

Efficient daylighting and thermal performance through tessellation of geometric patterns in building façade: A systematic review

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ABSTRACT

In the realm of sustainable architecture and construction, facade design plays a crucial role in regulating building energy consumption by controlling factors such as daylight and thermal comfort. Traditional approaches have evolved to incorporate geometric patterns like tessellations, which offer both aesthetic and functional benefits. However, understanding the intricate relationship between tessellation patterns and energy efficiency remains a complex task. Although numerous literature reviews exist on energy-efficient building facades, only a few have specifically addressed the geometric aspects of facade design and their impact on energy performance. This study conducts a systematic review of existing literature, employing the PRISMA framework to uncover the nuanced effects and potential limitations of tessellation patterns. Of the 611 papers identified in the initial search, a large number were excluded based on selection criteria and screening, leaving a total of 36 papers for review. Among these, 22 studies specifically focused on tessellated patterns. The review identifies significant gaps in the literature: 40 % of studies concentrated on static shading screens, while only 28 % and 23 % addressed static and dynamic double-skin facades, respectively. Research on dynamic shading screens remains largely unexplored. Daylight performance was the most studied energy indicator (73 %), while thermal performance accounted for only 18 % of the focus. Additionally, 62 % of the studies focused on hot-arid and semi-arid climates. These findings highlight the need for further research on dynamic shading screens, the integration of daylight and thermal performance, diverse climate contexts, sustainable materials, smart controls, and practical designs for real-world application. The significance of this study extends beyond academia to architects, urban planners, and policymakers involved in sustainable building design and construction.

Introduction

With the increasing global focus on energy efficiency and occupant comfort, there is a growing need to incorporate sustainability-related performance aspects into building design, particularly in relation to thermal comfort and daylighting (Soares et al., 2017). In architecture, the facade plays a key role in defining a building's orientation toward the street, creating an inviting and visually prominent entry point (Askarizad & Jafari, 2019; Askarizad, Dastoum & Garau, 2024).

The inclusion of openings in building facades is crucial for facilitating the entry of daylight, which is recognized as the most favorable light source due to its alignment with human visual preferences and needs (Abdollahi Rizi et al., 2023). These openings significantly enhance the well-being and visual comfort of building occupants (Fathy et al., 2020; Li & Tsang, 2008). Effective utilization of daylight improves both visual and thermal comfort indoors, reducing reliance on artificial

lighting and leading to significant energy savings (Kwong, 2020; Ngarambe et al., 2022). Therefore, optimizing daylighting performance should be prioritized during the early phases of building design and throughout a building's operational lifespan, especially when creating energy-efficient, visually conducive environments is a key objective (Garcia-Fernandez & Omar, 2023; Yu et al., 2022).

The building envelope serves as a prominent expression of a designer's creativity, alongside the physical dimensions and form of the structure (Loonen et al., 2013). Unfortunately, architectural choices often prioritize aesthetics alone, neglecting opportunities to enhance performance capabilities, which is a notable drawback (Li et al., 2020). However, modern building envelopes can contribute significantly to energy conservation by reducing the need for artificial lighting, either by harnessing solar energy or shielding against excessive sunlight (Nikolaidis, 2023). As design requirements grow more demanding, with considerations for environmental impact, budget constraints, and tight

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project schedules, the complexity of facade design increases (Fernando et al., 2023). Additionally, creating intricate geometric patterns that are both affordable and high-performing presents a significant challenge, often prone to errors (Caetano & Leitão, 2021).

As a result, contemporary versions of perforated screen facades are gaining popularity among architects, especially those focused on sustainable building envelopes (Al-Kodmany, 2018; Hameedalddeen & Mostafa, 2022). Geometric patterns used in perforated screens facilitate the entry of daylight into interior spaces (Naik et al., 2022; Srisamranrungruang & Hiyama, 2020). These screens serve a dual purpose: beyond their aesthetic appeal, they play a crucial role in enhancing environmental performance by effectively filtering and distributing light within the space (Emami & Giles, 2016; Lumpkin et al., 2020).

Tessellation, a mathematical concept employed in geometric design, is commonly used in architecture, as well as in other disciplines (Pottmann et al., 2015; Takva et al., 2023). The origins of tessellation can be traced back to civilizations predating Sumer, where it was a primary method for decorating the walls of architectural structures in Sumerian society (Cai, 2023; Wu & Sun, 2018). This geometric technique has appeared in many ancient cultures, including Ancient Egypt, Byzantium, the Moors, Rome, Greece, Persia, Arabia, China, and Japan. Tessellations have been used in floor and ceiling decorations, as well as in Persian and Byzantine designs dating back to ancient Roman times (Bonner, 2017; Fatta & Mediati, 2020; Gray, 2021).

While many literature reviews examine energy-efficient building facades, few focus specifically on the geometric aspects of facade design and their impact on energy efficiency. Kheiri (2018) reviews optimization methods for improving energy efficiency in building design, emphasizing the role of building envelope parameters and geometric configurations. The study covers techniques such as gradient-based and gradient-free methods, hybrid algorithms, and meta-models to enhance efficiency and accuracy. It finds that MATLAB is the most commonly used platform for optimizing building energy performance, with EnergyPlus being the most frequently employed simulation tool. The research predominantly focuses on non-residential buildings (65 %), with residential buildings accounting for 35 %. Rhino is the leading visualization tool, used in over half of the studies, followed by Design-Builder. The study notes a rising trend in the use of Genetic Algorithms (GA) and Particle Swarm Optimization (PSO), while calculus-based and direct search methods are more evenly distributed. Kheiri (2018) also highlights the importance of balancing accuracy with computational time and calls for future research to develop more practical and robust optimization approaches in architectural design.

Chen et al. (2020) review the internal and external factors influencing energy efficiency in building design, focusing on building characteristics, service systems, and occupant behavior. They find that elements such as building shape, orientation, insulation, and compactness significantly impact energy consumption, especially in extreme weather conditions. Technological advances in Heating, Ventilation, and Air Conditioning (HVAC) systems, lighting, and smart controls are identified as key areas for energy savings, though they often involve high upfront costs. Occupant behavior also plays a critical role, with smart control interventions reducing energy use by 10–28 % for HVAC systems and 43–71 % for lighting. Additionally, ground-coupled heat pumps can lower electricity consumption by 30–70 % compared to traditional air-to-air heat pumps. These findings underscore the importance of considering both technological and behavioral factors in optimizing building energy efficiency (Chen et al., 2020).

Gan et al. (2020) critically review existing research on computer simulation and optimization methods aimed at minimizing life cycle energy consumption and carbon emissions in buildings. The study identifies current practices and future research needs, emphasizing that optimizing reinforced concrete beams can reduce embodied energy by 10 %, while improvements in floor system designs can cut embodied carbon by 15–20 %. Combined optimizations can achieve up to 60 % reductions in embodied energy and carbon. Building shape and

orientation can reduce energy use by 30–40 %, while natural ventilation can save up to 25 % in energy, with wind-driven ventilation methods saving up to 45 %. Energy conservation measures can reduce building energy use by 40 % without compromising comfort. Optimizing Combined Cooling, Heating, and Power (CCHP) systems can lower CO₂ emissions by 30 %, renewable energy systems by 32 %, and window retrofitting by 27 %. The study highlights the increasing importance of life cycle design optimization, particularly through the integration of advanced technologies such as machine learning and data-driven design (Gan et al., 2020).

Hafez et al. (2023) provide a systematic review of research on energy efficiency in sustainable buildings, highlighting challenges, motivations, and recommendations for improvement. The study notes that the building sector consumes 30–40 % of global energy and is a major contributor to greenhouse gas emissions. Key strategies identified include energy benchmarking, implementing energy-saving measures, and integrating renewable technologies such as Building Integrated Photovoltaics. The study also identifies research gaps, particularly in the development of local rating systems and innovative energy concepts. Based on an analysis of 134 papers, the review emphasizes the potential for substantial environmental, economic, and social benefits through improved energy efficiency in buildings (Hafez et al., 2023).

Preet et al. (2022) identify a link between the geometric design parameters of double skin facade systems, heat, and fluid dynamics, and their overall performance. The study emphasizes that for optimal energy savings, the air cavity width in double skin facades should range between 150 mm and 400 mm, with widths exceeding 300 mm posing a risk of overheating. The study also highlights that outlet height and wind speed significantly impact performance, though wind effects are negligible if the speed is under 4 m/s at a height of 5 m. Moreover, the interaction between more than two geometric parameters remains an area that requires further numerical and experimental investigation (Preet et al., 2022).

Vassiliades et al. (2022) present a comprehensive review of the geometrical and architectural characteristics associated with the building integration of active solar energy systems. The study finds that integrating these systems can achieve energy efficiencies of 11–18 % on roofs and 13–18 % on facades, with maximum electrical efficiencies of 85 % and 72 %, respectively. For example, a photovoltaic double-skin ventilated facade can achieve energy savings of 28.4 %, while photovoltaic insulating glass units offer up to 30 % savings compared to traditional glass windows (Vassiliades et al., 2022).

Li et al. (2021) discuss recent advances in energy-efficient shape-morphing building envelopes, focusing on both structural design and material engineering for energy saving and harvesting. They explore the designs and performances of four representative categories of shape-morphing facades, showing that these facades can significantly enhance energy efficiency, achieving over 146 kWh in yearly energy surplus. Compared to static designs, shape-morphing facades improve energy harvesting efficiency by 20–50 %, potentially covering 115 % of net energy demand in office spaces (Li et al., 2021).

A study by Li et al. (2020) analyzed advancements and challenges in designing energy-efficient building envelopes, focusing on form and shading systems. Among 99 reviewed papers, 26 involved architectural form optimization. The study notes that over 85 % of projects relied on theoretical models, often neglecting design aesthetics, with only 5 % including experimental prototypes (Li et al., 2020).

