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Review

Thermo-Environmental Performance of Modular Building Envelope Panel Technologies: A Focused Review

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Abstract: Modular construction is becoming famous for buildings because it allows a high degree of prefabrication, with individual modules easily transported and installed. Building envelope optimization is vital as it protects buildings from undesirable external environments by expressly preventing the incursion of outside elements. This research uses a systematic literature review to appraise the characteristics of modular envelope panels, focusing on hygrothermal and energy performance. A total of 265 articles were subjected to rigorous filtering and screening measures. The findings reveal notable inconsistencies in modular envelope terminologies and a lack of consistent performance measures, which present significant challenges for research and development efforts. Furthermore, the results indicate a predominant focus on hygrothermal and energy performance in existing studies, with limited attention to environmental impacts and other performance factors. Moreover, the existing literature primarily addresses modular envelope solutions in temperate climates, offering inadequate information for hot and hot–humid climate contexts. To address these gaps, this study proposes categorizing modular envelope panels into four distinct categories: active, passive, smart, and green/vegetated wall panels. These findings will benefit researchers, architects, building envelope designers, policymakers, and organizations developing building performance-related assessment ratings, standards, and codes. The study suggests adopting the categorization of modular envelope panels provided in this study and developing modular panels suitable for hot and humid climates to fill the existing knowledge gap.

Keywords: building envelope; building facades; facade modules; modular panels; systems; sandwich panels; energy savings; cooling; heat transfer

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1. Introduction

Owing to growing awareness of environmental pollution and the need for energy conservation, sustainability concerns are now crucial in the construction of buildings. The 21st century is characterized by increasing energy demand from all human activities, as the application of energy resources is growing, leading to shortages that are becoming a global concern [1]. The world experienced a 23% increase in energy expenditure between 1990 and 2005; this expense is expected to rise by 68% and more than 90% by 2025 and 2035, respectively [2,3]. The basic requirements of sustainable buildings that can be achieved through advanced building envelope structures include high energy efficiency, energy autonomy, and enhanced living conditions [4]. Buildings, as the primary energy consumption element, can integrate renewable energy sources (RESs) into building envelopes using some unique installation processes under the modular situation to shape multifunctional façade modules (MFMs) [1].

Building envelopes are critical systems that separate the indoor environment from the outdoor climate, forming a barrier to protect the indoor environment from unfavorable conditions. During their lifetime, building envelopes are subjected to heat, air, and moisture loads from indoor and outdoor environments, which makes their hygrothermal performance utterly dependent on the type, properties, and assembly of the materials used, in addition to the installation and detailing of the building [5]. Building envelope prefabrications have recently witnessed numerous technological advancements, offering new opportunities [6]. Facilities are increasingly integrating new construction materials, such as using sustainable and energy-efficient products, which create unique conditions for improving efficiency and general safety, thus providing a comfortable built environment for future generations [7]. The role of building envelopes in determining building energy consumption is vital, as a vast energy resource is required to balance the thermal energy losses or gains that occur through the building envelopes to control climate. Applying electrical power and non-renewable fossil fuels for space cooling or heating are the main contributors to energy consumption [8].

Energy saving is fundamental in different sectors and essential for transitioning to a decarbonized society [9]. The contributions of renewable sources are crucial for attaining energy efficiency, making their exploitation more than an obligated step, as the building sector is accountable for a substantial segment of the primary energy demand [7]. Globally, there is an urgent need to reduce greenhouse gas emissions. Buildings are the most significant contributors to global warming emissions, so improving their energy performance through implementing renewable energy technologies is a way to reduce energy use and, thus, carbon footprint [10].

In active building envelopes, advancements in materials technology and building automation systems increasingly mimic the intelligent response of human behavior and skin to environmental stimuli. This phenomenon enables the controlled regulation of energy flow through a building's thermal barrier, which benefits energy savings and occupants' comfort [11]. New technologies and construction processes are being developed to improve building envelope sustainability and efficiency [12]. Responsive and adaptive building design covers the choreography of movement, functional movement, environmental responsiveness, and aesthetics to make buildings more useful and energy efficient and contribute towards more comfort, aesthetic appeal, and delightful experiences. Several studies have been conducted to develop innovative, adaptable, and intelligent building facades and envelopes that highlight their thermal behavior and adaptability to different climatic contexts [13].

Furthermore, modular building envelope panels are needed to facilitate easy transportation, installation, and replacement of building envelopes and facades. A modular building is an off-site mounting construction comprising modular units [14]. Off-site prefabrication systems are gaining popularity in the construction industry because they combine fast construction with fewer but sustainable resources while minimizing occupant disruption [15]. Modular systems have several advantages over conventional construction processes, including faster and safer production, accurate completion time prediction, superior quality, fewer on-site workers, less resource waste, and more environmentally friendly solutions [14]. Modularity is also considered to be the ability of a building envelope or system to respond to the high degree of adaptability required by the operating context. It is recognized as repeating an element with precise and known characteristics linked to its functionality and sustainability, which can provide an adequate solution [16]. Despite having several advantages, the private sector still relies heavily on the conventional on-site construction method rather than modular construction [14]. Modular building envelope panels are utilized in many construction projects, such as institutional, commercial, industrial, residential, prefabricated structures, temporary structures, renovation, and retrofitting, because of their advantages: quick construction, cost-effectiveness, energy efficiency, and design adaptability. Developers, architects, and contractors increasingly select them because of their versatility and adaptability.

Numerous research papers have reviewed building envelope systems. Luo et al. [17] showed that technical research on active building envelope (ABE) systems for renewable and sustainable energy has expanded considerably, while the ratio of ABE to façade studies remains consistent. Another review study [18] focused on the dynamic insulation systems of building envelopes. The results indicate that using dynamic insulating air can lead to over 40% energy savings compared to buildings using static insulation. Finch et al. [19] examined building envelope systems for the circular economy, evaluation parameters, performance, and critical problems, identifying two key trends limiting circularity in the building envelope: the widespread presence of fixings that irreversibly damage components and the extensive use of chemically modified materials. Villegas et al. [20] reviewed active materials for adaptive building envelopes, indicating that passive dynamic control systems in buildings are well-developed and promising. On new experimental projects, thermal and comfort indexes must be evaluated because passive systems use sensitive materials that users cannot switch off or work on. Narbuts and Vanaga [21] reviewed innovative building envelope technologies to improve total building energy efficiency and reduce greenhouse gas emissions, showing that active PCM can reduce room temperature by 6.8 °C in summer, aerogel has excellent insulation and low density, silica aerogel outperforms traditional insulation materials by 2–4 times with energy savings of up to 35%, and active and adaptive systems enable real-time control of building envelope performance, improving energy efficiency and indoor comfort. None of these studies specifically address modular building envelopes, let alone the development of envelope panels.

Moreover, previous reviews on building envelopes [22–24] have not considered the hygrothermal performance of modular building envelope panels. Thus, information explicitly addressing modular wall envelope panel solutions in hot and hot–humid climates is limited in the current literature. This research aims to undertake a focused review of advancements in the study of modular envelope panels to improve building hygrothermal and energy performance in hot and humid climates. Therefore, a focused review and development of high-performance modular building envelope panels can contribute to realizing a sustainable built environment.

2. The Approach

The research approach follows a three-step systematic review process indicating the study's main procedure, including steps and factors considered. The first step of the systematic review was the identification of records through an extensive search and review using the Scopus and Web of Science databases employing the following keywords: modular, building envelope, sandwich panels, facades, green walls, energy performance, cooling, heat transfer, and wall systems. Documents published before 2012 were initially excluded from the study to focus on developments within the last ten years. The search yielded 265 papers subjected to various detailed inspection and screening levels. The first screening process removed all articles that did not discuss building envelopes based on abstract and conclusion analysis, which reduced the total number of articles to 131. The second filtering process removed all articles discussing building envelopes unrelated to hygrothermal properties, materials, and energy, reducing the total number of articles to 67. The third filtering process removed all articles published in languages other than English or without access to full content, removing 26 papers. The remaining 41 research papers were downloaded and reviewed using an analysis of the abstract, introduction, and methodology to determine their relevance to the topic, which resulted in the removal of 11 articles not specifically addressing modular building envelope panels. As shown in Table 1, the remaining 30 documents were thoroughly reviewed and documented. Figure 1 presents the data collection approach adopted for the systematic review. Table 1 lists the papers sorted by year in the systematic literature review, with the associated ID numbers and country where the research was conducted. In addition to excluding studies that do not address hydrothermal or environmental performance, other performance requirements like strength and durability have fewer implications for the building location. Since most of the established envelope panels are concentrated in temperate climates (Table 2), focusing on establishing the study gap between temperate and hot and hot–humid climates is essential.

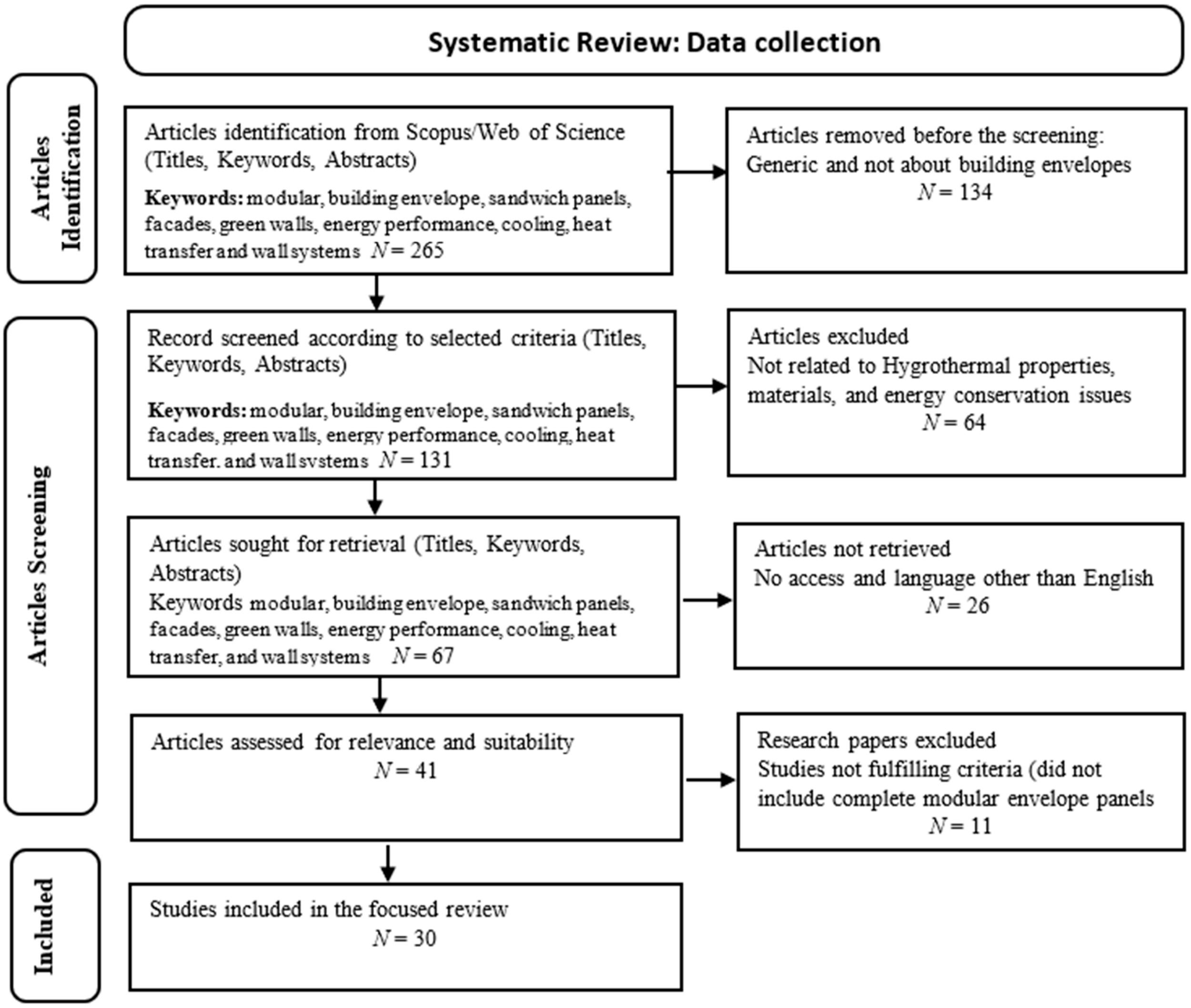


Figure 1. Data collection and systematic review approach.

