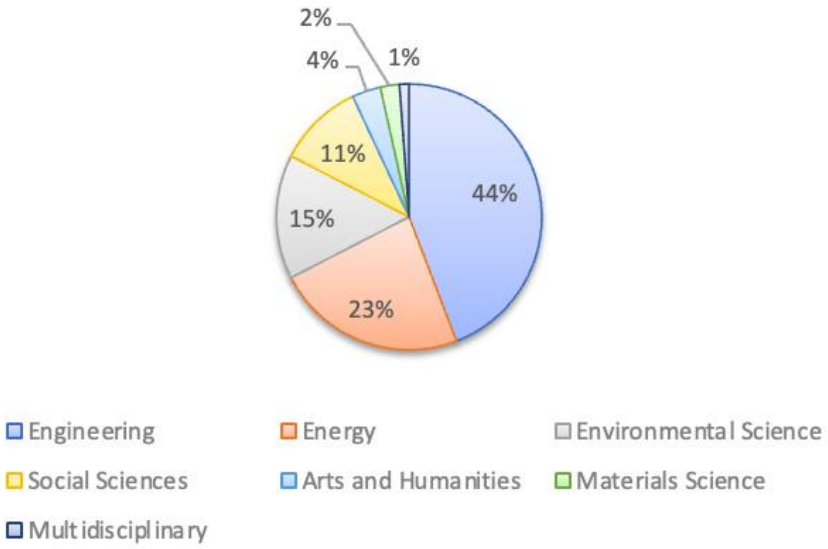


**Figure 2**. Document by Subject Area

**Table 2**. Most Published Journal

| Journal/Source Name | Total of document |
|---|---|
| Journal of Building Engineering Buildings | 5 |
| Lecture Notes in Civil Engineering Energy and Buildings | 4 |
| A Be Architecture and the Built Environment | 4 |
| Alexandria Engineering Journal Applied Energy | 3 |
| Energy for Sustainable Development Energy Reports | 2 |
| Green Energy and Technology | 2 |
| Renewable and Sustainable Energy Reviews | 4 |
| Sustainability Switzerland | 4 |
| Advances in Science, Technology, and Innovation | 3 |
| Edelweiss Applied Science and Technology | 2 |
| Energy Proceed | 2 |
| International Conference on Efficient Building Design Material and HVAC Equipment Technologies | 2 |
| International Journal of Energy Production and Management | 2 |
| IOP Conference Series Materials Science and Engineering | 1 |
| Journal of Architecture Engineering Journal of Building Physic | 1 |
| Sigma Journal of Engineering and Natural Science | 1 |
| Smart and Sustainable Environment | 1 |

## Countries' Involvement in Research

European countries dominate research on building facade design, thermal comfort, and energy efficiency. Italy ranks first due to the number of publications published. This publication is mostly concentrated on methods to increase thermal comfort using vegetation, natural ventilation, and material innovation. Other countries doing a lot of research are the UK, Germany, and Spain. Outside Europe, the two countries with the highest number of publications in this research are China and the United States. These two countries are also included in the top ten countries that are most actively contributing. The results of the bibliometric analysis show that 75 countries have engaged in international research in this area, and 44 countries meet the minimum threshold of five publications. Apart from these major countries, several other countries, such as Malaysia, Croatia, Canada, and Cyprus, have become more involved in recent years. This shows an increasing interest in research on facade design and energy efficiency worldwide. In addition, the pattern of collaboration between countries in this research is shown through the VOSViewer network visualization, with Italy and the UK as the centers of the global research network. This research shows how countries focused on energy efficiency and sustainable architecture are increasingly expanding the scope of their research.