Naik et al. (2022) reviewed research on dynamic solar screens and their impact on building energy performance, indoor environmental quality, and occupant comfort, particularly in tropical climates. The study suggests that dynamic screens with geometric patterns offer significant energy savings, ranging from 27 to 48 %, in tropical and warm climates, and could be cost-effective alternatives to high-performance glazing technologies. However, the impact of dynamic solar screens on different building types and occupant well-being remains largely unexplored (Naik et al., 2022).

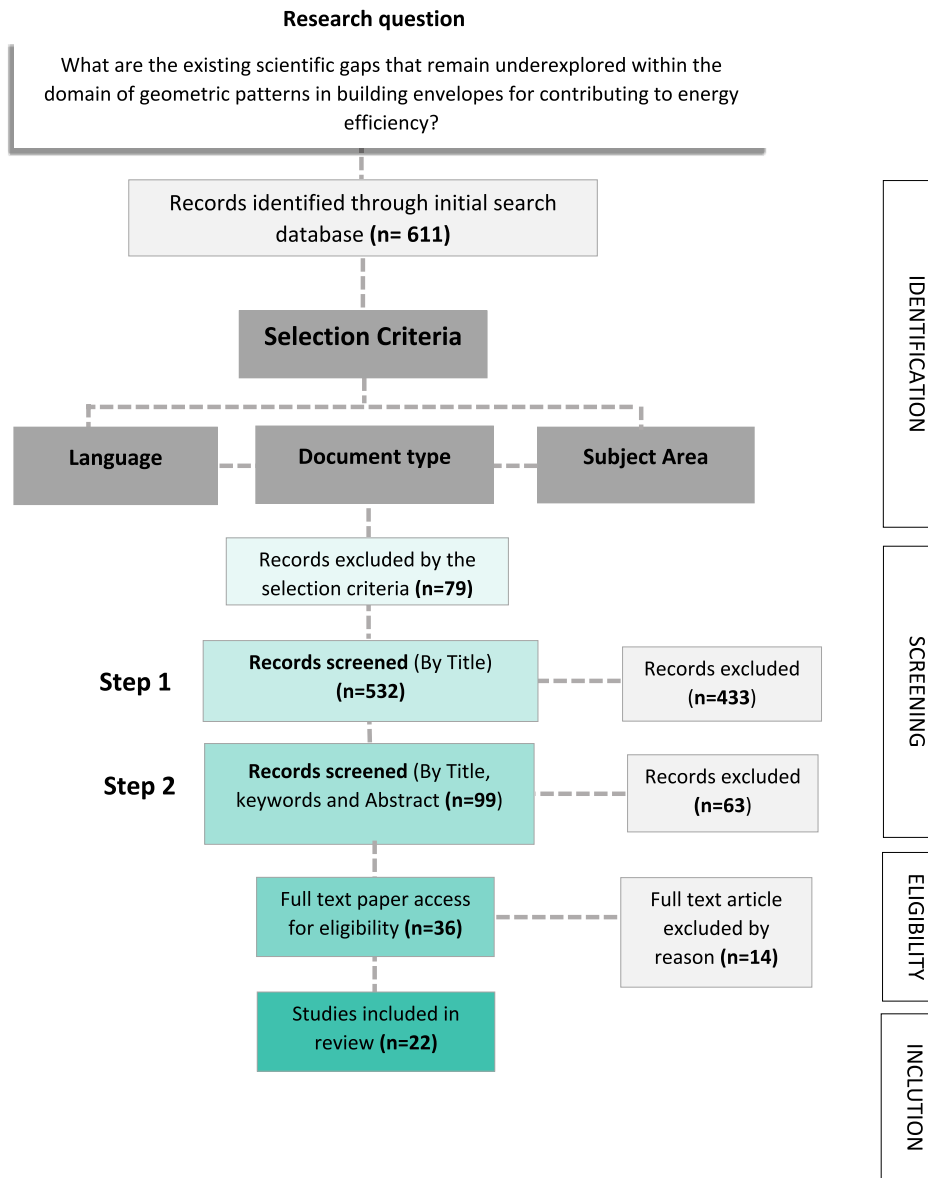


Fig. 1. Methodology approach based on PRISMA flow diagram.

Ibrahim et al. (2023) explore the integration of Islamic geometric patterns (IGPs) into modern architectural designs with a focus on sustainability. Among the 40 reviewed papers, the peak of research occurred in 2018, with four papers in 2022 addressing both energy efficiency and aesthetics. Of these, 28 papers focused on sustainability, primarily in environmental and economic contexts. The study reveals a gap in fully integrating sustainability into IGP designs, despite their potential to improve resource efficiency and reduce costs (Ibrahim et al., 2023).

Despite the growing focus on energy-efficient building facades, there is still no systematic review specifically addressing the tessellation of geometric patterns in building envelopes and their relationship to energy efficiency. Therefore, this study aims to explore the intricate connection between tessellation patterns and energy efficiency in building facades, seeking to identify critical research gaps through a systematic literature review. Conducting an effective systematic literature review begins with formulating clear and representative research questions (Susca et al., 2022). This study seeks to answer the following question:

- What are the existing scientific gaps that remain underexplored within the domain of geometric patterns in building facades contributing to energy efficiency?

To achieve this objective, a comprehensive literature search was performed using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, identifying relevant papers and research gaps in this area. This systematic review offers valuable insights for researchers in architecture, urban design, and sustainable energy resources, helping them understand the potential of geometric patterns in building envelopes for fostering a sustainable built environment. The following sections outline the methodology of the literature review, present findings including a general overview, research background, and key insights and discuss results to identify gaps and propose future research directions. The paper concludes with remarks on the architectural implications of these findings.

Material and methods

PRISMA method

For this study, a systematic literature review was conducted. The systematic review approach has gained significant popularity among experts and researchers due to its structured and comprehensive methodology (Murata et al., 2014). The key distinction between systematic reviews and other types of reviews lies in the methodical procedures used to synthesize findings. These procedures ensure unbiased searches, enhancing both the efficiency and quality of the review process. Specifically, the term “systematic” refers to a research protocol designed to maintain objectivity by clearly outlining various steps, including defining specific questions, outlining the study’s focus, detailing the research strategy, and specifying the inclusion and exclusion criteria (Tranfield et al., 2003).

In this study, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework was employed. PRISMA is a well-established protocol for systematic reviews that includes a 27-item checklist and a four-phase flow diagram (see Fig. 1) (Liu et al., 2022). Its primary objective is to enhance the transparency and accuracy of literature reviews. PRISMA was chosen over alternative protocols due to its comprehensiveness, widespread application across various disciplines, and ability to promote consistency in the review process (Haghani, 2023). The PRISMA method consists of four phases:

The PRISMA method consists of four phases: (1) Identification, where a combination of keywords is used to search scientific databases and retrieve potentially relevant studies; (2) Screening, where unrelated documents are removed; (3) Eligibility which involves ranking and selecting the most relevant papers for full-text analysis; and (4) Inclusion, the final number of studies to be included in the review is determined (Moher et al., 2010).

Search strategy

The search was conducted using Scopus, one of the most widely recognized academic databases. Scopus was selected for its extensive coverage of high-quality, peer-reviewed literature relevant to the subject (Sharifi et al., 2024). To ensure the accuracy of the review, a set of carefully curated keywords was employed, including: Tessellation, Geometric Patterns, Islamic Geometric Patterns, Façade, Thermal Performance, Daylighting, and Energy Efficiency. The inclusion of Islamic Geometric Patterns was particularly motivated by the rich tradition of geometric design in Islamic art and architecture, which has significantly influenced the development of tessellation patterns. These patterns are not only prevalent in cultural and religious architecture but also embody principles of symmetry and mathematical precision, which are highly relevant to modern sustainable design practices. The search was performed on December 12th, 2023, with no timespan restrictions, targeting titles, keywords, and abstracts. The document types were limited to articles, conference papers, reviews, and book chapters.

The search protocol employed Boolean operators to refine the search, ensuring comprehensive coverage of relevant literature. The primary search terms included: TITLE-ABS-KEY (Geometric OR “Geometric Pattern” OR “Islamic Geometric Pattern” OR Tessellat*) AND (Facade OR “Building Envelope” OR “Building Skin”) AND (“Energy Efficiency” OR “Thermal Performance” OR “Thermal Comfort” OR Daylight*). A two-stage keyword selection process was implemented to identify relevant articles: Stage 1 (keywords group “A”) included interchangeable terms such as “Geometric”, “Geometric Pattern”, and “Tessellation” to capture the breadth of geometric-related literature. Stage 2 (keywords group “B”) refined the search to focus on Building Envelopes and Facades. To further narrow the focus and address the initial insufficient results, a third group of keywords (keywords group “C”) was introduced, targeting terms related to Energy Efficiency.

Boolean operators such as OR and AND were used to combine

Table 1
Summary of the keywords used during the identification phase.

| Keyword A | Boolean Operator | Keyword B | Boolean Operator | Keyword C |
|-----------------------------|------------------|---------------------|------------------|-----------------------|
| Geometric | | Facade | | “Energy Efficiency” |
| OR | | OR | | OR |
| “Geometric Pattern” | | “Building Envelope” | | “Thermal Performance” |
| OR | AND | OR | AND | OR |
| “Islamic Geometric Pattern” | | “Building Skin” | | “Thermal Comfort” |
| OR | | | | OR |
| Tessellation | | | | Daylight* |

Table 2
Keywords Categories.

| Category | Keywords |
|----------------------|--|
| General Term | Facade, “Building Envelope”, “Facade Design” |
| Specific Application | Geometric, “Geometric Pattern”, “Islamic Geometric Pattern”, Tessellation |
| Desired Outcome | “Energy Efficiency”, “Thermal Performance”, “Thermal Comfort”, Daylighting |

keywords across these three groups (see Table 1). This refined search strategy helped to achieve more precise and relevant results for the systematic review.