Table 1. Research studies/articles included in the review with their respective ID.

Article IDs	Author(s) and Year of Publication	Source	Country
{1}	Rozins & Iejavs, 2014 [25]	Scopus	Latvia
{2}	Z. Liu et al., 2015 [8]	Scopus	China
{3}	Voth et al., 2015 [26]	Web of Science	USA
{4}	Zhu et al., 2016 [27]	Scopus	Wuhan, China
{5}	Luo et al., 2016 [28]	Web of Science	China
{6}	Manso & Castro-Gomes, 2016 [29]	Scopus	Portugal
{7}	Serra et al., 2017 [30]	Scopus	Italy
{8}	Baldassarri et al., 2017 [31]	Scopus	Europe (50 cities)
{9}	Iommi, 2018 [13]	Scopus	Italy
{10}	Ibañez-Puy et al., 2018 [32]	Web of Science	Spain
{11}	Brandl et al., 2018 [33]	Scopus	Austria
{12}	J. Li et al., 2018 [34]	Scopus	China
{13}	Zuazua-Ros et al., 2018 [35]	Scopus	Spain
{14}	Bock, 2019 [10]	Scopus	UK, Spain, and Sweden

Table 1. *Cont.*

Article IDs	Author(s) and Year of Publication	Source	Country
{15}	Santi et al., 2019 [36]	Scopus	Italy
{16}	Weiland et al., 2019 [37]	Scopus	German
{17}	Pečur et al., 2020 [38]	Scopus	Croatia
{18}	Arkar et al., 2020 [4]	Scopus	Switzerland, Slovenia, Sweden
{19}	He et al., 2020 [39]	Scopus	China
{20}	Oquendo-Di Cosola et al., 2020 [12]	Web of Science	Italy
{21}	Bagarić et al., 2020 [40]	Scopus	Croatia
{22}	Djamai et al., 2020 [41]	Scopus	France
{23}	Chang et al., 2021 [42]	Scopus	Republic of Korea
{24}	Torres et al., 2021 [43]	Scopus	Spain
{25}	Azami & Sevinç, 2021 [44]	Web of Science	Iran
{26}	Martín-Gómez et al., 2021 [45]	Web of Science	Spain
{27}	Yasir Khan et al., 2021 [46]	Scopus	India
{28}	Scioti et al., 2022 [47]	Scopus	Italy
{29}	Bevilacqua et al., 2022 [7]	Scopus	Mediterranean—Italy
{30}	Katsigiannis et al., 2022 [15]	Scopus	Germany

Table 2. Summary of findings related to modular envelope panels between 2012 and 2022.

Reference {Article IDs}	Developed Panels	Study Findings
Rozins & Iejavs, 2014 [25] {1}	Lightweight cellular wood material (CWM)	Recommends cellular wood material sandwich panels with insulation. Thermal conductivity in the parallel direction (0.0977 $W \cdot m^{-1} \cdot K^{-1}$) is 34% better than perpendicularly measured (0.148 $W \cdot m^{-1} \cdot K^{-1}$).
Z. Liu et al., 2015 [8] {2}	Active solar thermoelectric radiant wall (ASTRW)	The ASTRW's inner surface temperature is 3–8 °C lower than the room's indoor temperature, controlling the thermal flux across the envelope. The overall cooling efficiency is 3.3% and 7.1% for 90° and 60° PV installation angles, respectively.
Voth et al., 2015 [26] {3}	Thin-walled hollow-core wood-strand sandwich panels	Sandwich panels fabricated with ponderosa pine strands performed better than commercially produced composite panels. Its normalized bending stiffness was 141–156% stiffer than OSB of equal thickness.
Zhu et al., 2016 [27] {4}	Shape-stabilized phase change material (SSPCM) wallboards	Building operation energy consumption in the SSPCM room was 6.4% and 17.8% lower than in the reference room in summer and winter, respectively.
Luo et al., 2016 [28] {5}	Thermoelectric radiant panel (TERP)	The analysis of the area and shape of the typical region indicated that the square-shaped region is the optimum for both system capacity and COP.
Manso & Castro-Gomes, 2016 [29] {6}	Geogreen system	The geogreen system reduces maximum interior surface temperatures and increases minimum internal surface temperatures by 7 °C; it reduces maximum income heat flux by 75% and maximum outgoing heat flux by 60%.
Serra et al., 2017 [30] {7}	Vertical greenery modular system (VGMS)	The results highlighted the potentiality of VGMS to reduce the indoor air temperature during the summer period by as much as 4 °C compared to the reference technology in a free-floating condition.
Baldassarri et al., 2017 [31] {8}	Cement-based composite (CBC) panels	Recommends a "dual layer" sandwich for summer and a "single layer" for winter. The environmental benefit of integrating PCMs is a 25% reduction in the sandwich insulating layer without affecting thermal performance.
Iommi, 2018 [13] {9}	Mediterranean Smart Adaptive Wall (MSAW)	Adequate heat storage capacity, considering the wall thickness and weight, with thermal capacity coefficients between 16.3 kJ/m^2K and 17.6 kJ/m^2K.
Ibañez-Puy et al., 2018 [32] {10}	VATE: Thermoelectric Cooling and Heating Unit (TCHU)	Implementing a thermoelectric system façade acts as a conventional window. It is considered a thermal bridge integrated into the envelope since the system has a lower insulation level than the façade.

Table 2. *Cont.*

Reference {Article IDs}	Developed Panels	Study Findings
Brandl et al., 2018 [33] {11}	Solar Thermal Activated Façade (STAF)	The absorber with the 14 vertical, parallel-arranged fluid pipes with one-side inflation shows the best thermal performance.
J. Li et al., 2018 [34] {12}	Integrated Modular Envelope System (IMES)	The study involved high-insulation panels, aerogel blankets, and thermal insulation materials. The comprehensive heat transfer coefficients for the two integrated envelopes were 0.124 W/(m^2K) and 0.257 W/(m^2K), with 75% and 45% energy savings, respectively, offering better insulation capacities than the current national standard.
Zuazua-Ros et al., 2018 [35] {13}	Ventilated Active Thermoelectric Envelope (VATE) module	The heating power varies between 66.8 and 273.6 W, and the COP of the whole system decreases from 2.1 to 1.0 as the voltage increases.
Bock, 2019 [10] {14}	Building Active Steel Skin Envelope (BASSE)	The cladding panel has 30.4% efficiency and generates 3321.14 kWh/year.
Santi et al., 2019 [36] {15}	Plant-bearing modular panels	Green façade with panels savings of heating energy of 17.60 €/sqm/year and saves AC energy 1851 €/m^2/year.
Weiland et al., 2019 [37] {16}	Solar thermal active panels with a mineral wool core	The V1.D and V4.D (aluminum HTP) have the highest performance and serviceability efficiency (58.3% and 58.4%), respectively. V2.D and V3.D (steel HTP) performances are 6.3 and 6.6% points lower (52.0% and 51.7%), respectively.
Pečur et al., 2020 [38] {17}	Prefabricated ventilated sandwich panel	Reduced summer heat gains by 29.07% and 50.65% compared to the non-ventilated façade and the ETICS system, respectively. The total annual primary energy consumption was less than 120 kWh/m^2.
Arkar et al., 2020 [4] {18}	Semi-transparent modular BIPV façade	The semi-transparent modular building-integrated PV façade decreases energy by 40% to 55% compared to the reference façade, with solar energy utilization efficiency of 44% to 63%.
He et al., 2020 [39] {19}	Modular concrete green wall system (3D-VtGW)	Reduced 11.20% AC load in summer and 9.12% annual AC load compared with baseline. Reduced LPD of baseline by 10.20%.
Oquendo-Di Cosola et al., 2020 [12] {20}	Living wall systems (LWS)	The felt-based LWS impacts almost 100% of the impact categories analyzed. At the same time, plastic-based LWS has the lowest influence on the total environmental impact.
Bagarić et al., 2020 [40] {21}	Ventilated recycled aggregate concrete (RAC) wall panel	Ventilated RAC wall panels outperformed both non-ventilated and ETICS walls in the summer period, reducing heat inflow by 57.19% and 76.11%, respectively. It behaves like a non-ventilated panel in winter. It is better than the ETICS wall, decreasing 1.12% and 8.36% heat outflow, respectively.
Djamai et al., 2020 [41] {22}	PCM-modified textile-reinforced concrete (TRC) foamed sandwich panel	The melting point of the PCM, at a scanning rate of 0.05 °C/min, is in the range of 23–27 °C, with a peak at 25 °C. The latent heat of the phase change is 160 kJ/kg.
Chang et al., 2021 [42] {23}	Cross-laminated timber (CLT) wall	The coefficient of the variation-root mean square error (CV(RMSE)) of the temperature and relative humidity inside the ply-lam CLT wall from experiments and simulation was 6.43% and 7.02%, respectively, satisfying the validation criteria. The ply-lam CLT wall with extruded polystyrene insulation is confirmed safe from moisture in all cities.
Torres et al., 2021 [43] {24}	"Plug and play" modular façade	This system achieves savings of 50% (time), 30% (materials), and 25% (waste). The strategy reduced the heating load from 110 kWh/m^2 to 14.5 kWh/m^2 (86% reduction).
Azami & Sevinç, 2021 [44] {25}	BIPV panels	The optimal BIPV-based Form Factor value of 0.71 implies the priority of roof-based scenarios. The BIPV coverage index is higher than 0.92.
Martín-Gómez et al., 2021 [45] {26}	Ventilated Active Thermoelectric Envelope (VATE)	It resulted in an improved coefficient of performance (COP) of the system.
Yasir Khan et al., 2021 [46] {27}	Ferro Cellular Lightweight Concrete Insulated Panel (FCIP)	FCIP raises internal room temperature by 2 °C in 2 h than 9.5 °C of brick masonry. Replacing FCIP with concrete/brick masonry envelope reduces running costs by 50%.

Table 2. *Cont.*

Reference {Article IDs}	Developed Panels	Study Findings
Scioti et al., 2022 [47] {28}	High-Performance Walls (HP Walls): expanded polystyrene-reinforced concrete (EPS-RC) precast bearing walls	The study optimized expanded polystyrene-reinforced concrete (EPS-RC) precast-bearing walls by adding recycled EPS particles to the mixtures. The thermal conductivity ranges from 1.77 W/mK for S7 (100% of the reference specimen S_0) to 0.45 W/mK for S4 (25% of S_0).
Bevilacqua et al., 2022 [7] {29}	Trombe wall (modular)	Reduce AC electric demand by 10.5%; reduce cooling needs by 9.5%; reduce CO_2 emissions by 185 kg per year.
Katsigiannis et al., 2022 [15] {30}	SmartWall (modular)	Reduce primary energy by 89%. PV-integrated SmartWall achieved 7.5 kWh/m^2 energy consumption.

