Energy & Buildings 323 (2024) 114757

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb

Invited Review Article

Applicability of developing an affordable eco-friendly switchable insulation for sustainable building envelopes in a hot climate: Comprehensive review

Alaa Salah [a,b], Sameh Nada [c], Hatem Mahmoud [d,e,*]

[a] Department of Environmental Engineering, Egypt-Japan University of Science and Technology E-JUST, Egypt
[b] Department of Architectural Engineering, College of Engineering, Fayoum University, Egypt
[c] Department of Energy, Egypt-Japan University of Science and Technology E-JUST, Egypt
[d] Sustainable Architecture Program, Egypt-Japan University of Science and Technology E-JUST, Egypt
[e] Department of Architectural Engineering, College of Engineering, Aswan University, Egypt

A R T I C L E I N F O

Keywords:
Thermal comfort
Hot temperature
Thermal insulation
Switchable U-value
Developing countries
Control strategies

A B S T R A C T

Traditional insulation materials have limitations concerning adaptability and sustainability. In contrast, Switchable Insulation Systems (SISs), which modulate their thermal properties based on environmental conditions, present a promising alternative. Despite that, their application-based affordability requires further research. This review investigates the applicability of developing SISs using low-cost, eco-friendly materials suitable for hot climates. The methodology includes three phases. First, data and statistical analyses identify research trends and gaps. Second, the selected SISs are examined to explore potential materials and technical aspects, focusing on concepts, materials, control strategies, and fabrication. Third, assessing the applicability of the selected systems. This study highlighted the limitations of using SISs that resulted from utilizing advanced technologies such as responsive smart windows, thermal switches, adaptive films, and thermal diodes, besides using complex controllers for optimization. A key strategy for promoting the adoption of SISs involves integrating appropriate systems with affordable, eco-friendly materials. Incorporating waste glass, recycled PET, fly ash, sheep wool, and coconut fiber into simple SIS designs (e.g., rotating panels, removable insulation, vertically sliding panels, dynamic insulation-PCM systems, and roller blinds) can yield low-cost, eco-friendly SISs while optimizing thermal mass and considering the technological and market potential to address energy savings, thermal performance, and environmental impact in different contexts.

1. Introduction

Insulation systems are pivotal in maintaining comfortable indoor environments, significantly boosting energy efficiency and minimizing environmental impacts. They minimize heat transfer between interior and exterior structures to reduce energy loss [1], regulate temperature, conserve energy, and lower utility costs [2,3]. They also reduce greenhouse gas emissions by reducing energy consumption [4]. Well-insulated buildings enhance occupant comfort, productivity, and overall well-being by providing stable and comfortable indoor environments. However, insulation systems have limitations, such as installation issues, material degradation over time [5], and thermal bridges [6,7,8]. Additionally, the production and disposal of certain insulation materials can cause environmental consequences such as greenhouse gas emissions and waste generation [9]. Regarding energy efficiency, the main reason for using insulation, adaptability is a crucial limitation. In hot

Abbreviations: DIS, Dynamic insulation system; SIS, Switchable insulation system; PCM, phase changing material; PLVTD, horizontal Planar Liquid-Vapor Thermal Diodes; TC, thermochromic; SPD, suspended particle device; SWFG, hybrid smart water-filled glass; Cs_xWO_3, Caesium tungsten bronze; VO_2, Vanadium dioxide; HDI, human development index; EMS, Energy Management Systems; SHGC, the solar heat gain coefficient; VT, visible transmittance; R-value, thermal resistance; U-value, thermal transmittance; HDPE, high-density polyethylene; SMA, shape memory alloy; STS, solid-state thermal switches; VIPs, Vacuum Insulation Panels; λ, thermal conductivity; PS, precipitated silica; FS, fumed silica; SG, silica gel; GS, glass spheres; PDLC, Polymer-dispersed liquid crystal; H, switching ratio; PET, polyethylene terephthalate; MSA, monolithic silica aerogels; LC, Liquid crystal; NIR, near-infrared light; MIT, metal-insulator transition; VAH, VO_2-aerogel hybrid; MPC, Model-predictive control; GA, Genetic algorithm; TV-MPC, time-varying model predictive control; AM, Additive Manufacturing; CNF, cellulose nanofibrils; IR, Infrared; EPDM, ethylene propylene diene monomer; Δt, Timeshift.

* Corresponding author at: Egypt-Japan University of Science and Technology E-JUST, New Borg Elarab city. P.O. Box 179, Alexandria, Egypt.
E-mail addresses: alaa.salah@ejust.edu.eg (A. Salah), sameh.nada@ejust.edu.eg (S. Nada), hatem.mahmoud@ejust.edu.eg (H. Mahmoud).