**Figure 3**. VOSViewer Analysis of Countries' Involvement


**Figure 4**. VOSViewer Analysis Countries Involvement During the Period 2006-2020

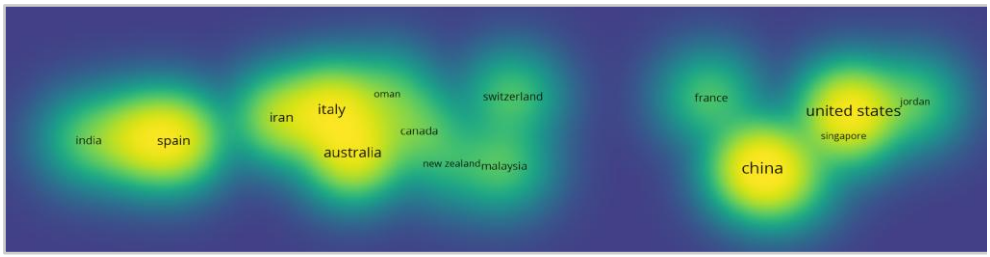


**Figure 5**. VOSViewer Analysis of Countries' Density Visualisation

**Table 3.** Participation of Country

| Country/Territory | Total of document |
|---|---|
| China | 8 |
| United States | 7 |
| Australia | 6 |
| Italy | 6 |
| Iran | 4 |
| Spain | 4 |
| United Kingdom | 4 |
| Austria | 3 |
| Egypt | 3 |
| Canada | 2 |
| France | 2 |
| Germany | 2 |

| Country/Territory | Total of document |
|---|---|
| India | 2 |
| Indonesia | 2 |
| Malaysia | 2 |
| Netherlands | 2 |
| Switzerland | 2 |
| Turkey | 2 |
| Argentina | 1 |
| Chile | 1 |
| Iraq | 1 |
| Jordan | 1 |
| Malta | 1 |
| Mauritius | 1 |
| Mexico | 1 |
| Morocco | 1 |
| New Zealand | 1 |
| Poland | 1 |
| Russian Federation | 1 |
| Saudi Arabia | 1 |
| Singapore | 1 |
| Slovenia | 1 |
| Sweden | 1 |
| Vietnam | 1 |

**Keyword Analysis**

Using VOSViewer, bibliometric analysis was carried out to map the relationship between keywords in research related to facade design and building energy efficiency. The results are visualized in the form of a color density map (see
Figure **6**), where areas with brighter colors indicate a higher frequency of keyword occurrences.

From this visualization, the two keywords that stand out the most with the brightest yellow intensity are "energy efficiency" and "thermal comfort," which indicates that these two topics are the main focus of the analyzed literature. Apart from that, keywords like “architectural design”, “energy utilization”, “structural design”, and “ventilation” also appear in fairly bright colors, indicating the significance of the topic in academic discourse regarding sustainable building design. Other keywords such as “facades, “building envelopes”, and “daylighting” appear in bluish-green areas, indicating lower but still relevant frequencies.

This visualization supports the finding that much of the literature has focused on improving energy efficiency and thermal comfort through adaptive and optimal facade design.