The studies examined in this research covered about 19 countries, with 17 countries accounting for 28 studies focusing on cold climates and only two countries, i.e., Iran and India, addressed modular building envelope panels in hot climates (Table 1), and even the Iranian case study is located in a city (Tabriz) situated in a temperate climate. This finding indicates that most modular envelope panels are intended for cold climates, implying that more research is needed to bridge this knowledge gap. It is challenging for envelope panels designed for a particular environment to support other climatic zones because of the opposing comfort requirements of the various climatic zones. Figure 2 illustrates the geographic region and distribution of the research publications on the topic "Modular Building Envelopes" with their respective IDs in relation to the world climate zones. It can be inferred that there are three research clusters: the largest in Europe, the second in China, and the third in the Iberian Peninsula. The three clusters are located in the green band, representing the temperate climatic zones of the world.

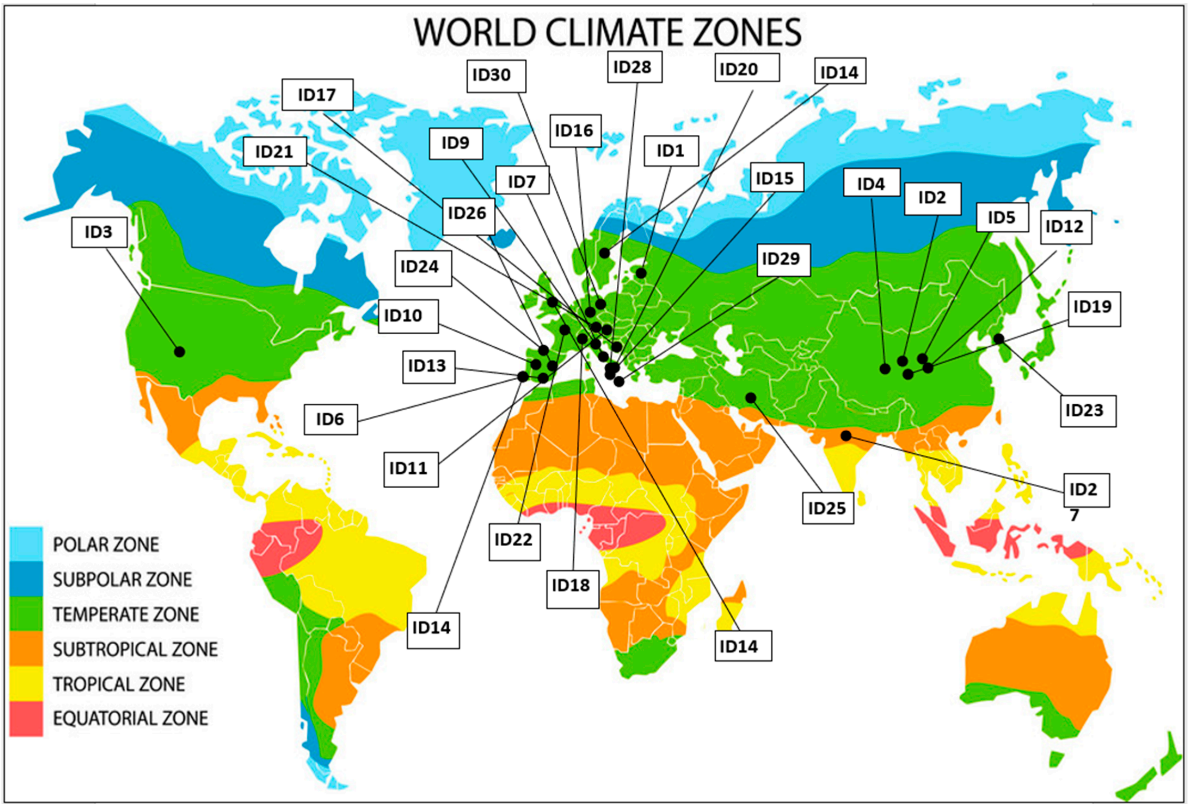


Figure 2. Geographic region and distribution of the research publications on the topic "Modular Building Envelopes" with their respective ID in relation to the world climate zones (source: authors' elaboration based on Scopus and Web of Science data).

3. Modular Building Envelope Panels and Systems: Research Status

Several studies have been conducted on applying modular envelope panels to enhance building envelope/facade performance, as summarized in Table 2. Bevilacqua et al. [7] investigated the performance of Trombe walls and their ability to provide proper ventilation, considering various climatic parameters to reduce summer thermal needs. Their results indicate that well-conceived Trombe walls can save energy in both summer and winter. The implemented ventilation strategies decreased air-conditioning electric demand by 10.5% compared to a traditional envelope while reducing CO_2 emissions by about 185 kg per year [7]. Another study [48] investigated a classic Trombe wall's heating and cooling potential as a passive solar system with a massive south-facing wall painted black on the external surface, an air layer, and a glazed exterior. The wall has vents at the top and bottom to allow air thermo-circulation in the air gap. The results showed that increasing the thickness greatly reduces the thermal load; however, the reduction rate slows beyond 125 mm. Using low-emission glazing instead of single pane in a Trombe wall system reduced winter heat losses and increased passive cooling in the summer. Torres et al. [43] studied the performance of the prefabricated plug-and-play modular system by reproducing the holistic methodology and integrating new technologies. The outcome indicates that the system achieved savings in a confirmed case of 50% (time), 30% (materials), and 25% (waste) compared to more conventional construction methods, translating to achieving significant economic savings [43].

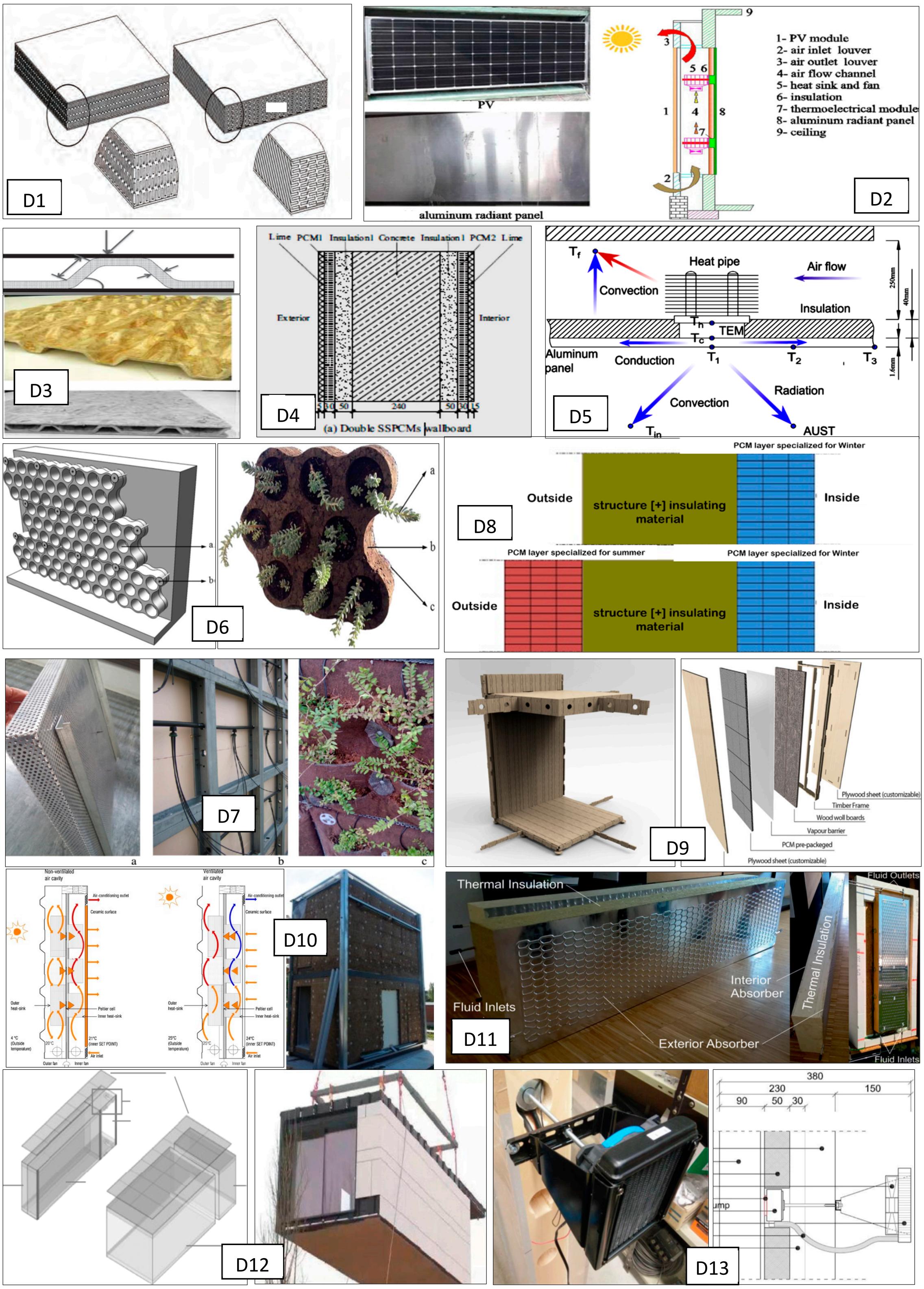
Furthermore, the integration of smart walls to promote sustainability and energy efficiency has been investigated. Smart walls are multifunctional wall systems that combine several technologies to improve a building's thermo-environmental performance by optimizing the envelope system. Smart walls can be installed on the building's exterior as a façade wall or interior in case of space restrictions or aesthetic constraints. The standard technologies incorporated into versatile modular system smart walls include solar photovoltaics, insulation materials, slim-type fan coils, timber-based frames, and high-performance windows. The energy performance of this prefabricated system is investigated at the component and building levels, revealing an 89% reduction in total primary energy [15].

Likewise, researchers have examined the integration of thermoelectric heat pumps into modular building envelope systems. Implementing thermoelectricity in buildings represents an alternative to improving the indoor thermal environment because the technology eliminates the need for refrigerants. The system creates the thermoelectric effect when an electrical current passes through a semiconductor group of unions, with one side of the cell absorbing heat and releasing it into the other depending on the direction of the current. If the direction changes, the effect is reversed [45]. Numerous studies have been conducted on Ventilated Active Thermoelectric Envelope (VATE) systems [35,45]. VATE is an industrial-scale modular prototype designed to be installed in building façades as an alternative heating and cooling solution in net-zero energy buildings. Zuazua-Ros et al. [35] evaluated the prototype VATE module's performance, revealing that heating power varies between 66.8 and 273.6 W depending on the input voltage tested. The overall system's COP decreases from 2.1 to 1.0 as voltage increases. Z. Liu et al. [8] investigated active a solar thermoelectric radiant wall (ASTRW) that uses radiant panel systems to provide a combination of radiant and convective cooling to the room [49]. The system is a solar wall technology integrated with thermoelectric radiant cooling and photovoltaic (PV) technologies. The PV system directly converts solar into electrical energy to power the thermoelectric cooling modes integrated into one enclosure surface as a radiant panel [8]. According to the experimental results, the ASTRW can lower the inner surface temperature by 3–8 °C, indicating its ability to control the thermal flux of the building envelope using solar energy and reduce the air conditioning system requirements [8].