https://doi.org/10.1016/j.enbuild.2024.114757
Received 26 May 2024; Received in revised form 26 August 2024; Accepted 2 September 2024
Available online 6 September 2024

climates, Winter temperatures have become more frigid (cold waves) in recent years in many regions, as a result of global climate change [10,11]. For example, despite Egypt's typically hot and arid environment, it endured an unusually cold winter in January and February 2022, marking the coldest winter in the last decade. This recurring issue affects the northern region of Egypt every year. During this period in Egypt, the temperature plummeted by 7–8 °C, reaching a level below 5 °C, which is lower than the typical norm for this time of year [11]. Furthermore, buildings in hot summer-cold winter climates experience significant temperature fluctuations, necessitating both cooling in summer and heating in winter. For example, heating in the hot summer-cold winter climate zone in China is seeing a rapid raising in urban energy use, particularly in heating, with an average annual growth rate of 50 % [12]. So, using effective strategies, like insulation, is crucial to mitigate these fluctuating weather conditions and reduce heating and cooling demand. Despite that, effective insulation in summer could be a reason for the increase in heating demand in winter [13,14], and vice versa in cold regions, necessitating a balanced approach to insulation design that considers both seasonal extremes. Static thermal properties, which do not change their insulating properties in response to changes in environmental conditions, lead to energy loss in buildings, for example, with fluctuating temperatures. However, traditional insulation materials are relatively inexpensive [15].

The building construction industry commonly uses commercially available insulation materials such as polystyrene and polyurethane foam, or fibrous materials such as glass wool and rock wool [16]. These materials provide thermal insulation; however, they are not environmentally friendly because of their manufacturing and disposal methods [17]. Sustainable practices should be employed to minimize these impacts [9].

Adaptive systems have great potential for overcoming the limitations of static systems. There are various types of adaptive systems. Hu and Yu [18] proposed a Thermo and light-responsive building envelope of a roof with thermochromic (TC) coating and walls with Phase change materials (PCM) under five distinctive climates. In a warm region, the simulation results revealed that the use of a TC roof saves total energy consumption by up to 13 % and reduces CO2 emission by 4 %; TC roof-PCM wall gives rise to total energy saving of up to 19 % and a reduction in CO2 emission by up to 5 %, especially for the building. Yan et al. [19] introduced a novel pipe-encapsulated PCM wall system that decreased the heat transferred through the wall compared to traditional walls in a hot climate. The system with night active heat removal reduced the accumulated heat transfer by 74.5 % over seven days, leading to a significant energy-saving potential.

Dynamic insulation systems (DISs) belong to climate-adaptive building skins that can change their thermal properties in response to environmental changes. They achieve low heat loss or high heat gains and significant energy savings compared to static insulation alternatives [20,21]. DISs adjust the transmissivity or thermal resistance of the building envelope to different weather conditions and vary their thermal properties within a range, resulting in potential energy savings, improved thermal comfort, and a zero-carbon footprint [22,23,24]. However, they are more expensive and less widely available [23].

Switchable insulation systems (SISs) fall under the umbrella of dynamic insulation technologies that can control their thermal properties by switching low/high thermal resistance values in a controlled manner [25], allowing for the peak shifting and shaving of HVAC demand [26,27]. These systems are used within building components like walls [26,28,29], windows [30,31,32], and roofs [25,33,34]. PCM and airflow can create a composite structure with switchable thermal resistance, effectively addressing overheating issues [35]. Integrating active insulation systems with thermal energy storage systems can enhance the flexibility of charging and discharging stored energy, thereby improving the overall thermal performance of the building envelope [36].

SIS systems can enhance the energy efficiency of buildings by reducing the heating and cooling energy by up to 12 % and overheating hours by 51 % [21,37]. By using temperature sensors, these systems can optimize energy savings, ranging from 7 % to 42 % in the US [38]. Applying SISs to slab foundations can reduce the heating and cooling energy loads, especially in cold climates [37]. The advantages depend on the materials and control strategies used with the actuation mechanisms.

Several review articles have explored the insulation materials, focusing on factors influencing thermal conductivity and heat transfer characteristics [39], integrating PCM in various building applications [40,41], and different types and classifications of insulation materials [42,43,44]. They also analyzed the properties of building insulation materials [16], environmental performance [3], moisture buffering value, fire performance, acoustic performance, life cycle assessment [45], and energy savings [46].

Various control strategies have been proposed for SISs, including time-scheduled and temperature-based settings [47], intelligent control algorithms for phase-change-material wall systems [48], genetic algorithms for optimal R-value settings in commercial buildings [49], and a multi-step control strategy using wall surface temperatures, set-point temperatures, and wall temperatures [50], highlighting the potential of SISs to achieve energy savings through effective control strategies, indicating their potential for energy efficiency.

Fabricating SISs in buildings faces challenges such as reducing costs without sacrificing performance or adaptability features [51]. The performance depends on many factors, such as the materials used, actuation integration, and design features (e.g., wall cavity depth and insulation layer width and thickness) [29]. For instance, material manufacturing techniques are determined by the material type, application, installation method, and desired properties, which affect their performance and characterization [15]. Further research is required to understand and optimize the potential of these techniques.