- OR broadens the search. For instance, “geometric” OR “geometric pattern” will retrieve articles that contain either “geometric”, “geometric pattern”, or both terms. This operator is used to include synonyms or related terms, ensuring a wider range of relevant results.
- AND narrows the search. For example, “building envelope” AND “thermal comfort” will only find articles that include both “building envelope” and “thermal comfort”. This operator is used to refine the search by combining multiple criteria, thus focusing on more specific results

A keyword search strategy was employed on Scopus to identify relevant studies on the impact of geometric patterns in building facades on energy performance. This strategy utilized a three-tiered categorization scheme (see Table 2): First Tier: General facade design terminology, such as “facade” and “building envelope”. This tier captures broad research on facade design. Second Tier: Specific applications related to geometric patterns, including terms like “geometric”, “geometric pattern”, and “tessellation”. This tier focuses on the geometric aspects of facade design. Third Tier: Desired outcomes in energy efficiency, with keywords such as “energy efficiency”, “thermal performance”, “thermal comfort”, and “daylight”. This tier targets studies that address the impact of geometric patterns on energy-related performance metrics. This categorization ensured a systematic search, effectively capturing research that explores how geometric facade designs can contribute to energy efficiency and thermal comfort in built environments.

In the initial search, 611 research papers were found using the specified keywords through Scopus. Subsequently, 79 papers excluded by considering the selection criteria. The selection criteria included limitations in language, subject area, and document type. The language of the documents was restricted to English, while the document types were limited to articles, conference papers, and book chapters. The subject areas encompassed Engineering, Energy, Computer Science, Environmental Science, Social Sciences, Materials Science, Arts and Humanities, and Multidisciplinary studies. Finally, the timeframe for document inclusion was restricted to publications from the year 2000

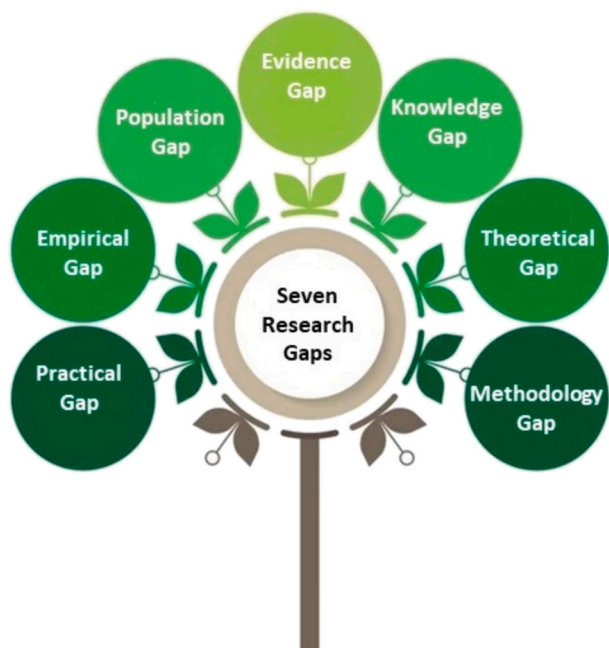


Fig. 2. Seven keys area of the research gaps diagram.

onwards. This limitation was implemented due to the scarcity of relevant articles between the year 1999 and 2000, with only one article found, albeit not entirely relevant to the scope of this study. The title, abstract, keywords, authors' names, affiliations, journal name, and publication year of the identified records were exported to an MS Excel spreadsheet. Duplicated articles and irrelevant articles were excluded.

A manual screening was conducted by the authors to exclude irrelevant articles based on skimming through the titles, keywords and abstracts of each paper. Subsequently, the remaining papers underwent eligibility assessment, with the full-texts carefully scrutinized. A comprehensive assessment was conducted on 36 publications, categorizing them according to their alignment with the search keywords. These 36 papers were dedicated to exploring the energy performance implications of geometric patterns in façade design, encompassing shading screens, responsive building envelopes, and double-skin facades. Among these, 22 studies specifically delved into tessellated patterns. Consequently, the research scope was narrowed down to 22 articles, as depicted in the highlighted the PRISMA flow diagram (Fig. 1), and its associated checklist. The PRISMA diagram consists of four stages, identification, screening, eligibility, and inclusion.

Furthermore, an inductive approach was used to analyze the content of the identified papers, translating the data into categorized research gaps. Information is extracted from each paper in sequence, adding relevant details to the data extraction sheet. This process continues until all papers are reviewed. Accordingly, the data is synthesized to address the research questions. Two independent reviewers assessed the risk of bias in the studies. Effect measures, like risk ratios or mean differences, were used for clarity in presenting results. Sensitivity analyses were conducted to ensure the reliability and validity of the findings.

Gaps categorization

In conducting this systematic review, a framework has been employed to categorize the research gaps identified within the included studies. This framework highlights seven key areas where discrepancies or limitations may exist (Fig. 2).

An Evidence Gap refers to an insufficient or inappropriate amount of data, information, or evidence to validate a specific claim, argument, or conclusion. This gap often indicates the need for further research or data

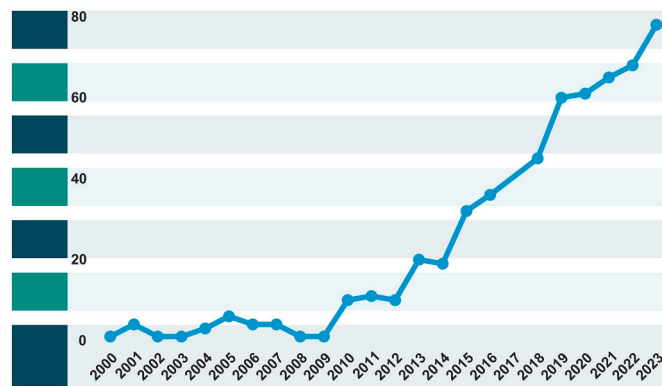


Fig. 3. The distribution of the retrieved literature over the time frame of the study.

Table 3
Countries with more than 10 publications in the identified literature.

| Country/territory | Number of publication |
|--------------------|-----------------------|
| China | 92 |
| United States | 79 |
| Italy | 46 |
| United Kingdom | 37 |
| Spain | 31 |
| Germany | 29 |
| Canada | 25 |
| France | 19 |
| Portugal | 19 |
| Iran | 18 |
| Australia | 17 |
| Switzerland | 16 |
| Netherlands | 15 |
| Brazil | 14 |
| Russian Federation | 13 |
| Ireland | 11 |
| South Korea | 11 |
| Poland | 10 |

collection to strengthen a study's foundation. A Knowledge Gap emerges when there is a lack of understanding or information about a particular topic or issue, highlighting the need for additional research or exploration to address this deficiency in existing knowledge. A Practical Gap signifies a deficiency in applying or implementing theoretical knowledge in real-world scenarios, suggesting challenges in translating concepts into actionable solutions. A Methodology Gap points to shortcomings or inadequacies in the research methods used in a study, indicating potential flaws or areas for improvement in the research process. An Empirical Gap is identified when there is a shortage of empirical evidence—data obtained through observation or experimentation. This gap prompts researchers to seek more direct evidence to either support or challenge a hypothesis. A Theoretical Gap occurs when there is a lack of well-established theoretical frameworks or models to explain a phenomenon, underscoring the need for theoretical advancements or the exploration of alternative theories. Lastly, a Population Gap arises when a study's findings, conclusions, or recommendations may not be broadly applicable or generalizable due to limitations in sample size or participant characteristics (Askarizad, Dueden & Garau, 2024).

By systematically analyzing the included studies through this framework, authors can more effectively categorize and evaluate the research gaps within the current body of literature.

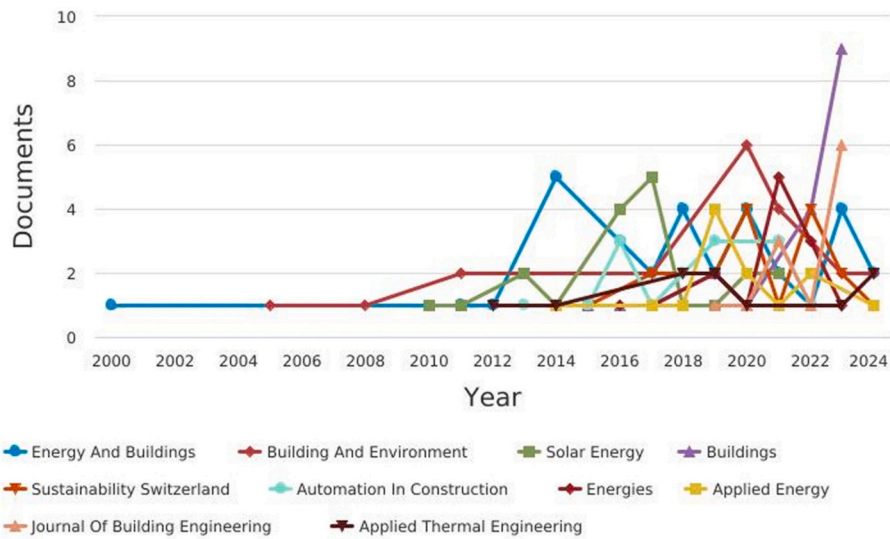


Fig. 4. Document per year by the source (Source: Scopus).