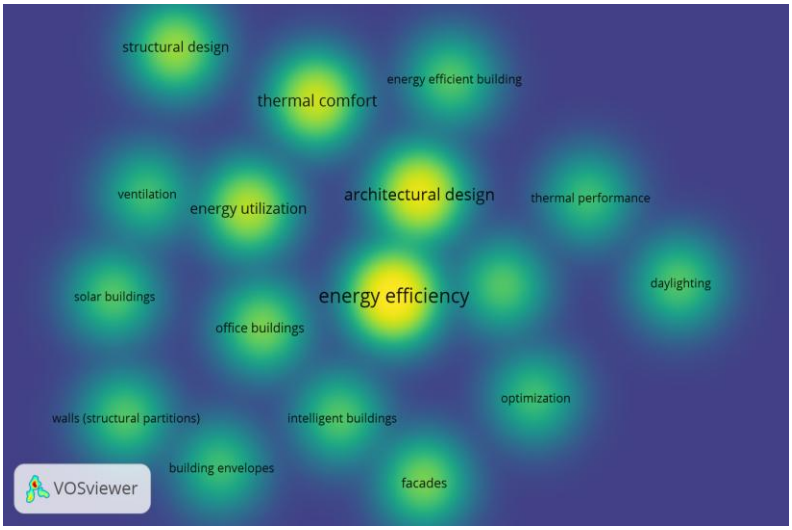


**Figure 6**. VOSViewer Analysis Keyword Density Visualization

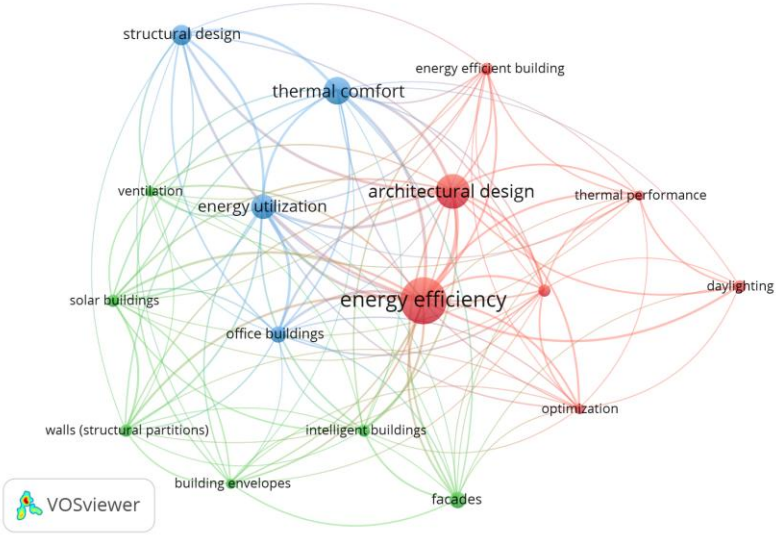


**Figure 7**. VOSViewer Analysis Keyword Network Visualization

This image (see Figure 7) shows the mapping of keywords with a minimum of five occurrences. The result was 16 keywords, which were divided into three different clusters based on their relationships and relatedness. The red cluster indicates the main keyword, "architectural design," which indicates that the main focus of this research is the role of architectural design in creating environmentally responsive and energy-efficient buildings. The green cluster, the so-called "building envelopes," emphasizes how important building envelopes are for controlling energy consumption and thermal comfort. The blue cluster, which corresponds to "thermal comfort," shows attention

to improving the thermal comfort of occupants through innovative facade design, ventilation management, and the selection of climate-appropriate materials, such as architectural design, building envelopes, and thermal comfort.

Bibliometric analysis results that group research keywords based on their relevance and frequency of occurrence. Using VOSViewer software, keywords with a minimum of five occurrences were mapped into multiple cluster main, each marked with a different color. Every cluster represents a particular research topic. For example, architectural design, building envelopes, and thermal comfort are some examples of research topics. The following table is made more concise and systematic to provide a better understanding of research trends and relationships between concepts in this field.

**Table 4**. Classification of color clusters

| No | Color | Contain |
|---|---|---|
| 1 | Red | Architectural design |
| | | Daylighting |
| | | Energy efficient |
| | | Energy-efficient building |
| | | Energy performance |
| | | Optimization |
| | | Thermal performance |
| 2 | Green | Building envelopes |
| | | Facades |
| | | Intelligent Buildings |
| | | Solar Buildings |
| | | Ventilation |
| | | Walls (structural partitions) |
| 3 | Blue | Thermal comfort |
| | | Energy utilization |
| | | Office building |

**Table 5**. Revised classification of color clusters

| No | Color | Category | Contain |
|---|---|---|---|
| 1 | Red | Integrated Design Strategy & Performance Goals | Architectural design, daylighting, energy efficiency, energy efficient building, optimization, thermal performance, visual comfort |
| 2 | Green | Envelope Technology & Passive Systems | Building envelopes, façades, intelligent buildings, solar buildings, ventilation, walls (structural partitions) |
| 3 | Blue | Building Function & Energy Demand | Thermal comfort, office buildings, structural design, energy utilization |

## Documents and Authorship

This study includes the most cited documents in Scopus, showing the most influential documents in this sphere (Table 6). From a total of 51 documents analyzed, this research covers five topics with the greatest impact regarding occupant thermal comfort, micro-building facade optimization, dynamic glass developments, lighting efficiency, and thermal performance, and increasing building energy efficiency through innovative materials. The main themes in these documents are closely related to energy efficiency and sustainable building innovation. Additionally, Scopus analysis identified the top 10 authors in this research field based on the number of their publications (Table 6). This list of authors indicates their influence and involvement in this research. These authors have made significant contributions to research on building materials, facade technology, life cycle assessment, and building energy simulation.