Researchers have reviewed dynamic insulation (DIS) from various perspectives. Fawaier and Bokor [20] viewed dynamic insulation as a promising approach for variable heat transmission rates through the building envelope, such as parietodynamic walls, permodynamic walls, and SISs. Zhang et al. [24] studied the thermal performance of thermally adaptive walls. They provided a comprehensive overview of these walls and concluded that incorporating the strengths of both PCM-integrated and dynamic-insulation walls offers unparalleled thermal adaptability. Stevens et al. [23] analyzed topology morphing insulation in building envelope design. Cui and Overend [52] systematically reviewed and classified switchable insulation technologies, focusing on their working principles, theoretical performances, and opportunities for improvement. These studies explored various aspects of the DIS, including its potential for varying heat transmission rates, the role of topology-morphing insulation in building envelope design, and factors affecting heat transfer rates.

Most of the aforementioned reviews have focused on concepts of DISs, heat-transfer modes and mechanisms, applications in buildings and non-buildings, and topology morphing. However, there is a shortage directing the developed systems towards affordability, especially regarding used materials and technical aspects. The main objective of this review is to investigate the applicability of developing affordable and eco-friendly SISs for building envelopes in hot regions. In this regard, this review aims to answer the following research questions:

- What are the research gaps and trends (most appropriate system) related to this topic?
- What is the applicability of developing affordable and eco-friendly selected systems for adoption in hot regions?

2. Methodology

As shown in Fig. 1, this review is based on three phases. The first depends on searching, filtering, screening, and selecting related research papers to identify research trends and growth areas and statistically

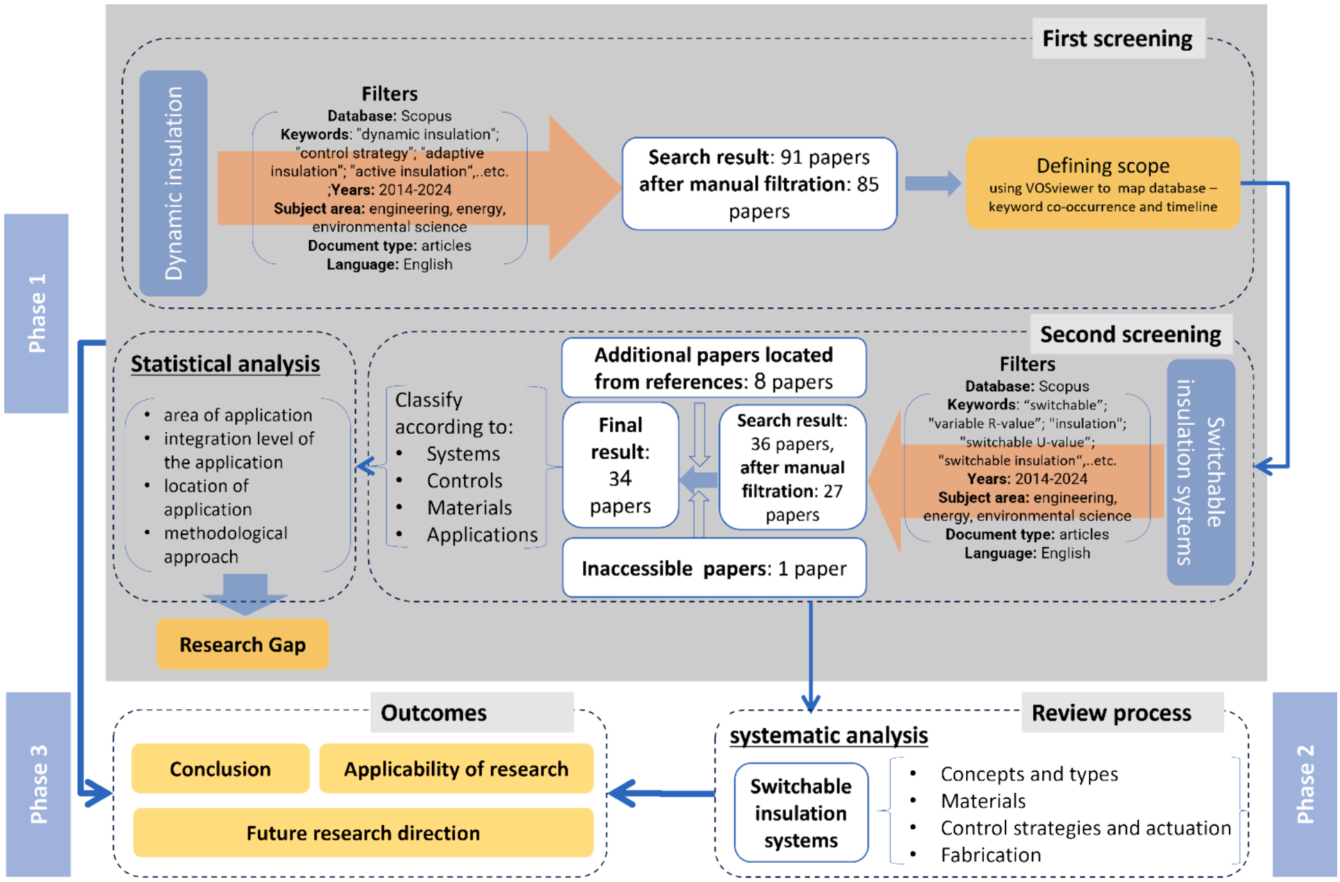

Fig. 1. Outline of the review methodology.

analyzing the extracted data to define the research status and gaps. The second presents a systematic analysis to track research evolution and identify key disciplines in research domains by studying SISs from material and technical perspectives by investigating types, concepts, materials, control strategies, and fabrication. Finally, the conclusions and outcomes are discussed.