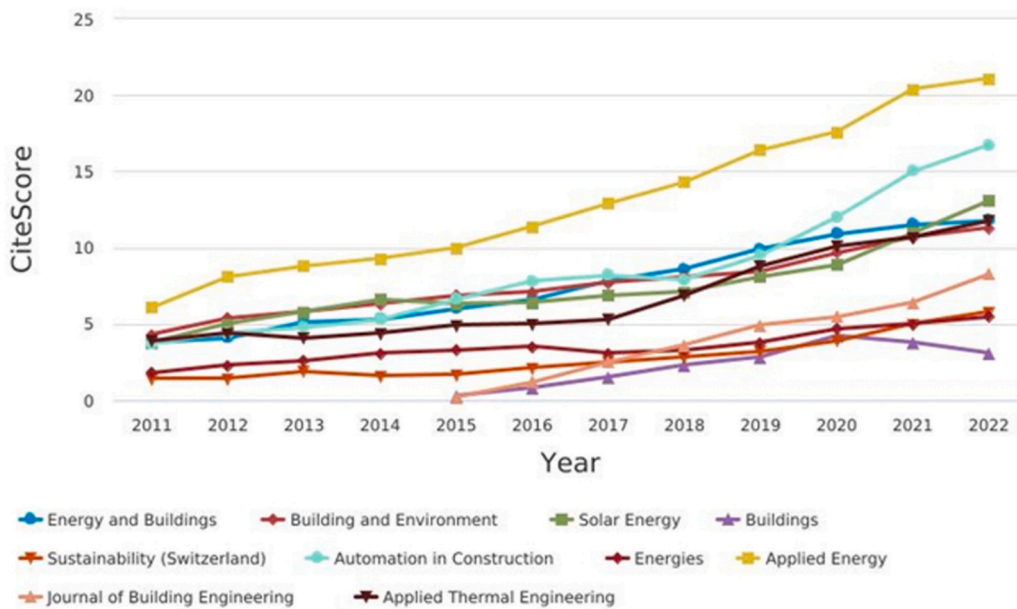


Fig. 5. CiteScore per year by the source (Source: Scopus).

Results and findings

Overview of the search results

This systematic review initially identified 611 records, of which 532 met the selection criteria. The findings show that, since 2010, the number of documents has risen significantly, reflecting growing attention to the energy crisis (Fig. 3). According to the Scopus database, the country's most frequently involved in these studies are China, the United States, Italy, the United Kingdom, and Spain (Table 3). This data reflects the countries of the authors' affiliations as listed in the Scopus database, indicating where the research is being conducted rather than the geographic distribution of the case studies.

The graph shows how the number of articles published by journals containing the searched keywords has changed over time (Fig. 4). The journal Buildings reached its peak in 2023 with 9 published documents. The next two most prolific journals in this theme are Building and

Environment and Journal of Building Engineering, each publishing 6 documents in 2020 and 2023, respectively.

In addition, the journal Applied Energy holds the highest CiteScore, reaching 21 in 2022, with a notable margin. Following closely is the journal Automation in Construction, which has shown a strong growth rate over the ten-year period from 2011 to 2022. In contrast to its high publication count, Buildings has the lowest CiteScore among the ten journals with the highest citation metrics (Fig. 5).

A word cloud visualization is included to provide a quick overview of the prominent themes emerging from the searched keywords (Fig. 6). The size of each word reflects its frequency of occurrence. The word cloud highlights terms related to geometric patterns and their impact on building design, particularly façade design. Keywords such as "performance," "sustainability," and "energy" suggest a focus on optimizing building energy efficiency. Additionally, terms like "daylight" and "comfort" indicate an interest in how geometric patterns influence daylight quality and the thermal comfort of building occupants. The

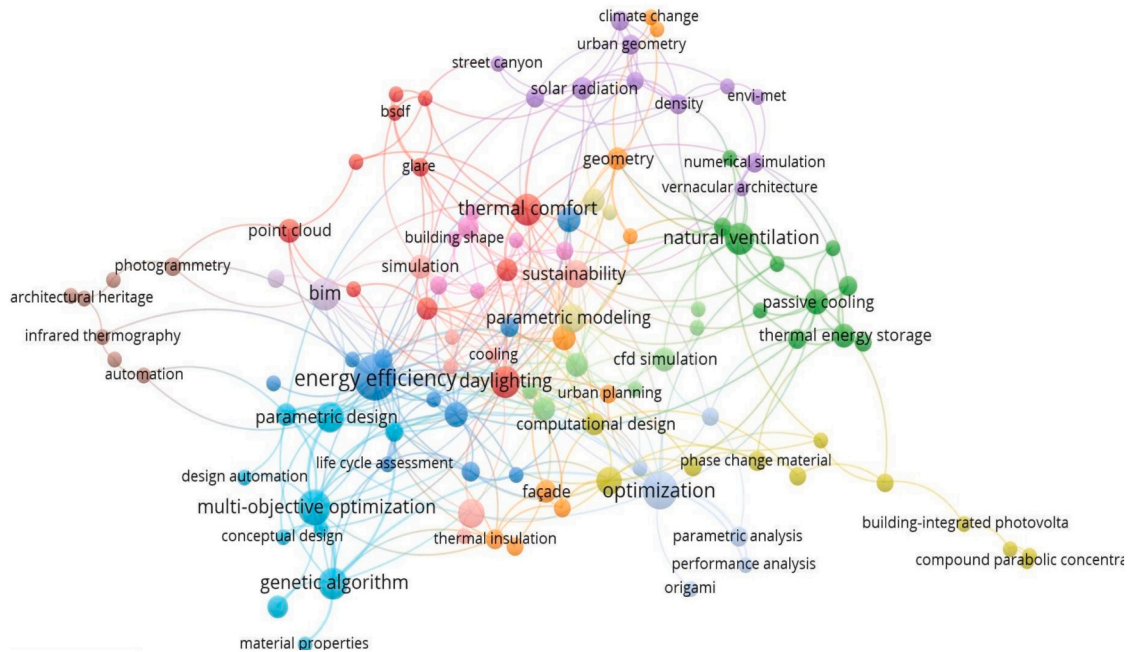


Fig. 7. Network visualizing graph, using: VOSviewer software.

façade design, with a specific focus on tessellated patterns. A total of 36 papers were reviewed, with 22 studies examining the impact of tessellation on efficient daylighting and thermal performance.

In a recently published study, [Kızılörenli and Maden \(2023\)](#) proposed alternative responsive façade systems based on semi-regular and demi-regular tessellations. Their findings indicate that these tessellated systems offer the anticipated visual comfort and daylight levels across various configurations, providing a usable and preferred space for potential users while maintaining the required daylight levels ([Kızılörenli & Maden, 2023](#)).

[Bande et al. \(2023\)](#) focused on strategies for reducing energy consumption in residential buildings in Al Ain through innovative design approaches, such as parametric façades and shading devices, while also considering social influences and environmental sustainability. Their results show that an innovative façade design led to a 25 % reduction in energy consumption and a 44 % improvement in daylight analysis ([Bande et al., 2023](#)).

[Kahramanoğlu and Alp \(2023\)](#) assessed the climate impact on office spaces by studying an origami-based responsive façade over a year. The study found that this façade design performed better than the baseline scenario in terms of daylight improvement, without impeding visibility ([Kahramanoğlu & Alp, 2023](#)).

[Ningsih et al. \(2022\)](#) investigated a hexagonal responsive façade system designed as a secondary architectural layer. The study reveals that a fully close hexagonal responsive façade system with 0 degrees' rotation can reduce sun radiation level down to 2–1.6 kWh/m² or 40 % radiation reduction. [Oghazian et al. \(2017\)](#) examined the impact of geometry and the non-uniform placement of solar screen openings on the daylighting performance of a south-facing office room. They found that Rhombus-shaped solar screens were the most effective for maximizing Special Daylight Autonomy, given their ability to optimize the area of each cell while maintaining overall opening size and material ([Oghazian et al., 2017](#)).

[Bande et al. \(2022\)](#) in their study aim to leverage advanced modeling and simulation tools, such as Rhino and Grasshopper, to optimize the façade design and achieve significant reductions in energy usage (25 %) and improvements in daylighting (44 %). [Goharian et al. \(2022\)](#) in another study indicate that parametric grid skins, such as Voronoi facades, are increasingly integral to modern architecture, but their

environmental performance must be carefully examined. The study demonstrates that controlling geometric turbulence significantly affects daylight performance, highlighting the importance of considering both architectural aesthetics and functional requirements in facade design ([Goharian et al., 2022](#)).

Yet another study conducted by [Hosseini and Heidari \(2022\)](#), investigates a methodological approach to offer an appropriate combination of kinetic behavior and movement with colored glass compositions to improve occupants' daylight performance. This study uses several compositions of colors and identifies the optimal one for each time. Moreover, the results emphasize the role of colored glass, especially blue color, in preventing visual discomfort ([Hosseini & Heidari, 2022](#)).

In a research paper, [Maksoud et al. \(2022\)](#) used parametric modeling to design a climate-responsive screen, aiming to utilize natural light effectively throughout the day while ensuring energy efficiency and thermal comfort. The study showed that, there was a notable enhancement in UDLI (100–2000) compared to the current corridor conditions, showing an increase of over 54 %. Additionally, there was a marked reduction in both vertical and horizontal radiation ([Maksoud et al., 2022](#)).

The main finding of a research was conducted by [Mohamed and Bande \(2022\)](#) is that by incorporating optimal IGP configurations inspired by the traditional architectural element, into the façade cladding systems of mid-rise buildings in Al Ain, significant reductions in energy consumption can be achieved. In addition, these configurations can maintain sufficient daylighting and quality views ([Mohamed & Bande, 2022](#)).

An experimental study by [Rehman and Surapaneni \(2021\)](#), replaces a glass facade with a Jaali screen in a 3D model to assess its impact on indoor lighting and thermal comfort. The study introduces a research methodology to create an optimized Jaali pattern, offering architects and building engineers a design solution to enhance the lighting and thermal quality of indoor spaces. The findings of the study show how the solid void ratio and thickness of the selected Jaali pattern were changed parametrically to arrive at a final optimized pattern that gives the best possible results for daylight and thermal analysis ([Rehman & Surapaneni, 2021](#)).