Additionally, a semi-transparent modular building-integrated photovoltaic façade was developed. Its performance was investigated, indicating a 40% to 55% reduction in energy needs compared to the reference façade, with solar energy utilization efficiency ranging from 44% to 63% [4]. However, the thermal performance of the Building Active Steel Skin Envelope (BASSE) was experimentally investigated and validated, indicating that the heat pump's coefficient of performance (COP) ranges from 4.1 to 4.6, generating 3321.14 kWh/year, which corresponds to an efficiency of 30.4% [10]. Moreover, the thermal performance of the Ferro Cellular Lightweight Concrete Insulated Panel (FCIP) has been investigated, and results show that heat transfer through the envelope is significantly reduced. The installation of FCIP allows for only a two °C increase in the internal temperature of the room chamber in two hours. In contrast, brick masonry allows for a 9.5 °C rise in the internal temperature of the room chamber over the same period [46].

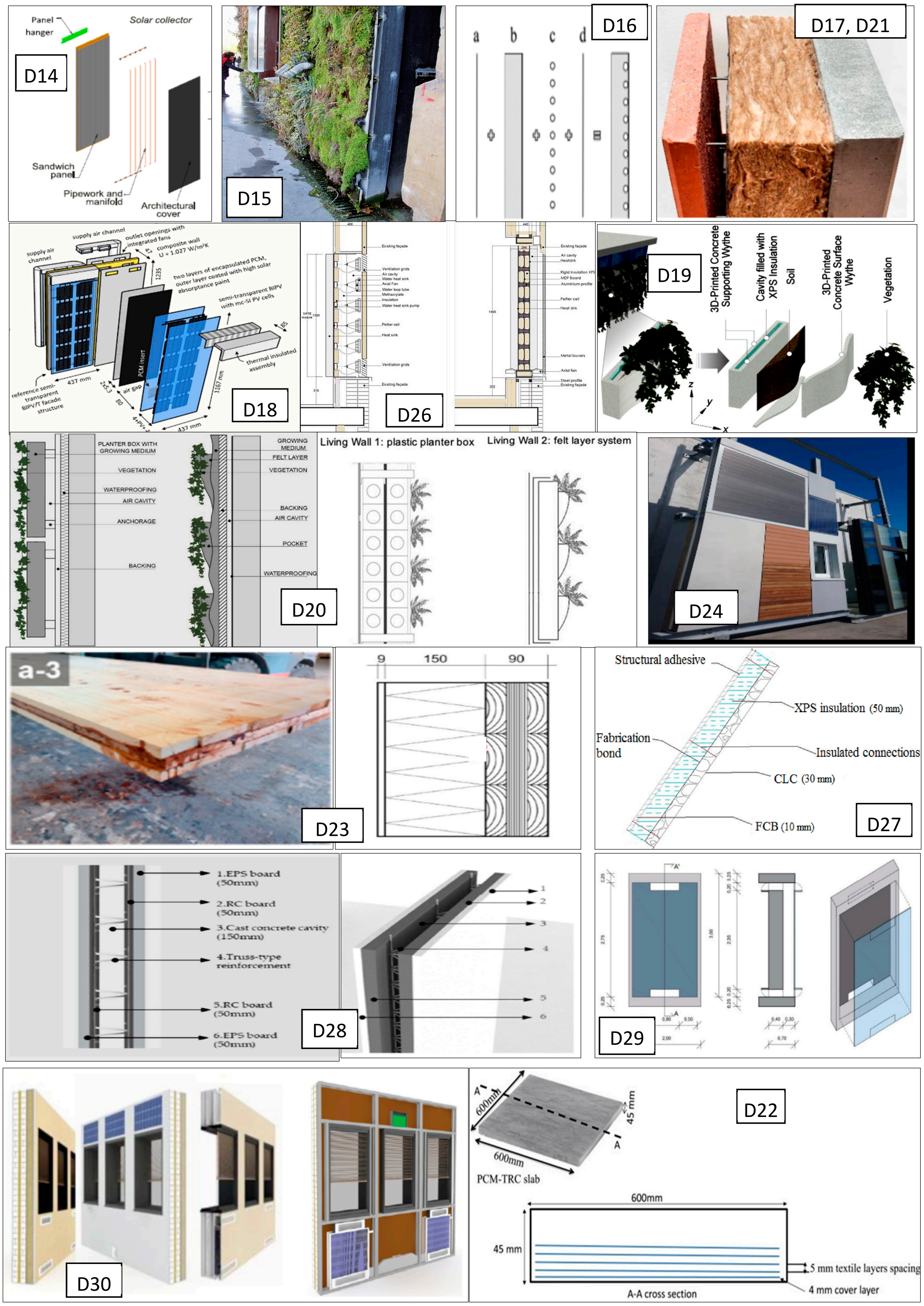
Another effective means of enhancing building envelope performance is implementing green building envelopes, which provide benefits such as increased efficiency, contributing to the immediate context through temperature regulation and reduced wind speed, and improved biodiversity in dense urban environments [50]. Green or vegetable façades are innovative, adaptable, and intelligent facades capable of improving the condition of the hygrothermal environment [12]. A comparative analysis of two living wall systems (LWSs) discovered that the felt-based LWS impacts nearly 100% of the categories analyzed during the LCA manufacturing, construction, and maintenance stages. In contrast, the plastic-based LWS has the least influence on the total environmental impact [12]. Another study [51] developed a new sustainable material known as fiber-reinforced recycled aggregate concrete (FRAC) by incorporating steel fiber (SF) and polypropylene fiber (PPF) into the RAC matrix. The study created a stress–strain constitutive damage evolution function model that accurately predicts the composite's unloading path, reloading path, residual strain development, and damage evolution. Moreover, a study [52] used Life Cycle Assessment to evaluate a straw bale wall in a lab and in situ to determine the strengths and weakness of the technique, indicating that straw bale wall reduces energy and carbon embodied in the building.

Therefore, the documented findings of the studies (Table 2) have considered the energy, hygrothermal, environmental mechanical, and performance of building envelope panels investigated with the need for further investigation on essential aspects such as envelope thermal bridging, infiltration, flexibility, aesthetics, intelligent envelopes panels and carbon footprints of the used materials. Figure 3a,b are graphic illustrations of the investigated modular building envelope modules/panels, each referenced by the article ID. The modular envelope panel diagrams are presented based on availability; some are 3-dimensional, and others are 2-dimensional illustrations. Figure 3a shows modular envelope panels with article IDs between 1 and 13. In contrast, Figure 3b illustrates the modular envelope panels with IDs between 14 and 30.



(**a**)

Figure 3. *Cont.*



(**b**)

Figure 3. (**a**) Graphic illustrations of the investigated "Modular Building Envelopes" modules/panels, each referenced by the article (**D1–D13**) (authors' collections based on available sources). (**b**) Graphic illustrations of the investigated "Modular Building Envelopes" modules/panels, each referenced by the article (**D14–D24**,**D26–D30**) (authors' collections based on available sources).

4. Analysis of Review Results

The main goal of analyzing the results is systematically segregating the data into various domains to identify the knowledge gap. A thorough literature review covering the last ten years revealed a significant knowledge gap regarding the context and content of the different developed building envelope panels. The study's inquiry considered essential envelope parameters, including the study's research categories, the methodologies used in the reviewed studies, the materials, the focus, the terminologies used to refer to modular building envelope panels, and practical and theoretical contributions of the reviewed research work, as presented in the following sub-sections.

4.1. Main Categories and Characteristics of Modular Envelope Panels

The primary research groups investigated in this study were identified and categorized into three main categories—'investigate,' 'contribute,' and 'compare'—with their corresponding examined characteristics and article IDs, as illustrated in Table 3. Several studies have investigated various envelope panel alternatives' thermal, hygrothermal, and energy performance. Other studies contributed to research methodologies, optimization, and development of envelope systems. At the same time, some studies compared various components of modular building envelope panels.

Table 3. Main categories of the reviewed research articles and their examined characteristics.

Main Category (Measures)	Examined Characteristics	Reference {Article IDs}
Investigate	Thermal and energy performance	Rozins & Iejavs, 2014 [25] {1}, Ibañez-Puy et al., 2018 [32] {10}, J. Li et al., 2018 [34] {12}, Scioti et al., 2022 [47] {28}, Katsigiannis et al., 2022 [15] {30}
	Heat transfer and solar energy utilization	Z. Liu et al., 2015 [8] {2}
	Energy performance	Zhu et al., 2016 [27] {4}, Zuazua-Ros et al., 2018 [35] {13}, Santi et al., 2019 [36] {15}
	Thermal behavior and performance	Manso & Castro-Gomes, 2016 [29] {6}, Weiland et al., 2019 [37] {16}
	Hygrothermal and energy performance	Iommi, 2018 [13] {9}, Pečur et al., 2020 [38] {17}, Bagarić et al., 2020 [40] {21}
	Hygrothermal performance	Chang et al., 2021 [42] {23}
	Energy generation and saving	Arkar et al., 2020 [4] {18}
Contribute	Dynamic simulation of thermoelectric radiant panel system (TERP)	Luo et al., 2016 [28] {5}
	Optimizing the thermal, acoustics, environmental, and mechanical performance	Serra et al., 2017 [30] {7}, Brandl et al., 2018 [33] {11}, Djamai et al., 2020 [41] {22}, Yasir Khan et al., 2021 [46] {27}
	Developing methodology to enhance energy, environmental, and spatial design	Baldassarri et al., 2017 [31] {8}, Azami & Sevinç, 2021 [44] {25}
	Developing an energy-generating sandwich panel	Bock, 2019 [10] {14}
	Developing energy-efficient modular concrete green wall	He et al., 2020 [39] {19}
	Achieve significant economic savings	Torres et al., 2021 [43] {24}
	Improve COP and energy performance	Martín-Gómez et al., 2021 [45] {26}
	Enhance thermal, ventilation, and energy performance	Bevilacqua et al., 2022 [7] {29}
Compare	Energy and mechanical performance of oriented strand board (OSB) and sandwich panels	Voth et al., 2015 [26] {3}
	Energy and environmental performance of two living wall systems (LWSs): a plastic-based modular system and a felt-based modular system	Oquendo-Di Cosola et al., 2020 [12] {20}

4.2. Methods Used for Investigating Modular Envelope Panels

The thirty reviewed articles covered a variety of research methodologies, such as simulations, mathematical modeling, laboratory/reduced scale experiments, and full-scale experiments, as shown in Table 4. Seventeen studies used various simulation tools, including DesignBuilder (v 5.03.7), COMSOL, TRNSYS (v 17), and PHONICS eQuest. The variation in the simulation tools is usually prompted by the studies' objectives, goals, and focus, as simulation programs have different capabilities, strengths, and weaknesses. Some simulation programs are excellent in estimating energy consumption, while others perfectly simulate the hygrothermal behavior of materials and contaminant transport. Furthermore, thirteen studies applied full-scale experiment methods, with some employing more than one method to conduct their research for triangulations, verifications, and validations. Employing several data collection and analysis techniques in investigations is essential to enhance the reliability and validity of the study outcome. The other methodologies frequently used in the studies after simulation and full-scale experiments include mathematical modeling employed by six studies and laboratory tests used by seven studies (Table 4). The issues and characteristics of the various methodologies examined are also captured in Table 4.

Table 4. Main research methods of the reviewed research articles and their examined characteristics.