Over the period (2014–2024), representing the newest theories, patents, and methodologies, the study conducted data searches using the Scopus database, while other relevant Internet resources, such as publishers Wiley and Springer journals, were accessed. Moreover, the research was within "Article title, abstract, keywords" with filtering criteria for the literature search, as shown in Table 1. A filter was applied to only include English articles related to the subject areas of engineering, energy, and environmental science. Articles must focus on materials, technologies, and DIS/SIS performance assessments to meet inclusion criteria. Keywords related to the context of dynamic and switchable insulation were used in different combinations, as illustrated in Table 2, the number of research results in 27 papers relevant to switchable insulation. Furthermore, eight additional articles and papers were added from the references.

The remainder of this paper is organized as follows.

Table 1
Filtering criteria for the literature search.

subject area	*years*	*document types*	*language*
engineering, energy, environmental science	2014–2024	articles	English

Table 2
Keywords and search strings used to conduct the study.

No.	*Keywords*	*No. of papers*
First screening		
1	"Variable R-value"; "insulation"	3
2	"Dynamic insulation"	46
3	"Control strategy" AND "dynamic insulation"	8
4	"Adaptive insulation"	7
5	"Active insulation"; AND thermal	28
6	"Dynamic insulation"; AND building	37
	Before manual filtering	91
	After manual filtering	85
Second screening		
7	"Switchable U-value"; "insulation"	3
8	"Switchable insulation"	20
9	"switchable"; AND "thermal"; AND "insulation"; AND "building"	29
	Before manual filtering	36
	After manual filtering	27

- Data analysis and statistical analysis (Section 3) are used to overview scientific landscapes using VOSviewer [53,54] and to define the research status and research gap. The content was classified into four subcategories according to the scope of the article, integration level, climatic region location, and methodological approach.
- Switchable insulation systems (Section 4) were analyzed for their mechanical adjustability, materials used, control strategies, actuation, and fabrication to determine the most related parameters and available options.

- The applicability of developing affordable, eco-friendly switchable insulation in hot climate regions (Section 5) from the materials and technical aspects based on the previous section.
- Conclusion (Section 6) summarizes the key points and highlights areas for future research.

3. Data analysis

Maps were created using VOSviewer [53]. Fig. 2 underscores a significant research gap in the study of SISs because it reveals the lack of studies on control strategies and insulation materials in thermal insulation. Moreover, Fig. 3 displays a timeline with the keyword network map, illustrating a rising interest in SISs in recent years and highlighting their substantial potential. Furthermore, Fig. 4 emphasizes a notable gap in this field, specifically the lack of studies investigating the relationship between insulating materials and SISs, although more studies have applied optimal control strategies to SISs to improve their performance. Upon closer examination of switchable insulation systems, Fig. 5 illustrates the research interests related to SIS. A more in-depth investigation is required to fully understand its operational mechanisms and potential applications.

3.1. Statistical analysis

3.1.1. Scope of research

These articles explore innovative developments in a wide range of fields, including systems, materials, and control strategies, as shown in Fig. 6These articles provide an in-depth analysis of innovative technologies' performance and examine their strengths and limitations in diverse contexts. Furthermore, they offer a detailed exploration of various optimization methods, providing insights into the most effective ways to enhance their efficiency and effectiveness.

Most of the literature has focused on innovating new systems and concepts (11 articles, Table A1), including thermally-insulated roller blinds[55], wall-integrated solid-state thermal switches [26], horizontal Planar Liquid-Vapor Thermal Diodes (PLVTD) [56], removable insulation systems [30], partitioned multifunctional smart insulation [57], closed translucent façade elements with switchable U-values [58], non-volatile thermal switches [28], hybrid smart water-filled glass (SWFG) [31], suspended particle device (SPD) switchable glazing [32], and movable SISs [29]. Furthermore, there is research interest in applying SISs in different climatic zones and contexts, as well as residential, commercial, and office buildings, and analyzing their performance (11 articles, Table A4). Only (seven articles, Table A3) focused on control strategies such as schedule-based controls, rule-based controls [25,47,50], and control optimization, such as genetic algorithms [25,47,59]. On the other hand, published research papers on material improvements are limited (five articles, Table A2), which are flexible hybrid composite films containing $CsxWO_3$ nanocrystals [60], VO_2-aerogel [61], silica-based core materials for thermal superinsulation [62], and PCM integrated in switchable insulation [35]. The literature mainly investigates parameters such as energy savings by comparing the thermal and energy performance of traditional insulation and SISs and comparing the performance of SISs using different control strategies.