The study by [Caetano and Leitão \(2021\)](#) focused on the framework's algorithms that generate different geometric patterns, exploring their

Table 4
Summary of the included articles.

| Author | Year | Performance | Function | Method | Software | Location | Geometric Pattern |
|---------------------------------|------|--|------------------|---|--|---|---|
| Bande et al. | 2023 | Energy consumption/ solar radiation | Residential | Simulation/ Optimization | Grasshopper- Honey bee- Energy Plus | Al Ain/Emirates | Triangular Pattern |
| Bande et al. | 2022 | Energy Consumption/ Daylight | Library | Simulation/ Optimization | Grasshopper | Al Ain/Emirates | Rosetta |
| Caetano & Leitão | 2021 | – | – | None simulation base | Para cloud Gem/ Grasshopper/ Dynamo | – | star-polygons |
| Chi D. et al. | 2017 | Daylight | Office | Orthogonal Array | Radiance-based | Seville/Spain | Simple geometric pattern |
| Giostra et al. | 2019 | Daylighting/Visual comfort | Office | Simulation/ Optimization | Grasshopper/Diva | | Folding Geometry/3D tessellation |
| Goharian et al. | 2022 | Daylight | Not specified | Simulation | Grasshopper | Northern hemisphere | Voronoi Geometry |
| Hosseini & Heidari | 2022 | Daylight | Office | Simulation/ Optimization | Grasshopper/ Honeybee/ Ladybug | Hot-arid/Iran | hexagonal modules (Orosi) |
| Hosseini et al. | 2020 | Daylight | Office | Grid-based simulation | Grasshopper/Diva | semi-arid climate | 8-Point-Star/8-Fold-Rosette |
| Gerber et al. | 2017 | Daylight | Office | Simulation | Grasshopper/Diva | Los Angeles/US | Agent as a Façade panel |
| Kahramanoğlu & Çakıcı | 2023 | Daylight | Office | Simulation/ Optimization | Grasshopper/ Climate Studio/ Ladybug | Istanbul/ Mediterranean | Square module/Miura-ori model |
| Kızılörenli & Maden | 2023 | Daylighting | Office | Simulation/ Modeling | Grasshopper/ Climate Studio | Mediterranean | Equilateral triangles/hexagons |
| Maksoud et al. | 2022 | Daylight/Thermal | Educational | Simulation/ Optimization | Grasshopper/ Ladybug | Hot-arid/ Emirates/Sharjah | Rosetta Pattern |
| Mohamed & Bande | 2022 | Daylight/Thermal | Educational | Simulation | Grasshopper/ Diva/Energy Plus | Hot- arid/ Emirates/Al Ain | 8-fold Star (Mashrabyah) |
| Nazari et al. | 2023 | Thermal comfort | Office | Simulation/ Optimization | Grasshopper | Tehran/Semi-arid | Simple Geometric Shapes |
| Ningsih et al. | 2023 | Thermal comfort | Residential | Simulation/ Optimization/ Fabrication | Grasshopper/ Ladybug | Tropical | Hexagonal |
| Oghazian et al. | 2017 | Daylighting | Office | Simulation | Grasshopper/ Honeybee | Tehran/Semi-Arid | Circle, Hexagonal, Square, Cross, jagged Hexagonal (circle), Rhombus and Tabl (decagram tile) |
| Rehman & Surapaneni | 2022 | Daylighting/Thermal comfort | | Simulation | Grasshopper/ Climate Studio | Delhi/India | 6-point/8-point/6&8 point/10- point/12-point/14-point Geometrical patterns |
| Tabadkani | 2018 | Daylighting | Office | Simulation/ Optimization | Grasshopper/Diva | Tehran/Semi-arid | Rosette modules/louvers |
| Emami N.; Giles H. | 2016 | Daylighting | – | Simulation/ Experiment | Diva/Flamingo nXt | Michigan | Hexagonal |
| Hachem & Alsayed | 2016 | Thermal Performance | Office | Simulation/ Optimization | Grasshopper/ EnergyPlus | Calgary/Canada northern midhigh latitude climatic | A simple folded plate geometry (saw-tooth)/A more complex folded-plate units based on pyramids |
| Youssef et al. | 2021 | Daylighting | Office | Simulation/ Optimization | Grasshopper/Diva | Cairo/Egypt | Hexagonal |
| Srisamranrungruang & Hiyama. | 2020 | Daylighting/Natural ventilation/Energy performance | | Simulation | Diva/Design Builder/ Rhinoceros | Japan | Simple Geometry (circle) |

Hosseini et al. (2020) conducted the first study investigating the daylight performance of various Islamic geometric patterns (IGPs) used in Orosies with different thicknesses. Their findings indicate that IGPs with thicknesses of 10 and 15 cm performed better than those with a 5 cm thickness. Designs like the 8-Point-Star and 8-Fold-Rosette proved particularly effective on the West façade, enhancing daylight performance while reducing visual discomfort (Hosseini et al., 2020).

Giostra et al. (2019) demonstrated that a standard curtain wall, solely through its folding geometry, can meet or exceed LEED target values for daylighting and glare control without additional shading devices. Their research shows that integrating opaque and transparent panels in three-dimensional configurations significantly improves visual comfort compared to a flat base scenario. However, while digital tools have advanced the articulation of these surface geometries, their practical application in buildings remains limited (Giostra et al., 2019).

Tabadkani et al. (2018) explored the design of an adaptive shading

pattern for an office space in Iran using parametric modeling. The study found that the distance between the Rosette and façade, as well as the depth of the louvers, significantly impacted indoor daylighting. The optimal configuration occurred when the Rosette distance was minimized to 10 cm and the louver depth was set at 60 cm (Tabadkani et al., 2018).

Chi et al. (2017) focused on optimizing perforated solar screen designs using four design variables: perforation percentage, matrix, shape, and orientation. Their study revealed that optimized designs increased the daylight area by 33 % and reduced over-lit areas by 35 % compared to models without perforated solar screens. This approach also demonstrated the potential to save significant time in the early stages of building design (Chi et al., 2017).

Gerber et al. (2017) aimed to partially automate the design process by integrating user preferences with optimization criteria in the early design phase. The study showed that incorporating multi-agent systems

Table 5
Classification of facades.

| Facade system | Description | Movement |
|--------------------|---|--------------------|
| Double skin facade | Two layers of building envelope with ventilated or unventilated air space | Static/ Dynamic |
| Shading screen | External elements to control solar gain and light penetration | Static/ Dynamic |

into architectural design results in unique design configurations that outperform standard shading options, particularly in daylight factor analysis (Gerber et al., 2017).

Hachem and Elsayed (2016) aimed to investigate the effects of geometric designs in equatorial-facing, double-skin facades on the energy performance of multi-story office buildings. Their study shows that while deviations from a basic flat facade may increase heating loads, they can also reduce cooling loads and significantly enhance energy generation potential through facade-integrated photovoltaic systems. The research underscores the critical role of facade geometry in optimizing solar energy usage, offering architects and engineers tools to model energy performance early in the design process and optimize solutions for multi-story building envelopes across various climates and locations (Hachem & Elsayed, 2016).

Emami et al. (2014) explored the design of shading screens inspired by Persian geometric ornamentation patterns, contributing to the development of screen walls to control daylighting and provide shading for buildings. Their research emphasizes the importance of both aperture size and overall perforation ratio in shading screen designs. The findings, backed by experimental and numerical data, demonstrate that reducing the perforation ratio leads to lower lighting levels (Emami et al., 2014).

A summary of the reviewed papers, including their characteristics; such as authors, publication year, performance type, case study functions, methods, software, climate context, and types of geometric patterns used, has been provided in Table 4. This table offers a comprehensive comparison of the various aspects of each study.

Analysis

This section offers a detailed analysis and discussion of the

methodologies and findings of the included studies. It addresses facade classifications, types of geometric patterns, energy performance indicators, evaluation methods, case study functions, and climate contexts. These aspects are clearly illustrated through various graphs, tables, and charts, providing a comprehensive and insightful overview.

Facade classification

The types of facades utilized in the reviewed studies have been systematically categorized in two distinct ways (Table 5). The first categorization is based on the facade system, classifying them into Double Skin Façade and Shading Screen. A Double Skin Façade consists of two layers of the building envelope with either ventilated or unventilated air space in between, while a Shading Screen comprises external elements designed to control solar gain and light penetration into the building. The second categorization is based on the movement of the facade, further classifying them into Dynamic and Static types. Dynamic facades can change their configuration or properties in response to external factors such as sunlight, temperature, or user interaction. In contrast, Static facades maintain a constant configuration without altering their properties (Fig. 10).

This dual classification approach offers a comprehensive framework for understanding the various facade systems, their operational characteristics, and potential applications discussed in the reviewed papers. The analysis reveals that the majority of studies (40 %) focused on the energy efficiency implications of geometric patterns on static shading screens, while dynamic shading screens remain largely unexplored, with only two papers addressing this topic. However, both static and dynamic double skin facades were closely investigated, accounting for 28 % and 23 % of the studies, respectively (Fig. 9).

Geometric patterns classification

Another classification of the reviewed papers is based on the types of geometric patterns used, categorized as Traditional Patterns and Modern Patterns. The analysis shows that the number of studies focusing on traditional and modern patterns is quite similar, with 12 and 10 studies, respectively. However, some modern patterns are derived from traditional designs, while only a few, such as the Voronoi pattern, are entirely independent of traditional influences (Figs. 10 and 11).