Methods Applied	Examined Characteristics	Reference {Article IDs}
Laboratory Tests	Thermal and energy performance	Rozins & Iejavs, 2014 [25] {1}, Scioti et al., 2022 [47] {28}
	Thermal, acoustics, and mechanical performance	Serra et al., 2017 [30] {7}, Yasir Khan et al., 2021 [46] {27}
	Energy generation and saving	Bock, 2019 [10] {14}
	Hygrothermal, energy, and mechanical performance	Pečur et al., 2020 [38] {17}, Djamai et al., 2020 [41] {22}
Simulation TRNSYS (v 17), SimaPro (v 8.3), HEAT (v 2 7.0, EDILCLIMA (v EC 709), FEM (SIMULIA 6.14 release), PHOENICS CFD, Ansys CFD (v 18.2), WUFI (v Pro 5.6/5.2), Design-builder (v 5.03.7), eQuest, COMSOL, HAM.	Thermal and energy performance	J. Li et al., 2018 [34] {12}, Pečur et al., 2020 [38] {17}, Scioti et al., 2022 [47] {28}, Katsigiannis et al., 2022 [15] {30}
	Energy performance	Zhu et al., 2016 [27] {4}, Santi et al., 2019 [36] {15}
	Energy, environmental, and spatial design	Baldassarri et al., 2017 [31] {8}
	Energy and hygrothermal performance	Iommi, 2018 [13] {9}, Bagarić et al., 2020 [40] {21}, Chang et al., 2021 [42] {23}
	Thermal, acoustic, and structural performance	Brandl et al., 2018 [33] {11}, Yasir Khan et al., 2021 [46] {27}
	Thermal performance and serviceability efficiency	Weiland et al., 2019 [37] {16}
	Energy generation and saving	Arkar et al., 2020 [4] {18}, Azami & Sevinç, 2021 [44] {25}
	Achieve significant economic savings	Torres et al., 2021 [43] {24}
	Enhance thermal, ventilation, and energy performance	Bevilacqua et al., 2022 [7] {29}
Full-scale and Field Experiment	Solar energy generation, utilization, and thermal performance	Z. Liu et al., 2015 [8] {2}, Arkar et al., 2020 [4] {18}
	Hygrothermal and energy performance	Zhu et al., 2016 [27] {4}, Zuazua-Ros et al., 2018 [35] {13}, Pečur et al., 2020 [38] {17}, Bagarić et al., 2020 [40] {21}, Chang et al., 2021 [42] {23}
	Thermal performance	Luo et al., 2016 [28] {5}, Manso & Castro-Gomes, 2016 [29] {6}
	Energy and thermal performance	Ibañez-Puy et al., 2018 [32] {10}, J. Li et al., 2018 [34] {12}, Martín-Gómez et al., 2021 [45] {26}
	Thermal environmental and mechanical performance	Serra et al., 2017 [30] {7}
Mathematical Modeling	Thermal performance	Luo et al., 2016 [28] {5}
	Energy and mechanical performance	Voth et al., 2015 [26] {3}
	Thermal and energy performance	Zhu et al., 2016 [27] {4}, He et al., 2020 [39] {19}
	Energy, environmental, and spatial design	Baldassarri et al., 2017 [31] {8}, Oquendo-Di Cosola et al., 2020 [12] {20}

4.3. Modular Envelope Panel Materials

Based on the articles analyzed in this study, modular building envelope panels have been developed using various materials depending on the envelope's type, characteristics, and configurations. The materials were categorized into finishing, core envelope, insulations, adhesive/binders, radiant panels/thermal storage, thermoelectric coolers, frames, active energy generators, accessories, and others, as shown in Table 5. The documentation of these materials is crucial for developing similar and more efficient envelope panels. One of the significant considerations for developing modular building envelope panels is the ability of the designed panel to compete with other commercially available panels in the market, especially in terms of appearance. The selection of insulation materials is vital for the hygrothermal performance of any developed modular envelope panel. When selecting building insulation materials, several factors are considered, including thermal resistance, sound resistance, damp proof, durability, density, contaminant emission characteristics, weight, availability, and other mechanical properties. The core envelope materials are usually the materials that are responsible for withstanding the mechanical properties of the envelope, including strength, stiffness, and durability. The reviewed studies have used several core materials, most of which are applied in temperate climates. The possibility of these materials performing in hot climates is subject to further investigations.

Table 5. Different materials used for making envelope panels.

Number	Material Category	Material Type
1	Finishing materials	Plaster (mortar), clay plaster, ceramic tiles, galvanized steel skins, aqua panel, color coating, galvanized steel, protective coating, metallic cover
2	Insulation materials	Insulations: expanded polystyrene insulation (EPS), wood fiber, climate board, softwood, vacuum insulation panel (VIP), ethylene propylene diene monomer (EPDM), extruded polystyrene (XPS) rigid insulation, XPS foams, glass wool, formaldehyde-free mineral wool Cavity: air cavity, air gap
3	Core envelope materials	Prestressed concrete, perforated bricks, low-density foam core, oriented strand board (OSB), recycled aggregate concrete (RAC), composite wall, 3D-printed concrete wythe, cellular lightweight foam concrete (CLC), self-load-bearing RAC, plywood sheets, wood wool panels, polyurethane foam, fiber cement board (FCB), alveolar polycarbonate in Lexan resin, polypropylene monofilament geomat grid, aluminum panel, substrates (felt-pad wastes, coconut peat), recycled polypropylene, fiber-cement
4	Adhesive/binders	Polyurethane, acrylate tape adhesive, araldite epoxy adhesive, geopolymer binder, Portland cement mortar
5	Radiant panel/thermal storage	Aluminum, heat sinks, PCM layer, heat sink, hydraulic radiant panel, water heat sink, aluminum heat transfer plate, steel heat transfer plate
	Thermoelectric coolers	Peltier thermoelectric (TE) cells module
6	Frames	Weatherboard-insulated aluminum frames, timber frames, methacrylate frames, metal structures, aluminum profiles
7	Active energy generators	PV/solar thermal panels, crystalline silicon PV panels, BIPV glass pane (with 24 monocrystalline silicon), PV modules
8	Accessories	Axial fans, electric board, polyamide profiles, supply air channels, aluminum anchorage, inlet/outlet louvers, irrigation pipeline, air grill, hanging systems (polypropylene monofilament), upper plate in expanded cork board, base plate
9	Other materials	Timber batten, soil, vegetation, plastics planter box, polyester fiber layer, polypropylene box, polymeric shell, circulating fluid, copper pipe, steel pipe, polybutylene pipe, composite material pipe, nonwoven viscous fabric layer, aluminum alloy, nonwoven geotextile layer with polypropylene fiber layer, biowaste material, recycled polypropylene, turf, ceiling

Furthermore, a study [53] demonstrated that reducing the sizes of structural members and the number of braces, shear walls, and columns in modular structures can increase flexibility in internal layout. Another study [54] reviewed the structural performance of modular buildings, and the results suggest the use of cold-formed steel shear wall systems as a lateral load-resisting system owing to their numerous advantages. A similar study [55] investigated a new vertical intermodular connection for modular steel buildings (MSBs). The results indicated that the post-tensioning (PT) connection has similar lateral stiffness to the welded connection, with greater energy dissipation capacity, and may be categorized as a partially semi-rigid solid connection. Both welded and PT specimens exhibit sufficient ductility capable of enduring drifts of up to three percent without experiencing welding fractures or buckling. Thus, the structural and mechanical properties of modular envelope panels have been well researched and documented [26,30,33,36–38,41]. The types of other materials used are presented in Table 5.

4.4. Terminologies Used for Modular Envelope

Different researchers have referred to modular building envelope panels in diverse ways. These terminologies have been categorized into four (4) groups—active wall panels, passive wall panels, smart wall panels, and green/vegetated wall panels—as presented in Table 6. The active wall panels are a group of modular building envelope panels that operate dynamically to generate electricity, heat, ventilate, or cool. This study documented eleven prominent panel terminologies used by eleven studies in this category, as presented in Table 6. The passive wall panels recorded thirteen different terminologies applied in thirteen studies, and both the smart wall and the green/vegetated wall panels had three terminologies each. These terminologies are mainly derived from the properties, materials, and nature of the operation of the walls.

Table 6. Different terminologies used for modular envelope.

Number	Categories	No. of Studies	Terminologies	Reference [Article IDs]
1	Active wall panels	11	(1) BIPV panels (2) Ventilated Active Thermoelectric Envelope (VATE) (3) Prefabricated ventilated sandwich panel (4) Semi-transparent modular BIPV façade (5) Building Active Steel Skin Envelope (BASSE) (6) Thermoelectric radiant panel (TERP) (7) Active solar thermoelectric (8) radiant wall (ASTRW) (9) VATE: Thermoelectric Cooling and Heating Unit (TCHU) (10) Solar thermal active panels with a mineral wool core (11) Solar Thermal Activated Façade (STAF) (12) BIPV panels	Z. Liu et al., 2015 [8] {2}, Luo et al., 2016 [28] {5}, Ibañez-Puy et al., 2018 [32] {10}, Brandl et al., 2018 [33] {11}, Zuazua-Ros et al., 2018 [35] {13}, Bock, 2019 [10] {14}, Weiland et al., 2019 [37] {16}, Pečur et al., 2020 [38] {17}, Arkar et al., 2020 [4] {18}, Azami & Sevinç, 2021 [44] {25}, Martín-Gómez et al., 2021 [45] {26}
2	Passive wall panels	13	(1) Ferro Cellular Lightweight Concrete Insulated Panel (FCIP) (2) Modular concrete green wall system (3D-VtGW) (3) Living wall systems (LWSs) (4) Ventilated recycled aggregate concrete (RAC) wall panel (5) PCM-modified textile-reinforced concrete (TRC) foamed sandwich panel (6) Trombe wall (modular) (7) "Plug and play" modular façade (8) Lightweight cellular wood material (CWM) (9) Thin-walled hollow-core wood-strand sandwich panels (10) Cement-based composite (CBC) panels (11) Integrated Modular Envelope System (IMES) (12) Cross-laminated timber (CLT) wall (13) High-Performance Walls (HP Walls): expanded polystyrene-reinforced concrete (EPS-RC) precast bearing walls	Rozins & Iejavs, 2014 [25] {1}, Voth et al., 2015 [26] {3}, Baldassarri et al., 2017 [31] {8}, J. Li et al., 2018 [34] {12}, He et al., 2020 [39] {19}, Oquendo-Di Cosola et al., 2020 [12] {20}, Bagarić et al., 2020 [40] {21}, Djamai et al., 2020 [41] {22}, Chang et al., 2021 [42] {23}, Torres et al., 2021 [43] {24}, Yasir Khan et al., 2021 [46] {27}, Scioti et al., 2022 [47] {28}, Bevilacqua et al., 2022 [7] {29}

Table 6. *Cont.*

Number	Categories	No. of Studies	Terminologies	Reference [Article IDs]
3	Smart wall panels	3	(1) SmartWall (modular) (2) Mediterranean Smart Adaptive Wall (MSAW) (3) Shape-stabilized phase change materials (SSPCMs) wallboards	Zhu et al., 2016 [27] {4}, Iommi, 2018 [13] {9}, Katsigiannis et al., 2022 [15] {30}
4	Green/vegetated wall panels	3	(1) Vertical greenery modular system (VGMS) (2) Geogreen system (3) Plant-bearing modular panels	Manso & Castro-Gomes, 2016 [29] {6}, Serra et al., 2017 [30] {7}, Santi et al., 2019 [36] {15}

4.5. The Focus of Various Modular Envelope Panel Studies

Various focus areas of the reviewed literature have been documented to understand the diversity of the issues covered by the modular envelope panel studies, categorizing them into four (4) groups, including hygrothermal performance, energy performance, environmental performance, and mechanical performance, as shown in Table 7. Most studies on modular building envelope panels emphasize hygro-thermal performance, as nineteen documented studies examined hygro-thermal performance. In contrast, twenty-two studies investigated energy performance, which is the focus of most studies. Nine and seven studies focus on environmental and mechanical performance, respectively. Hygro-thermal and energy performance are inextricably linked because most studies on building envelope hygro-thermal performance are conducted to reduce energy consumption. When a building envelope's heat transfer is optimized to provide acceptable thermal comfort indoors, the cooling load of the air conditioning system is reduced, resulting in significant energy savings and, by implication, decreasing carbon emissions.