3.1.2. Integration level of application

Integrating SISs into various components of building envelopes is gaining traction in energy-efficient buildings at multiple levels., as shown in Fig. 7. The literature highlights a particular focus on integrating SISs into walls (29 %), closely followed by windows and translucent facades (26 %) and roof, ceiling, or attic applications (26 %). In contrast, integration into the floor slab is currently the least explored. While some studies investigated the integration into the overall building envelope (10 %), others explored specific combinations such as walls and windows, or roof and wall (9 %) to achieve a higher energy saving. This distribution underscores the considerable interest in switchable insulation for regulating heat flow through walls and windows, offering promising potential for enhancing building energy efficiency and occupant comfort.

3.1.3. Location of application

As illustrated in Table 3 and Fig. 8, the countries most related to this research topic are developed countries. Only one study in Iran, a developing country, discussed dynamic cool roofs. All studies were

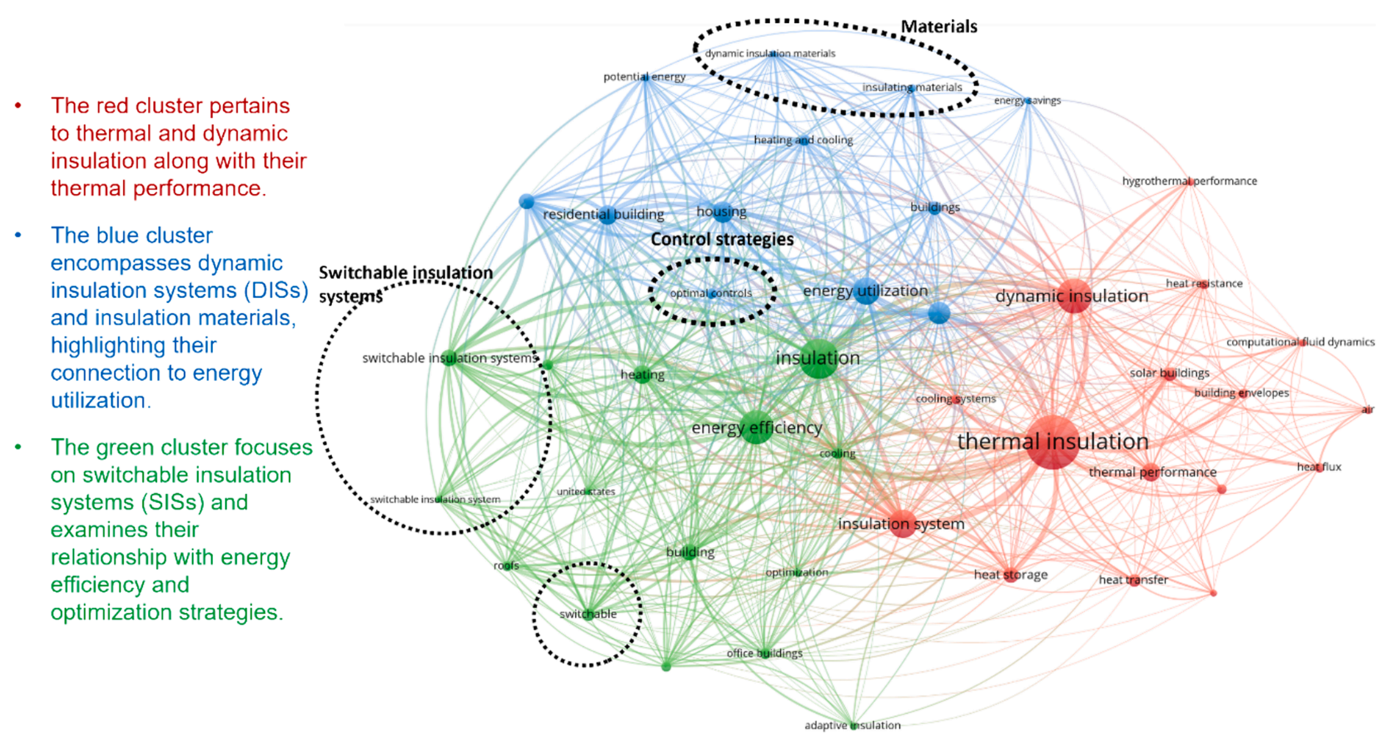

Fig. 2. Keywords networks map of dynamic insulation systems presenting three main clusters.