The selected patterns varied based on the context of each study,



Shading Screen- Static Shading Screen- Dynamic

Shading Screen, involves external elements designed to control solar gain and light penetration into the building

Double Skin Facade- Static Double Skin Facade- Dynamic

Double skin Facade is a system consisting of two layers of building envelope with a ventilated or unventilated air space in between,

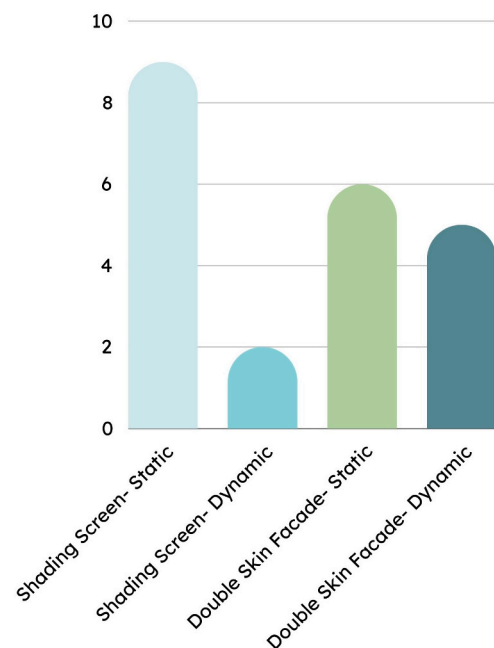


Fig. 9. Percentage of each types of facade in the studied documents.

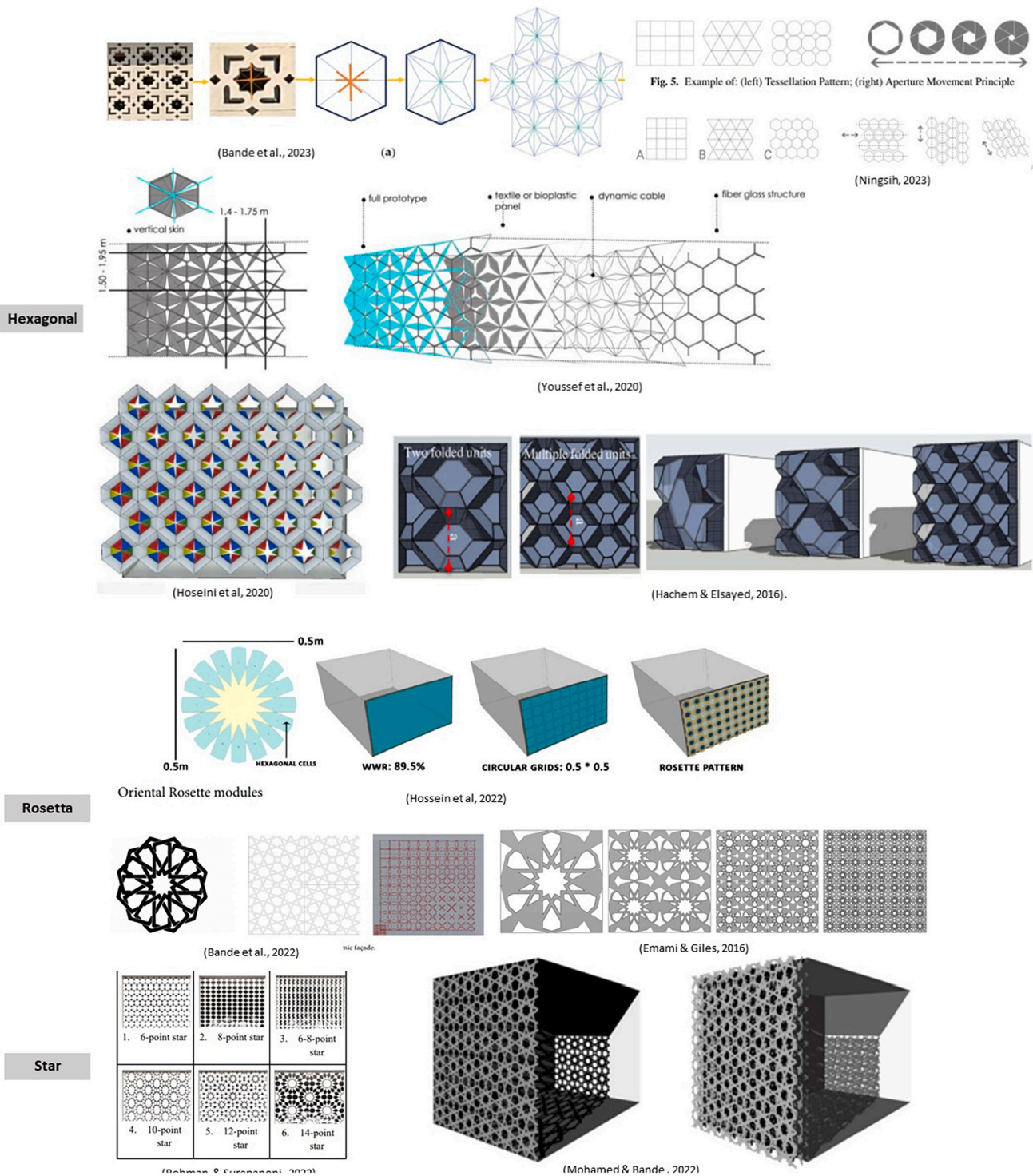


Fig. 10. Geometric patterns used in the included studies.

including modules of Islamic Geometric Patterns (IGPs) such as Rosetta, Simple Geometric Patterns (circle, square, hexagon), and Folded Geometry. The bar chart (Fig. 12) highlights that Hexagonal patterns were the most commonly used, while other patterns were relatively underexplored. It is important to note that all the patterns analyzed were grounded in tessellation principles.

Indicators of Energy Performance

Daylight performance emerged as the most frequently studied energy performance indicator, representing 73 % of the studies analyzed.

Thermal performance was the focus of 18 % of the studies, while the integration of lighting and thermal performance received less attention, accounting for only 9 % of the total (Fig. 13a). This indicates that daylight performance was prioritized in the evaluation of energy performance, whereas combined analyses of thermal and daylight factors were relatively underexplored. The disproportionate focus highlights the need for more comprehensive studies that investigate the integrated performance of both thermal and daylight characteristics in geometric patterns used in façade design. Such research could offer valuable insights into optimizing energy efficiency and occupant comfort in

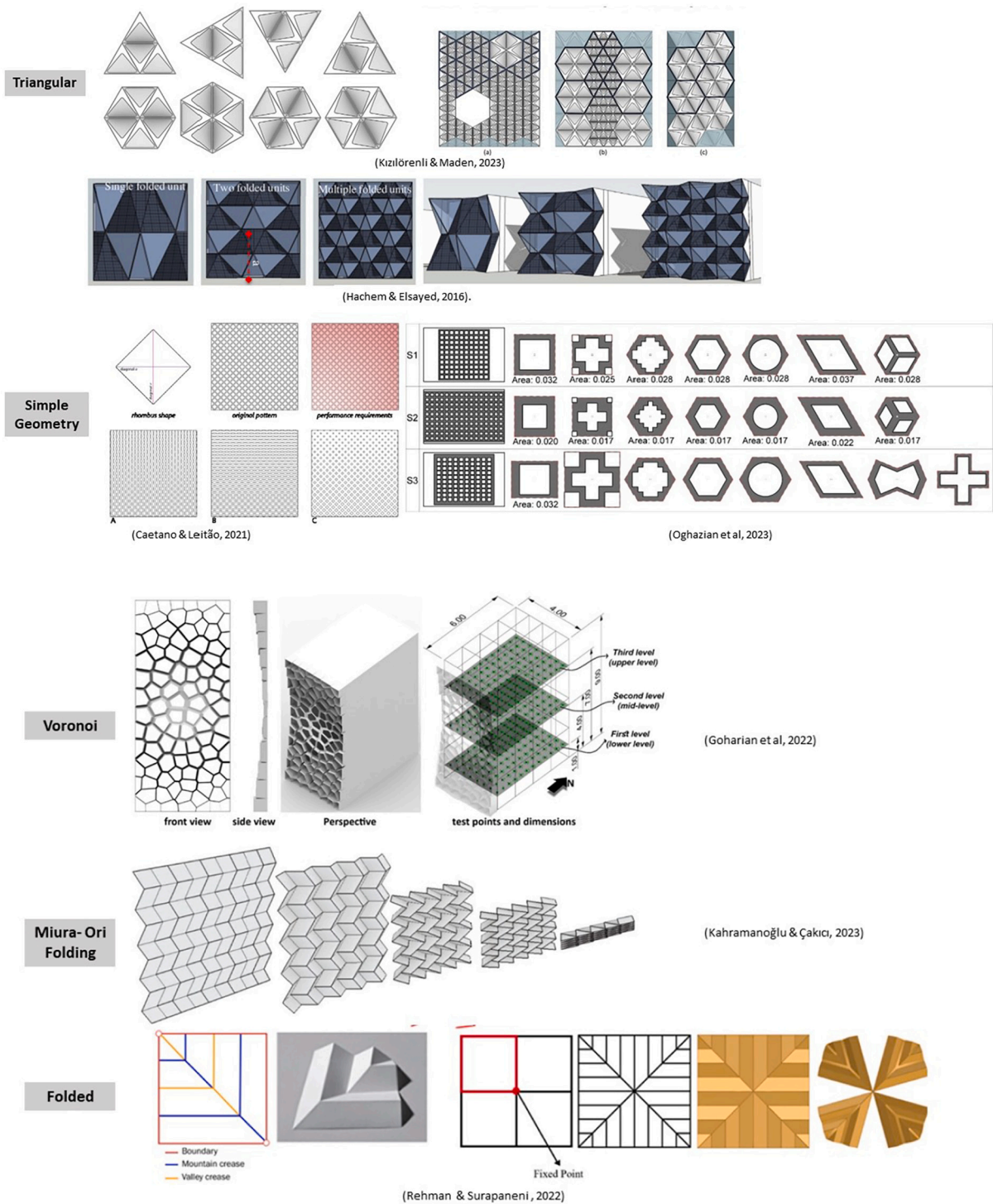


Fig. 11. Geometric patterns used in the included studies.

building design.