Table 7. The focus of the reviewed studies.

Number	Focus Areas	No. of Studies	Terminologies	Reference [Article IDs]
1	Hygrothermal performance	19	(1) Thermal comfort (2) Hygrothermal performance (3) Thermal stress (4) Cooling and heating (5) Heat transfer (6) Thermal aspects (7) Thermal performance (8) Thermal efficiency (9) Thermal bridging (10) Thermal conductivity (11) Temperature resistance (12) Moisture resistance	Z. Liu et al., 2015 [8] {2}, Voth et al., 2015 [26] {3}, Luo et al., 2016 [28] {5}, Manso & Castro-Gomes, 2016 [29] {6}, Serra et al., 2017 [30] {7}, Baldassarri et al., 2017 [31] {8}, Iommi, 2018 [13] {9}, Ibañez-Puy et al., 2018 [32] {10}, Brandl et al., 2018 [33] {11}, J. Li et al., 2018 [34] {12}, Santi et al., 2019 [36] {15}, Weiland et al., 2019 [37] {16}, Pečur et al., 2020 [38] {17}, Bagarić et al., 2020 [40] {21}, Djamai et al., 2020 [41] {22}, Chang et al., 2021 [42] {23}, Martín-Gómez et al., 2021 [45] {26}, Yasir Khan et al., 2021 [46] {27}, Scioti et al., 2022 [47] {28}
2	Energy performance	22	(1) Energy performance (2) Energy efficiency (3) Energy savings (4) Energy consumption (5) Net-zero energy buildings (6) Coefficient of performance (COP) (7) Energy generation (8) CO_2 emission	Rozins & Iejavs, 2014 [25] {1}, Z. Liu et al., 2015 [8] {2}, Voth et al., 2015 [26] {3}, Zhu et al., 2016 [27] {4}, Baldassarri et al., 2017 [31] {8}, Iommi, 2018 [13] {9}, Ibañez-Puy et al., 2018 [32] {10}, J. Li et al., 2018 [34] {12}, Zuazua-Ros et al., 2018 [35] {13}, Bock, 2019 [10] {14}, Santi et al., 2019 [36] {15}, Pečur et al., 2020 [38] {17}, Arkar et al., 2020 [4] {18}, He et al., 2020 [39] {19}, Oquendo-Di Cosola et al., 2020 [12] {20}, Bagarić et al., 2020 [40] {21}, Torres et al., 2021 [43] {24}, Azami & Sevinç, 2021 [44] {25}, Martín-Gómez et al., 2021 [45] {26}, Scioti et al., 2022 [47] {28}, Bevilacqua et al., 2022 [7] {29}, Katsigiannis et al., 2022 [15] {30}

Table 7. *Cont.*

Number	Focus Areas	No. of Studies	Terminologies	Reference [Article IDs]
3	Environmental performance	9	(1) Environmental impact (2) Materials, waste, economic savings (3) Daylight (4) Ventilation (5) Acoustic performance (6) Thermal comfort (7) Spatial	Serra et al., 2017 [30] {7}, Baldassarri et al., 2017 [31] {8}, Arkar et al., 2020 [4] {18}, He et al., 2020 [39] {19}, Oquendo-Di Cosola et al., 2020 [12] {20}, Torres et al., 2021 [43] {24}, Yasir Khan et al., 2021 [46] {27}, Bevilacqua et al., 2022 [7] {29}, Katsigiannis et al., 2022 [15] {30}
4	Mechanical performance	7	(1) Mechanical performance (2) Mechanical stress (3) Durability (4) Structural performance (5) Serviceability efficiency	Voth et al., 2015 [26] {3}, Serra et al., 2017 [30] {7}, Brandl et al., 2018 [33] {11}, Santi et al., 2019 [36] {15}, Weiland et al., 2019 [37] {16}, Pečur et al., 2020 [38] {17}, Djamai et al., 2020 [41] {22}

5. Discussion of the Results

Researchers have employed various measures to evaluate the performance of building envelope panels and have arrived at different conclusions, which have been presented in the following subsections.

5.1. Energy Savings of Various Modular Envelope Panels

Several studies have used energy savings to test the performance of building envelope panels. The 'smart wall' modular envelope panels recorded the highest energy savings of 89%, achieving 7.5 kWh/m^2 energy consumption. The lowest energy savings, 6.4% in summer and 17.8% in winter, was recorded by the Shape-Stabilized Phase Change Material (SSPCM) wallboards, as illustrated in Figure 4. Although studies have reported various degrees of energy savings using different optimization mechanisms, they fall short of realizing net-zero energy buildings of 100% energy savings. However, achieving net-zero buildings was not the ultimate goal of some studies. Figure 4 illustrates annual energy savings, except ID:4 (SSPCMs), which are summer and winter savings.

Moreover, modular building envelope panels integrate many renewable technologies, including solar photovoltaics, to generate energy in addition to energy savings. A modular envelope panel called 'Building Active Steel Skin Envelope (BASSE)' by Bock [10] generated about 3321.14 kWh/year, translating to about 30.4% efficiency. Such generation rates, envelope optimization, and other measures can provide near net-zero energy buildings. Another study [13] on a modular envelope wall called 'Mediterranean Smart Adaptive Wall (MSAW)' studied heat storage with a storage thermal capacity coefficient between 16.3 kJ/m^{2}K and 17.6 kJ/m^{2}K. Such storage systems are capable of saving a considerable amount of energy.

5.2. Effect of Heat Flux Control

Several building envelope panel optimization strategies were used to achieve the energy-saving achievements reported in Section 5.1. These strategies included combining insulation and other thermal control optimization methods to manage heat influx and outflux through the building envelope assembly. Studies have realized significant reductions of heat flux from outdoors to building indoors, with the RAC-ETICS envelope reducing heat flux by 76.11%, which is the highest reduction, while Gogreen walls reduced heat flux by 75%, and RAC-non-ventilated envelopes reduced heat flux by 57.19%, as illustrated in Figure 5. However, regarding heat outflux, the Gogreen wall achieved the highest reduction (60%) compared to RAC-ETICS and RAC-non-ventilated walls, with 8.36 and 1.12%, respectively (Figure 5). Any envelope heat flux accomplishment directly contributes to building energy savings. Figure 5 shows two patterns that distinguish between heat influx and heat outflux.

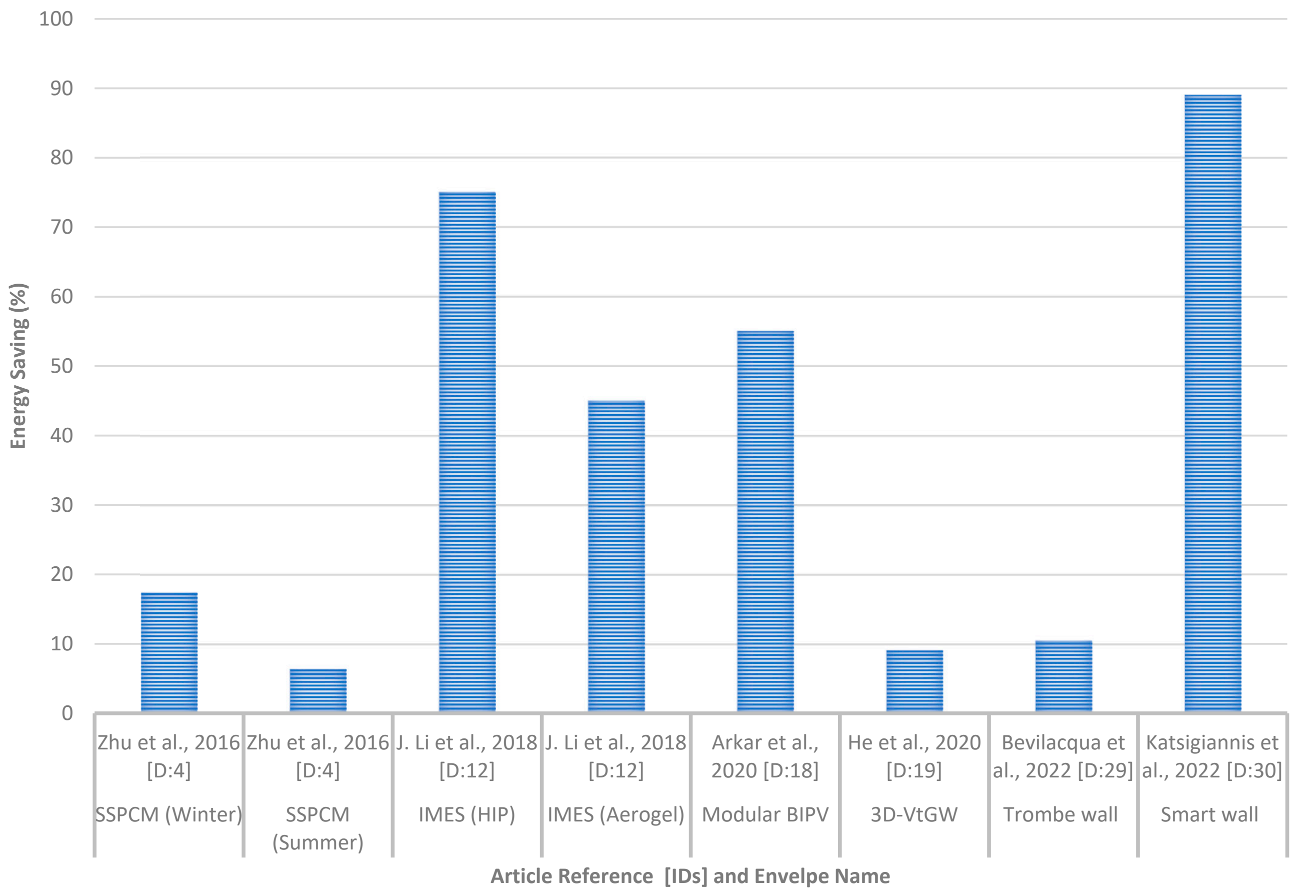


Figure 4. Energy saving achievements as reported by some studies [4,7,15,27,34,39].

Moreover, another factor influencing envelope heat flux is the thermal conductivity of the material and assembly. Some studies investigated the thermal conductivity of modular building envelope panels. Lightweight cellular wood material (CWM) [25] envelope panels decreased building envelope thermal conductivity between 0.148 and 0.0977 W.m^{-1} K^{-1}, i.e., 34% better than the reference specimen. The study optimized expanded polystyrene-reinforced concrete (EPS-RC) precast-bearing walls by adding recycled EPS particles to the mixtures. A modular envelope panel called 'High-Performance Wall Systems (HP Walls)': expanded polystyrene-reinforced concrete (EPS-RC) precast-bearing walls [47] decreased building envelope thermal conductivity between 1.77 and 0.05 W.m^{-1} K^{-1}. Another study [34] investigated the heat transfer coefficient of a modular envelope panel called the Integrated Modular Envelope System (IMES). The envelope reduced the heat transfer coefficient of 0.124 W.m^{-1} K^{-1} by integrating a high insulation panel (HIP) and 0.257 W.m^{-1} K^{-1} by incorporating aerogel. Thus, incorporating high-performing insulation materials can decrease the overall heat transfer coefficient of the envelope assembly and subsequently reduce building energy consumption.