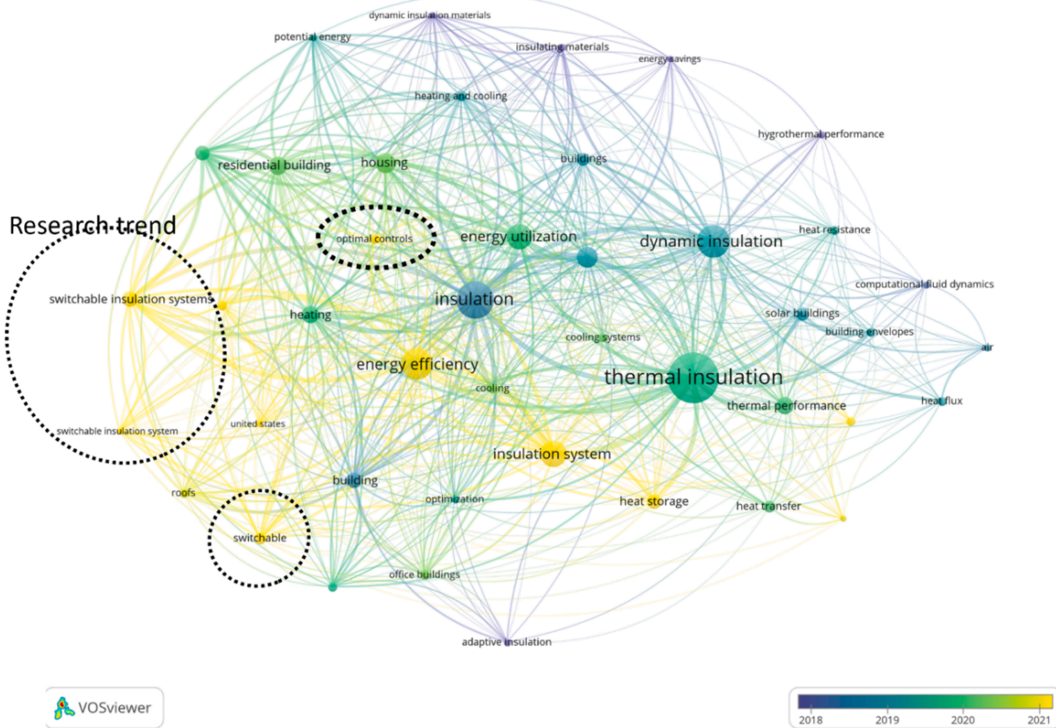

Fig. 3. Research trends of topics related to dynamic insulation. This map highlights the growing interest in SISs.

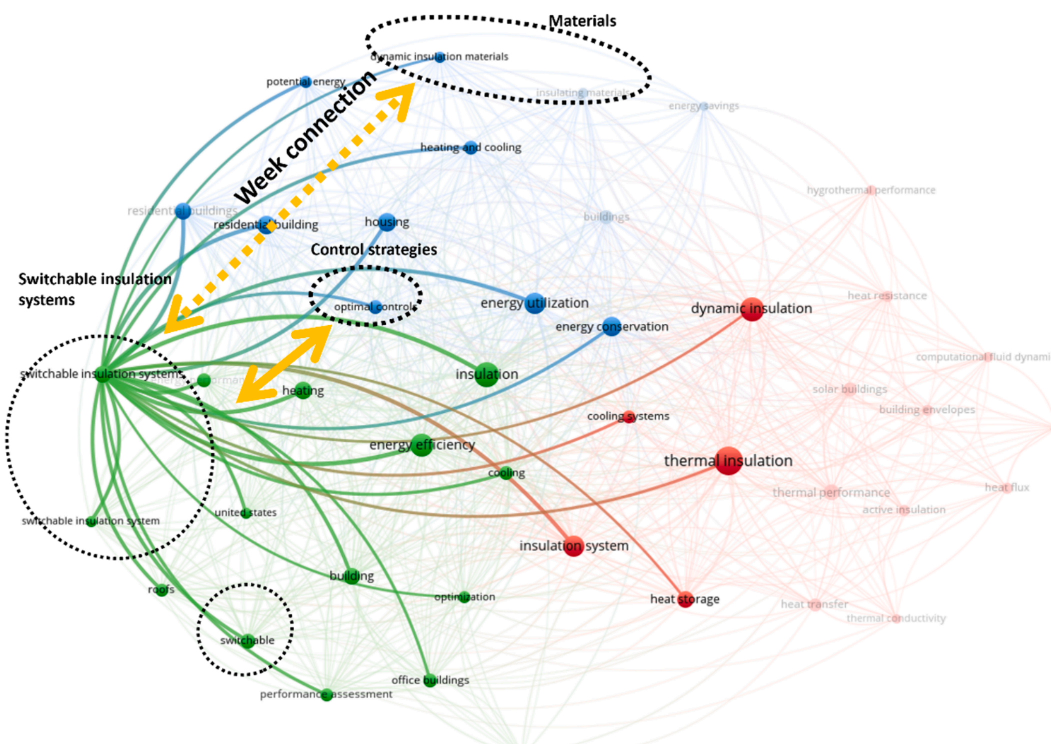

Fig. 4. The main aspects of SIS are presented through connections between keywords. This map highlights an apparent shortage of research on insulation materials and SISs.

conducted in developed countries and were characterized using advanced materials and techniques. On the other hand, developing countries are characterized by a less developed industrial base, lower human development index (HDI), and low per capita national income [63], highlighting the importance of developing affordable switchable systems applicable to this context.