Method of evaluation

The analysis of methodologies used in the reviewed studies shows that the combined approach of Simulation and Optimization is the most prevalent, accounting for over 50 % of the studies. The standalone use of simulation, without optimization, follows as the second most utilized method, representing approximately 37 % of the studies. Experimentation was employed less frequently, making up around 10 % of the studies (Fig. 13b). These results indicate a strong reliance on the Simulation/

Optimization approach, likely due to its ability to provide comprehensive analyses by integrating both techniques effectively. The notable use of standalone simulation emphasizes its value as a distinct and powerful tool in this field. On the other hand, the lower percentage of studies utilizing experimentation suggests that, while valuable, this method may be less commonly applied due to its resource-intensive nature or its specific relevance to certain research contexts.

Climate contexts of the studies

The review reveals that the majority of studies (62 %) were

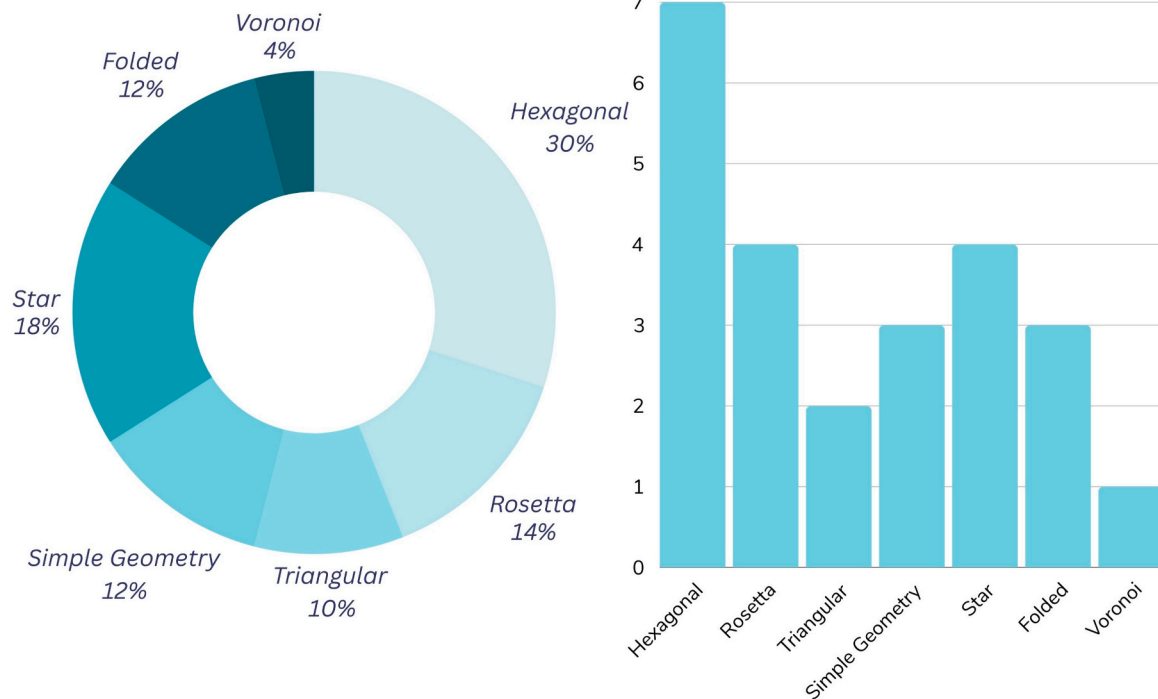


Fig. 12. Number of geometric patterns used in the included studies.

conducted in hot-arid and semi-arid climates. Additionally, there were three studies focused on Mediterranean climates, two in tropical regions, and two in cold climates, with only one study examining a sub-tropical climate (Fig. 13c). These findings demonstrate a predominant emphasis on hot-arid and semi-arid climates within the existing literature. While other climates, such as Mediterranean, tropical, cold, and sub-tropical, are also represented, they are studied less frequently. Understanding the distribution of climatic focus in current research provides valuable insight into the geographic scope and applicability of the findings, while highlighting potential areas for future exploration in underrepresented climate zones.

Function of the case studies

The primary focus of the buildings under study was on office spaces, which accounted for 67 % of the sample. This was followed by two residential, three educational buildings, and one commercial establishment (Fig. 13d). These results highlight a significant concentration on office buildings in current research, reflecting a strong interest in this category within architectural and energy performance investigations. While residential, educational, and commercial properties are represented, they are studied less frequently. Analyzing the prevalence of different building types in existing studies provides valuable insights and suggests future research could explore a broader range of building categories and their functions.

Discussion

The systematic review of papers on the energy efficiency implications of tessellation geometric patterns in façade design has uncovered a variety of research gaps. These gaps range from the need for a more comprehensive assessment of shading screens' impact on key aspects such as energy efficiency in heating, cooling, lighting, as well as thermal comfort, daylighting performance, and overall building energy use. There's also a clear need for long-term studies across different climates and seasons, assessing factors like occupant comfort, satisfaction, and well-being, with particular focus on visual comfort, glare reduction, and maintaining outside views.

Another significant gap lies in exploring the integration of smart technologies and automation in dynamic shading systems to achieve optimal energy performance. Research could also delve deeper into aesthetic and cultural implications, exploring user-centric design and integrating shading solutions with diverse building types and orientations. Furthermore, the real-world validation of simulation results, the development of implementation guidelines, and economic feasibility analysis are highlighted as critical yet under-explored areas.

In addition, more focused studies on glare reduction, aperture size, and assessment metrics refinement are necessary, along with the exploration of additional environmental factors. Biomimetic strategies, inspired by nature, also represent exciting opportunities for innovative shading solutions, offering potential in controlling dynamic daylight. Specific shading technologies such as kinetic façades, Jaali patterns, and double-skin façades present further areas for research, with gaps identified in material selection, the Venturi effect, and understanding seasonal variations. Developing advanced predictive models to account for these variables is essential.

Addressing these research gaps will play a crucial role in advancing the field, fostering more effective, sustainable, and user-friendly shading solutions. The study also tackled the potential for reporting biases, ensuring the risk of bias was minimized through comprehensive assessments of each synthesis. Thematic scopes of the research gaps, as demonstrated in Fig. 14, provide a visual overview of these key focus areas for future exploration. These insights reflect the multifaceted challenges and opportunities in optimizing façade design through tessellation patterns, indicating significant room for growth and innovation.

While many literature reviews have explored energy-efficient building facades, only a limited number have examined the geometric aspects of facade design and their impact on energy efficiency. For instance, Preet et al. (2022) investigated the connection between double facade geometry, thermal performance, and airflow, highlighting the need for further research into the complex interactions between these factors. Vassiliades et al. (2022) reviewed the integration of active solar energy systems in building design, and Li et al. (2020) discussed advancements in shape-shifting building envelopes while noting the focus

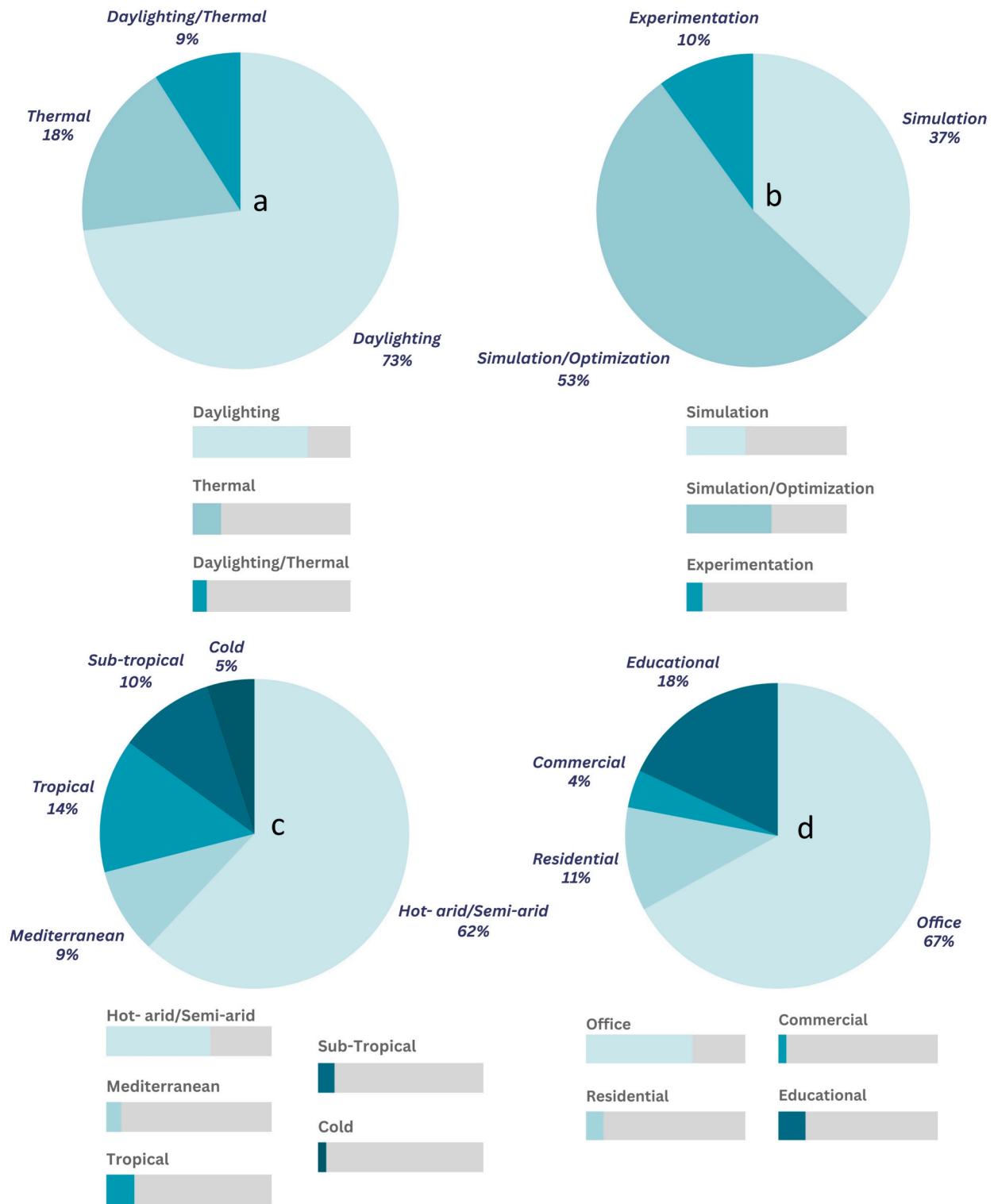


Fig. 13. (a) Indicators of energy performance: (b): Method (c): Climate context. (d): Case study function.

of research on optimizing building form for energy efficiency. Another study by Li et al. (2020) emphasized that a large portion of research centers on building form optimization for energy efficiency.