5.3. Future Directions

Based on the above analysis, limited studies have extended their investigations to cover building envelope panels' environmental impact from production to operations. A study examined the CO_2 emissions of a modular Trombe wall in which the wall reduced CO_2 emissions by 185 kg per year by optimizing the envelope to reduce cooling and energy demand. Another study [43] explored the performance of the "plug and play" modular façade, which achieved 50% time savings, 30% material savings, and 25% waste savings. Due to the importance of environmental impact, mainly due to carbon emissions, which contribute to global warming and greenhouse gas emissions, modular building envelope panel studies should consider environmental impacts.

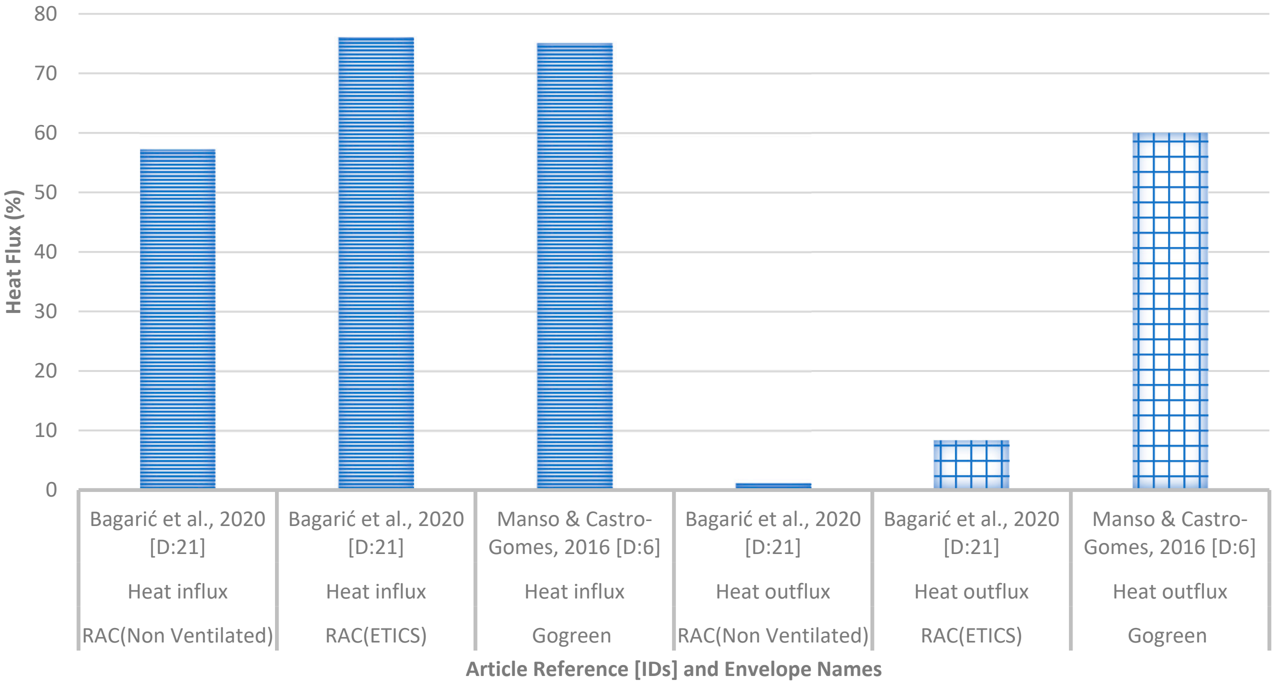


Figure 5. % Reduction of heat flux (in, out) from reviewed building envelope studies [29,40].

Furthermore, the current challenges of modular building envelope panels involve differences in performance across various climates, inconsistent installation practices, varying standards for application and utilization, air leakage, energy consumption, diverse performance reporting units, differing structural system requirements, lack of standardized classifications, and constraints related to uniformity in shape, size, and form. The future of modular envelope panels involves creating uniform guidelines that regulate their manufacturing (considering different climates), installation, performance requirements, and maintenance.

6. Conclusions and Recommendations

6.1. Conclusions

This study investigated the terminologies, characteristics, and performance of modular building envelope panels through a systematic, comprehensive review by applying multiple criteria in the review process, arriving at 30 relevant articles from Scopus and Web of Science. The findings reveal that modular building envelopes are referenced using various terminologies, with most studies focusing on temperate climates. Limited research exists for hot and hot–humid climate regions. Furthermore, researchers have used different materials to construct modular building envelopes, emphasizing hygrothermal and energy performance. Simulations and full-scale experiments were commonly employed as methodologies to investigate the performance of these panels. The specific results can be summarized as follows:

- Inconsistent assessment standards and methods were observed in investigating modular building envelopes. Researchers employed diverse research methods, resulting in parameter variations and variations in units used to express their findings. Multiple performance indicators were utilized, such as the demand/load for air-conditioning electric, primary energy, heating load, BIPV coverage index, coefficient of performance (COP), summer heat gains, thermal capacity coefficient, energy efficiency, surface temperature, cooling efficiency, room temperature, heat inflow/outflow, PCM melting points, thermal performance, and thermal conductivity. Among these indicators, COP, air-conditioning electric demand, energy efficiency, and surface temperature were frequently employed, leading to a fragmented system for reporting the performance of modular envelope panels.

- Energy savings was identified as the primary performance indicator for building envelope optimization. However, comparing the results of various studies proved challenging due to the diverse methodologies and indicators employed.
- Establishing standard terminology for modular building envelope panels is crucial to facilitate clarity and understanding and to address the current abundance of naming systems. Specific classifications have been established based on technical and functional attributes to distinguish between modular envelope panels, including active, passive, smart, and green/vegetated panels. Furthermore, the concentration of research on modular envelope panels in cold climates indicates the need for further investigation to bridge this knowledge gap to balance the regional and contextual disparities.
- Four (4) focus areas in modular building envelope research were observed, including hygrothermal, energy, environmental, and mechanical performance. However, compared to hygrothermal and energy performance studies, limited research exists on envelope panels' environmental impact and performance. Consequently, more research is required to highlight their potential environmental impacts.

In conclusion, this study contributes valuable insights into modular building envelope panels' hygrothermal and energy performance. The findings emphasize the need for standardized assessment methods, further research to address existing gaps, and the importance of regional balance in investigations.

6.2. Recommendations

This study highlights several recommendations to facilitate the widespread adoption of modular building envelope systems. First and foremost, there is a pressing need to establish comprehensive assessments, rating standards, and best practice guidelines for these systems. These standards and guidelines can ensure consistency and enable effective comparison of their performance across different projects. Additionally, it is crucial for scholars and practitioners to utilize consistent units when quantifying the performance of modular building envelopes. Standardizing reporting units enhances clarity and facilitates a better understanding of their capabilities.

Furthermore, establishing a uniform set of terminologies for classifying modular building envelope systems is recommended. The proposed classification consists of four categories: active wall panels, passive wall panels, smart wall panels, and green/vegetated wall panels. This uniform terminology can facilitate effective communication and knowledge exchange among researchers, industry professionals, and other stakeholders. The primary focus of the manufacturing industry is typically on prototyping to minimize the expenses associated with making envelope panels using various molds and combinations, which necessitate many production lines. If this study's suggested types and classifications are implemented, the industry will benefit since it can ensure consistent supply and demand.

Finally, the study emphasizes the importance of further research in developing modular building envelopes customized for hot and hot–humid climatic conditions. These customizations should not only strive to achieve contextual balance but also focus on assessing their environmental performance and impact, thus contributing to the realization of sustainable buildings on a global scale. By implementing these recommendations, the adoption of modular building envelope systems can be accelerated, leading to more sustainable and energy-efficient construction practices by optimizing the system's energy-saving, mechanical, and thermo-environmental capabilities and raising awareness about its benefits among estate and building developers. The insights from this research contribute to the growing body of knowledge in this field and provide a valuable foundation for future studies and advancements in modular building envelope technology.

6.3. Significance of the Study

By adopting the recommended measures, the outcomes of this study hold significant benefits for researchers, policymakers, and relevant organizations in advancing the development of building performance-related standards and codes in an informed and effective manner. The study outcome provides valuable tools to standardize modular building envelope performance, measurement units, categorization, and the incorporation of climatic considerations into their design, application, and maintenance.

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References

1. Li, Y.; Chen, L. Investigation of European modular façade system utilizing renewable energy. *Int. J. Low-Carbon Technol.* **2022**, *17*, 279–299. [CrossRef]
2. Ng, P.K.; Mithraratne, N. Lifetime performance of semi-transparent building-integrated photovoltaic (BIPV) glazing systems in the tropics. *Renew. Sustain. Energy Rev.* **2014**, *31*, 736–745. [CrossRef]
3. Park, H.S.; Koo, C.; Hong, T.; Oh, J.; Jeong, K. A finite element model for estimating the techno-economic performance of the building-integrated photovoltaic blind. *Appl. Energy* **2016**, *179*, 211–227. [CrossRef]
4. Arkar, C.; Žižak, T.; Domjan, S.; Medved, S. Dynamic parametric models for the holistic evaluation of semi-transparent photovoltaic/thermal façade with latent storage inserts. *Appl. Energy* **2020**, *280*, 115994. [CrossRef]
5. Nore, K. NTNU Open: Hygrothermal Performance of Ventilated Wooden Cladding. Ph.D. Thesis, NTNU, Torgarden, Norway, 2010. Available online: https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/231575 (accessed on 7 July 2022).
6. Knaack, U.; Klein, T.; Bilow, M.; Auer, T. (Eds.) *Façades: Principles of Construction*, 2nd ed.; Books on Google Play; Birkhäuser: Basel, Switzerland, 2014. Available online: https://play.google.com/store/books/details?id=I_DnBQAAQBAJ&rdid=book-I_DnBQAAQBAJ&rdot=1&source=gbs_vpt_read&pcampaignid=books_booksearch_viewport (accessed on 7 July 2022).
7. Bevilacqua, P.; Bruno, R.; Szyszka, J.; Cirone, D.; Rollo, A. Summer and winter performance of an innovative concept of Trombe wall for residential buildings. *Energy* **2022**, *258*, 124798. [CrossRef]
8. Liu, Z.; Zhang, L.; Gong, G.; Han, T. Experimental evaluation of an active solar thermoelectric radiant wall system. *Energy Convers. Manag.* **2015**, *94*, 253–260. [CrossRef]
9. Telichenko, V.; Benuzh, A.; Eames, G.; Orenburova, E.; Shushunova, N. Development of Green Standards for Construction in Russia. *Procedia Eng.* **2016**, *153*, 726–730. [CrossRef]
10. Bock, M. A building integrated solar thermal collector with active steel skins. *Energy Build.* **2019**, *201*, 134–147. [CrossRef]
11. Gallo, P.; Romano, R. Adaptive Box Window, developed with innovative nanomaterial, for a sustainable architecture in the Mediterranean area. *Energy Procedia* **2017**, *122*, 883–888. [CrossRef]
12. Oquendo-Di Cosola, V.; Olivieri, F.; Ruiz-García, L.; Bacenetti, J. An environmental Life Cycle Assessment of Living Wall Systems. *J. Environ. Manag.* **2020**, *254*, 109743. [CrossRef] [PubMed]
13. Iommi, M. The mediterranean smart adaptive wall. An experimental design of a smart and adaptive facade module for the mediterranean climate. *Energy Build.* **2018**, *158*, 1450–1460. [CrossRef]
14. Ferdous, W.; Bai, Y.; Ngo, T.D.; Manalo, A.; Mendis, P. New advancements, challenges and opportunities of multi-storey modular buildings—A state-of-the-art review. *Eng. Struct.* **2019**, *183*, 883–893. [CrossRef]