3.1.4. The methodological approach

SISs have been widely explored using various research methodologies, as illustrated in Fig. 9. Simulation techniques are considered the

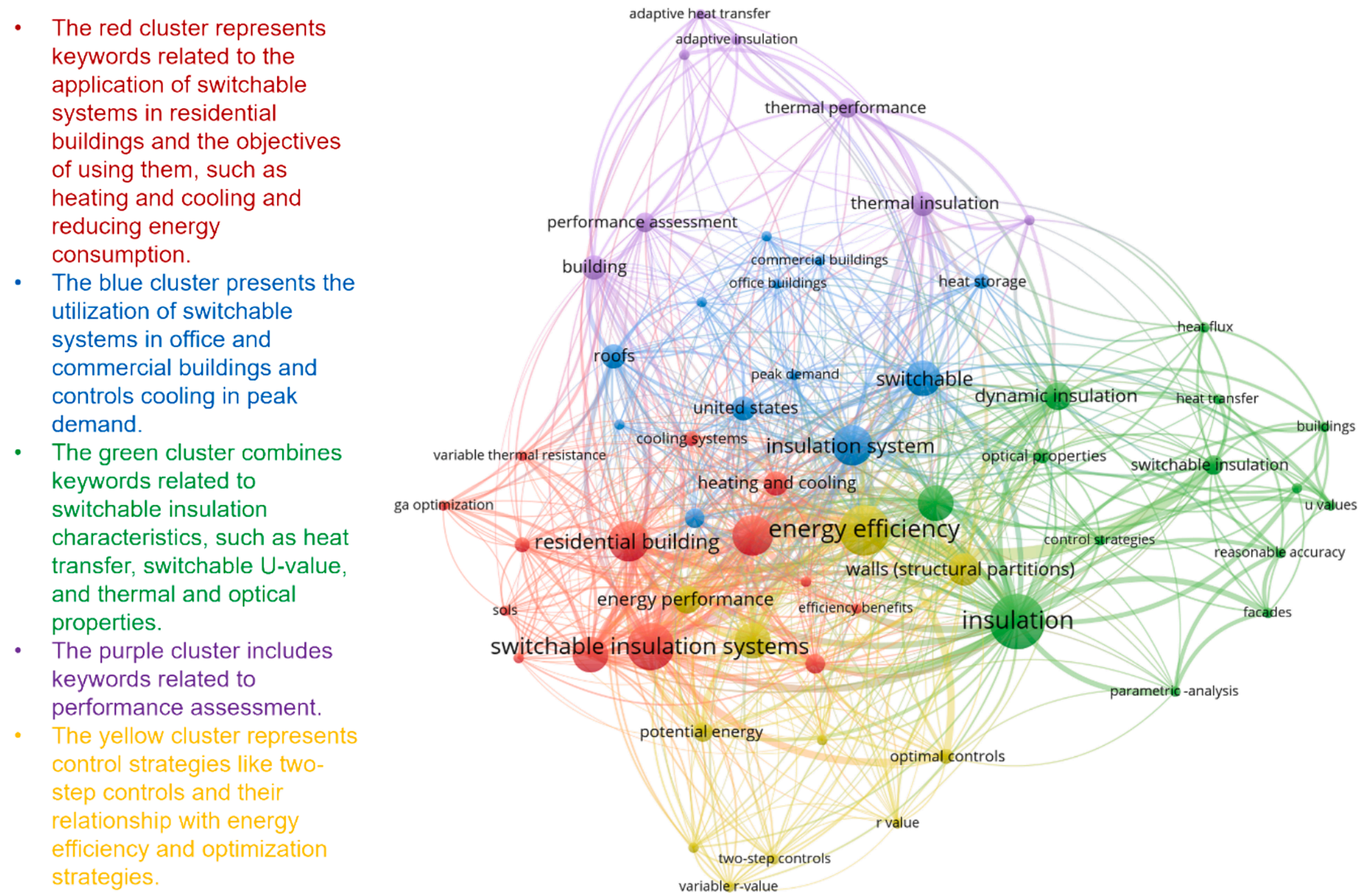

Fig. 5. Keywords network map of switchable insulation systems.

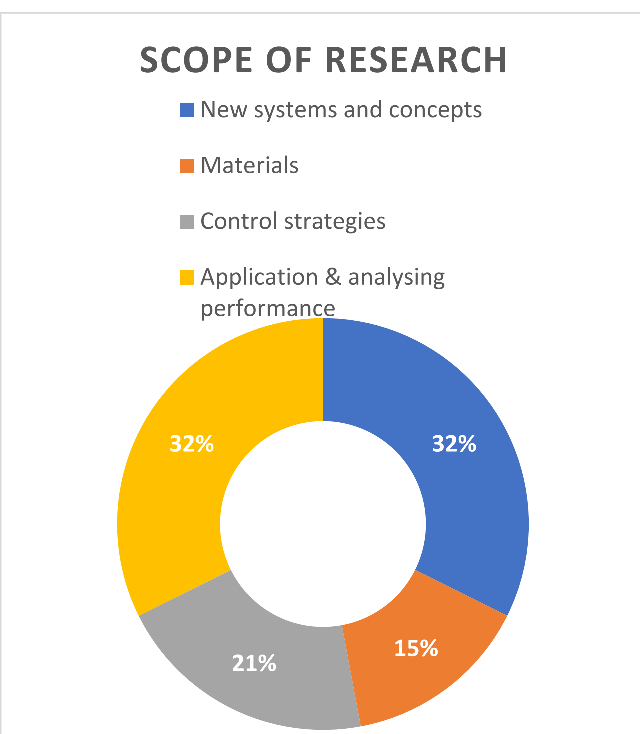

Fig. 6. Scope of research in switchable insulation systems.

primary approach, with as many as 15 studies (48 %) using them to analyze the performance or behavior of these systems to evaluate energy savings, heating and cooling demands, and thermal performance, or to perform CFD analysis. Most of the tools used in the simulation were used for modeling or validation.