Ibrahim et al. (2023) explored the sustainability implications of Islamic Geometric Patterns (IGPs), which are a subset of tessellation patterns. The study highlighted that while IGPs have been examined for their potential contributions to sustainability, other geometric patterns with similar potential have been largely overlooked in existing research.

Despite the study's focus on sustainability, it was found that the number of papers addressing environmental sustainability and energy sufficiency specifically remains relatively low. This finding underscores the need for further research in these areas to better understand the broader sustainability applications of geometric patterns in facade design, beyond just IGPs.

Niyati et al. (2022) investigated the role of geometric patterns in shading screens and their influence on energy efficiency, but this study



Fig. 14. Thematic scopes of gaps.

was limited to dynamic shading screens, overlooking static shading systems and double-skin facades. In contrast, the current review provides a more comprehensive analysis by covering geometric patterns in various shading systems, including both shading screens and double-skin facades.

A key contribution of the present study is the systematic categorization of research gaps in this field, identifying seven key areas where discrepancies or limitations may exist. This novel framework allows for an accurate assessment of deficiencies in existing literature, offering a clear and structured view of the current challenges in the field. These research gaps are visually summarized in Fig. 15, providing a helpful overview of the areas needing further exploration. The identification of

these gaps not only highlights unexplored opportunities but also establishes a foundation for future research aimed at improving energy efficiency, sustainability, and building performance through innovative geometric facade designs.

Conclusion

The present systematic review examined prior research on the role of various geometric patterns in building facades to enhance energy efficiency. The review sought to identify research gaps, highlight methodological limitations, and propose directions for further exploration of their underexplored effects. As stricter design standards have led to more complex facades, the challenge lies in balancing intricate aesthetics with cost-efficiency and performance. Prioritizing appearance alone can hinder energy efficiency, as energy performance requires optimized designs that enhance both daylighting and thermal performance. Therefore, achieving facades that are both visually appealing and sustainable demands a holistic approach—one that integrates aesthetics with functionality to balance visual appeal and energy efficiency.

The systematic analysis of literature on the energy efficiency implications of tessellation geometric patterns in facade design reveals several intriguing research gaps. The analysis shows that 40 % of the research focused on static shading screens, with only 28 % and 23 % of studies addressing static and dynamic double skin facades, respectively. Dynamic shading screens remain underexplored, despite their potential advantages in energy control and adaptability. The review highlights that daylight performance is the most studied aspect, appearing in 73 % of the research, while thermal performance received considerably less attention, with only 18 % of studies focusing on this factor. This suggests an imbalance in the current research, with insufficient integration of daylight and thermal performance in facade designs.

Furthermore, 62 % of the studies concentrated on hot-arid and semi-arid climates, leaving many other climatic conditions underrepresented, such as tropical, Mediterranean, or cold climates. This narrow focus limits the generalizability of the findings and underscores the need to explore facade performance across a wider range of climatic conditions to enhance building energy efficiency globally. There's also a call for further research on sustainable materials, smart controls, and practical

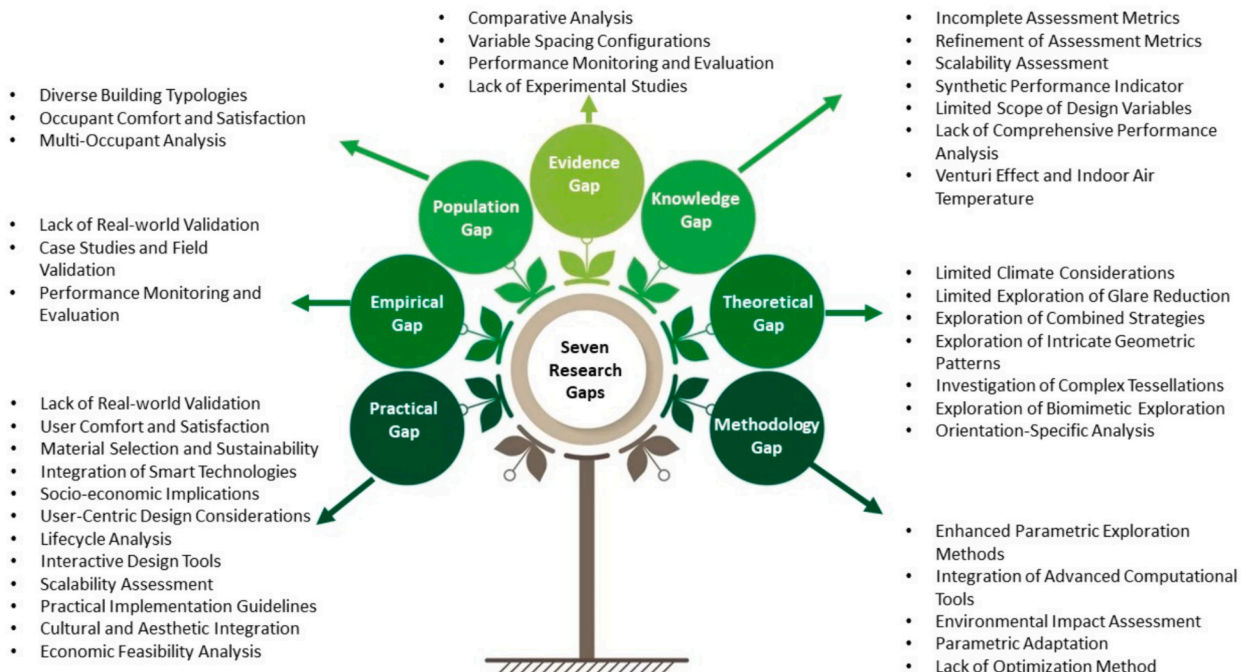


Fig. 15. Seven areas of the research gaps.

design considerations for real-world applications.

Additionally, most research focuses on specific time periods rather than examining how shading effectiveness changes throughout the year and across different climates. There is a significant gap in understanding how shading screens impact the occupants inside the building, particularly in terms of comfort, satisfaction, and well-being. Further research is needed on using eco-friendly materials and construction techniques for creating geometric patterns in shading screens, including an assessment of the environmental impact of these materials over their lifespan. The potential of smart technologies and automation to improve shading performance is vast and requires broader investigation. While many studies rely on simulations, it is essential to confirm these findings through real-world applications. Moreover, more practical guidelines are needed, taking into account cost, ease of installation, and compliance with building codes. Further investigation is required into specific aspects of shading, such as the effect of pattern size on glare and the best methods for measuring the performance of various geometric patterns. Lastly, there are significant opportunities for additional research on specific shading technologies, including areas like material selection, airflow management, year-round performance variations, and the development of machine learning models to predict system performance.

Despite the comprehensiveness of this research within its particular field, there were still some limitations and constraints that may affect the results to varying degrees. Since the study focuses solely on the tessellation of geometric patterns in facade design, other factors contributing to building energy efficiency are beyond its scope and may be overlooked. The limited availability of data or studies specifically addressing the energy efficiency implications of tessellated geometric patterns could also restrict the depth of analysis. Additionally, the findings may be limited in their generalizability due to the specific focus on these patterns, making it challenging to apply the results to broader contexts. While a focused set of keywords was carefully selected to capture the most relevant literature on geometric patterns and energy efficiency in building facades, the limited number of keywords used may have inadvertently excluded some pertinent studies. This limitation suggests that while the findings are robust, they could be further enhanced by future research that employs a broader or more diverse set of keywords to ensure more comprehensive coverage of the topic. Lastly, constraints such as limited resources, including time and funding, may have restricted the depth and breadth of the research conducted.

This study highlights the energy efficiency implications of tessellated geometric patterns in facade design, revealing both their potential and limitations. By thoroughly examining the existing literature and identifying research gaps, it contributes to a deeper understanding of how geometric patterns can enhance energy efficiency in buildings. The findings emphasize the need for further investigation and stronger methodological approaches in this field. The relevance of this research extends beyond academia to architects, urban planners, and policy-makers involved in sustainable building design and construction. The goal is to inspire informed decision-making and innovative solutions that balance aesthetic appeal with energy efficiency, promoting a more sustainable built environment for current and future generations.

CRedit authorship contribution statement

Mana Dastoum: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Carmen Sanchez Guevara:** Writing – review & editing, Validation, Supervision, Conceptualization. **Beatriz Arranz:** Writing – review & editing, Validation, Supervision, Conceptualization.

Declaration of competing interest

There is no conflict of interest associated with this study.

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