15. Katsigiannis, E.; Gerogiannis, P.A.; Atsonios, I.; Bonou, A.; Mandilaras, I.; Georgi, A.; Papadopoulou, S.; Tsoutis, C.; Founti, M. Energy assessment of a residential building renovated with a novel prefabricated envelope integrating HVAC components. *IOP Conf. Ser. Earth Environ. Sci.* **2022**, *1078*, 012130. [CrossRef]
16. Fiume, F.; Callegaro, N.; Albatici, R. Modular Construction for Emergency Situation: A Design Methodology for the Building Envelope. In *Advances in Science, Technology & Innovation*; Springer: Cham, Switzerland, 2021; pp. 131–141. [CrossRef]
17. Luo, Y.; Zhang, L.; Bozlar, M.; Liu, Z.; Guo, H.; Meggers, F. Active building envelope systems toward renewable and sustainable energy. *Renew. Sustain. Energy Rev.* **2019**, *104*, 470–491. [CrossRef]
18. Fawaier, M.; Bokor, B. Dynamic insulation systems of building envelopes: A review. *Energy Build.* **2022**, *270*, 112268. [CrossRef]
19. Finch, G.; Marriage, G.; Pelosi, A.; Gjerde, M. Building envelope systems for the circular economy: Evaluation parameters, current performance and key challenges. *Sustain. Cities Soc.* **2021**, *64*, 102561. [CrossRef]
20. Villegas, J.E.; Camilo, J.; Gutierrez, R.; Colorado, H.A. Active materials for adaptive building envelopes: A review. *J. Mater. Environ. Sci.* **2020**, *2020*, 988–1009. Available online: http://www.jmaterenvironsci.com (accessed on 21 September 2022).
21. Narbuts, J.; Vanaga, R. Revolutionizing the Building Envelope: A Comprehensive Scientific Review of Innovative Technologies for Reduced Emissions. *Environ. Clim. Technol.* **2023**, *27*, 724–737. [CrossRef]
22. Correia Lopes, G.; Vicente, R.; Azenha, M.; Ferreira, T.M. A systematic review of Prefabricated Enclosure Wall Panel Systems: Focus on technology driven for performance requirements. *Sustain. Cities Soc.* **2018**, *40*, 688–703. [CrossRef]
23. Kamali, M.; Hewage, K. Life cycle performance of modular buildings: A critical review. *Renew. Sustain. Energy Rev.* **2016**, *62*, 1171–1183. [CrossRef]
24. Wang, X.; Zhang, Y.; Xiao, W.; Zeng, R.; Zhang, Q.; Di, H. Review on thermal performance of phase change energy storage building envelope. *Chin. Sci. Bull.* **2009**, *54*, 920–928. [CrossRef]
25. Rozins, R.; Iejavs, J. Evaluation of thermal properties of wood based composite panel walls. *Res. Rural Dev.* **2014**, *2*, 109–114.
26. Voth, C.; White, N.; Yadama, V.; Cofer, W. Design and evaluation of thin-walled hollow-core wood-strand sandwich panels. *J. Renew. Mater.* **2015**, *3*, 234–243. [CrossRef]
27. Zhu, N.; Liu, P.; Liu, F.; Hu, P.; Wu, M. Energy performance of double shape-stabilized phase change materials wallboards in office building. *Appl. Therm. Eng.* **2016**, *105*, 180–188. [CrossRef]
28. Luo, Y.; Zhang, L.; Liu, Z.; Wang, Y.; Wu, J.; Wang, X. Dynamic heat transfer modeling and parametric study of thermoelectric radiant cooling and heating panel system. *Energy Convers. Manag.* **2016**, *124*, 504–516. [CrossRef]
29. Manso, M.; Castro-Gomes, J.P. Thermal analysis of a new modular system for green walls. *J. Build. Eng.* **2016**, *7*, 53–62. [CrossRef]
30. Serra, V.; Bianco, L.; Candelari, E.; Giordano, R.; Montacchini, E.; Tedesco, S.; Larcher, F.; Schiavi, A. A novel vertical greenery module system for building envelopes: The results and outcomes of a multidisciplinary research project. *Energy Build.* **2017**, *146*, 333–352. [CrossRef]
31. Baldassarri, C.; Sala, S.; Caverzan, A.; Lamperti Tornaghi, M. Environmental and spatial assessment for the ecodesign of a cladding system with embedded Phase Change Materials. *Energy Build.* **2017**, *156*, 374–389. [CrossRef]
32. Ibañez-Puy, M.; Martín-Gómez, C.; Bermejo-Busto, J.; Sacristán, J.A.; Ibañez-Puy, E. Ventilated Active Thermoelectric Envelope (VATE): Analysis of its energy performance when integrated in a building. *Energy Build.* **2018**, *158*, 1586–1592. [CrossRef]
33. Brandl, D.; Schober, H.; Hochenauer, C. Analysis of heating effects and deformations for a STAF panel with a coupled CFD and FEM simulation method. *J. Facade Des. Eng.* **2018**, *6*, 116–131. [CrossRef]
34. Li, J.; Lu, S.; Wang, W.; Huang, J.; Chen, X.; Wang, J. Design and Climate-Responsiveness Performance Evaluation of an Integrated Envelope for Modular Prefabricated Buildings. *Adv. Mater. Sci. Eng.* **2018**, *2018*, 1–14. [CrossRef]
35. Zuazua-Ros, A.; Martín-Gómez, C.; Ibáñez-Puy, E.; Vidaurre-Arbizu, M.; Ibáñez-Puy, M. Design, assembly and energy performance of a ventilated active thermoelectric envelope module for heating. *Energy Build.* **2018**, *176*, 371–379. [CrossRef]
36. Santi, G.; Bertolazzi, A.; Croatto, G.; Turrini, U. Vertical turf for green faÇades: A vertical greenery modular system integrated to the building envelope. *J. Green Build.* **2019**, *14*, 111–132. [CrossRef]
37. Weiland, F.; Kirchner, M.; Rensinghoff, V.; Giovannetti, F.; Kastner, O.; Ridder, D.; Tekinbas, Y.; Hachul, H. Performance assessment of solar thermally activated steel sandwich panels with mineral wool core for industrial and commercial buildings. *J. Phys. Conf. Ser.* **2019**, *1343*, 012098. [CrossRef]
38. Pečur, I.B.; Bagarić, M.; Milovanović, B. Development and application of a prefabricated façade panel containing recycled construction and demolition waste. *J. Facade Des. Eng.* **2020**, *8*, 101–125. [CrossRef]
39. He, Y.; Zhang, Y.; Zhang, C.; Zhou, H. Energy-saving potential of 3D printed concrete building with integrated living wall. *Energy Build.* **2020**, *222*, 110110. [CrossRef]
40. Bagarić, M.; Banjad Pečur, I.; Milovanović, B. Hygrothermal performance of ventilated prefabricated sandwich wall panel from recycled construction and demolition waste—A case study. *Energy Build.* **2020**, *206*, 109573. [CrossRef]
41. Djamai, Z.I.; Larbi, A.S.; Salvatore, F. A Non-paraffinic PCM Modified Textile Reinforced Concrete Sand-Wich Panel. *Lect. Notes Civ. Eng.* **2020**, *54*, 453–458. [CrossRef]
42. Chang, S.J.; Kang, Y.; Yun, B.Y.; Yang, S.; Kim, S. Assessment of effect of climate change on hygrothermal performance of cross-laminated timber building envelope with modular construction. *Case Stud. Therm. Eng.* **2021**, *28*, 101703. [CrossRef]
43. Torres, J.; Garay-Martinez, R.; Oregi, X.; Torrens-Galdiz, J.I.; Uriarte-Arrien, A.; Pracucci, A.; Casadei, O.; Magnani, S.; Arroyo, N.; Cea, A.M. Plug and play modular façade construction system for renovation for residential buildings. *Buildings* **2021**, *11*, 419. [CrossRef]

44. Azami, A.; Sevinç, H. The energy performance of building integrated photovoltaics (BIPV) by determination of optimal building envelope. *Build. Environ.* **2021**, *199*, 107856. [CrossRef]
45. Martín-Gómez, C.; Zuazua-Ros, A.; del Valle de Lersundi, K.; Sánchez Saiz-Ezquerra, B.; Ibáñez-Puy, M. Integration development of a Ventilated Active Thermoelectric Envelope (VATE): Constructive optimization and thermal performance. *Energy Build.* **2021**, *231*, 110593. [CrossRef]
46. Yasir Khan, M.; Baqi, A.; Sadique, R. Thermal and acoustic behavior of energy saving wall panel. *Arch. Civ. Eng.* **2021**, *67*, 303–316. [CrossRef]
47. Scioti, A.; De Fino, M.; Martiradonna, S.; Fatiguso, F. Construction Solutions and Materials to Optimize the Energy Performances of EPS-RC Precast Bearing Walls. *Sustainability* **2022**, *14*, 3558. [CrossRef]
48. Abolhasani, N.; Saghafi, M.J.; Fayaz, R.; Kari, B.M. Modular Building Envelope Panel with Heating and Cooling Capability. *Naqshejahan Basic Stud. New Technol. Archit. Plan.* **2016**, *6*, 41–31. Available online: http://bsnt.modares.ac.ir/article-2-11429-en.html (accessed on 24 June 2022).
49. Liu, S.; Schulz, U.W.; Sapar, M.H.; Qian, S. Evaluation of the environmental performance of the chilled ceiling system using life cycle assessment (LCA): A case study in Singapore. *Build. Environ.* **2016**, *102*, 207–216. [CrossRef]
50. Perini, K.; Ottelé, M.; Haas, E.M.; Raiteri, R.; Perini, K.; Ottelé, M.; Haas, E.M.; Raiteri, R. Greening the building envelope, facade greening and living wall systems. *Open J. Ecol.* **2011**, *1*, 1–8. [CrossRef]
51. Wang, C.; Xiao, J.; Liu, W.; Ma, Z. Unloading and reloading stress-strain relationship of recycled aggregate concrete reinforced with steel/polypropylene fibers under uniaxial low-cycle loadings. *Cem. Concr. Compos.* **2022**, *131*, 104597. [CrossRef]
52. D'Alessandro, F.; Bianchi, F.; Baldinelli, G.; Rotili, A.; Schiavoni, S. Straw bale constructions: Laboratory, in field and numerical assessment of energy and environmental performance. *J. Build. Eng.* **2017**, *11*, 56–68. [CrossRef]
53. Lacey, A.W.; Chen, W.; Hao, H.; Bi, K. Structural response of modular buildings—An overview. *J. Build. Eng.* **2018**, *16*, 45–56. [CrossRef]
54. Jammi, A.; Sanjeevi, A.J. Structural performance of modular buildings: A review. *ICRTICE Int. Conf. Recent Trends Innov. Civ. Eng.* **2021**, *77*, 19–42. [CrossRef]
55. Sanches, R.; Mercan, O. Vertical post-tensioned connection for modular steel buildings. In Proceedings of the 12th Canadian Conference on Earthquake Engineering, Quebec City, QC, Canada, 17–20 June 2019; pp. 1–8. Available online: https://www.researchgate.net/publication/335703944_Vertical_post-tensioned_connection_for_modular_steel_buildings#fullTextFileContent (accessed on 22 April 2022).