**Table 6**. Top 10 Authors in the Research Area

| Author | Title | Source Title | Year |
|---|---|---|---|
| (Fahmy et al., 2020) | Comparison of Occupant Thermal Comfort with an Adaptive Model in Naturally Ventilated Classrooms | IOP Conference Series: Materials Science and Engineering | 2020 |
| (Permana et al., 2021). | Optimization of Micro-House Building Façade in Tropical Area Using Computational Fluid Dynamics (CFD) Simulation | Advances in Science, Technology and Innovation | 2021 |
| (Sok & Sanders, 2016) | New Developments in Dynamic Glass: Towards a New Generation of Electrochromic Devices | Challenging Glass Conference Proceedings - Challenging Glass 6 | 2016 |
| (Liu et al., 2023) | Numerical Simulation Analyses on Envelope Structure Performance Under Different Climate Conditions | Buildings | 2023 |
| (Halawa et al., 2018) | A Review on Energy-Conscious Designs of Building Envelopes for Sustainability | Renewable and Sustainable Energy Reviews | 2018 |
| (Lin et al., 2018) | Design Optimization Considering Variable Thermal Comfort Requirements: A Machine Learning-Based Framework | Sustainability (Switzerland) | 2018 |
| (Mahdavinejad et al., 2024) | The Impact of Facade Geometry on Visual Comfort and Energy Efficiency in Office Buildings | Energy Reports | 2024 |
| (Leskovar & Premrov, 2011) | An Approach in Architectural Design of Energy-Efficient Office Buildings | 2nd International Conference on Energy and Indoor Environment for Hot Climates | 2017 |

| Author | Title | Source Title | Year |
|---|---|---|---|
| (Yu et al., 2020) | A State-of-Art Review of Concepts, Criteria, Methods, And Factors for Reaching 'Thermal-Daylighting Balance.' | Energy Proceed | 2017 |
| (Paule et al., 2017). | Electrochromic Glazings: Dynamic Simulation of Visual and Thermal Comfort | Energy Proceed | 2017 |

## CONCLUSION

This research maps research trends in sustainable architecture, especially in building facade design and its influence on thermal comfort, with a bibliometric approach to 51 Scopus documents from 2016 to 2024. The results of the analysis show that *thermal comfort* and energy efficiency are the most dominant and frequently studied keywords. The VOSViewer visualization confirms that these two topics are at the center of focus of the global literature on energy-efficient facade design.

Geographically, the largest contributions to publications come from China, the United States, and Italy. These three countries dominate international collaboration in research related to building facades, while the Southeast Asia region, including Indonesia, is still less explored. Keyword clustering identified three main focuses: integrated architectural design strategies and building performance, envelope technologies and passive systems, and energy utilization in office buildings. This reflects a growing multidisciplinary approach in efforts to improve building energy efficiency.

Although the adaptation of technologies such as natural ventilation and the use of natural light is a major concern, the integration of intelligent technologies such as Artificial Intelligence (AI) in facade design simulations is still not widely used as a research topic. Likewise, the application of analytical tools such as EDGE to evaluate the energy efficiency of facades in tropical climate contexts is still very limited. In fact, tropical regions face specific challenges, such as high humidity and intensive solar radiation, which require a contextual design approach.

This research has limitations, namely that it only uses data from Scopus, is in English, and spans the last decade. This approach may ignore relevant local literature or methods developed before 2016. Additionally, only open-access, full-text documents were analyzed, which may limit the diversity of methodological perspectives.

The implications of these findings highlight that although attention to energy efficiency in facade design is increasing globally, further efforts are needed to develop research appropriate to tropical local contexts. Future studies are recommended to expand the scope of the database, integrate AI in adaptive facade simulations, and conduct tool-based evaluations such as EDGE in educational buildings and public facilities. In this way, the research results can make a real contribution to the implementation of facade designs that are not only energy efficient and adaptive but also contextual according to local climate and needs. This study helps understand building facade design trends and forms the foundation for more sustainable and

thermally comfortable buildings of the future. This research uses data sourced from the Scopus database, which can be accessed, so there is no conflict from any party or data source.

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