First, EnergyPlus (11 times), Energy Management Systems (EMS) (three times) [64], and MATLAB (six times) [65] are among the most used software tools for energy analysis, management, and optimization across various domains. They can be used independently or in combination to provide a comprehensive energy management and optimization approach. Second, COMSOL Multiphysics (three times) is applicable for simulating coupled phenomena and multiphysics using advanced numerical methods [66,67]. Finally, DesignBuilder [68], LBNL WINDOW [69,70], IDA ICE (Indoor Climate and Energy) [71], FLUENT [29,72] and TRNSYS were less frequently used.

In contrast, experimental methods were employed in two studies (7 %) to assess and validate the feasibility of such insulation systems. Furthermore, experimental, theoretical, and numerical approaches were used and were less frequently used independently (1 % for each). However, these approaches were used in combination (39 %). The integrated application of theoretical, numerical, simulation, and experimental methods in these studies supports a comprehensive investigation of SISs' performance. This complex approach offers a deeper understanding of these systems' capabilities and potential applications.

3.2. The research status of switchable insulation

Based on the above analysis, the status of SIS-related research can be summarized as follows:

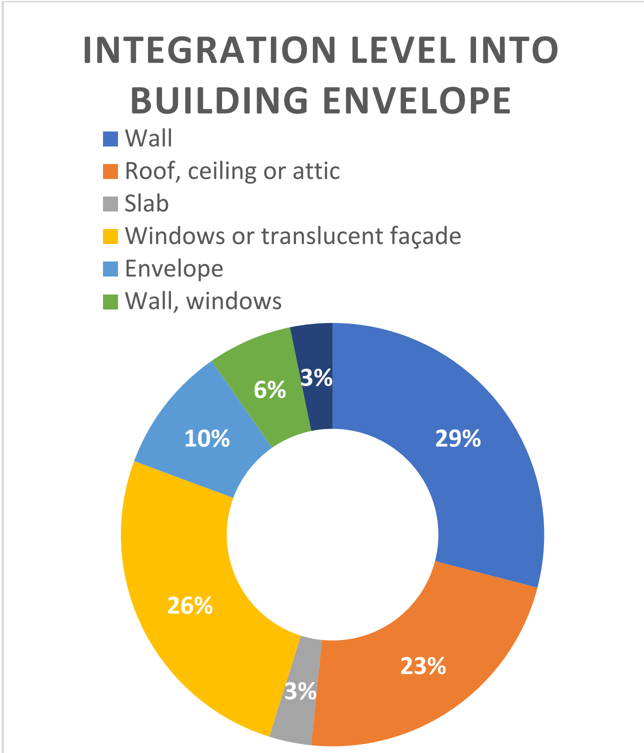

Fig. 7. Integration level of switchable insulation systems application into building envelops.

Table 3
Number of publications in most related countries.

Country	*No. of publications*
US	13
UK	3
Ireland	4
China	3
Central Europe	1
Germany	3
France	1
Iran	1
Norway	1
Belgium	2
Spain	1

- Integration and Application: Numerous studies have investigated the ability to integrate SISs into building envelope components. This integration can potentially improve building energy efficiency and thermal comfort; however, there is an apparent shortage of research on integrating eco-friendly insulation materials and SISs.
- Methodological approaches: Research on SISs has employed several methodologies, including simulations and experiments. Simulation tools are often used to analyze SISs' performance and behavior, while experimental methods are limited. However, mixed approaches are more common, and are used to assess and validate their feasibility.
- Global research focus: Research on SISs is primarily conducted in developed countries, with a limited focus on developing countries. This reveals a gap in knowledge transfer and technology adoption, particularly in hot climate regions, where the applicability of SISs can be significantly practical.

In conclusion, SISs show enormous promise, but are not used in developing countries, particularly in hot regions where economic solutions are needed. In addition, there is a lack of research on integrating eco-friendly insulation materials with SISs. Research indicates that SISs offer significant opportunities to improve energy efficiency and thermal comfort in sustainable building envelopes in hot areas. Further research is required to enhance these technologies, tackle cost obstacles, and promote their wider adoption.

4. Switchable insulation systems

This study selected SIS as a promising technique for developing adaptive systems based on affordability. This approach can be applied based on its mechanical adjustability, material type, thermal performance parameters, control strategies, and fabrication to determine the most related parameters and available options (Fig. 10).

4.1. Mechanical adjustability

In the context of building insulation, mechanical adjustability and response mechanisms in SIS allow the system to alter its insulation properties [52] in response to external stimuli through its ability to modify or adjust the physical properties or configuration of the insulation material to enhance its performance (Table A1, Table A4). These can be classified as follows:

- Dynamic panels/parts: panels or materials that can mechanically change their configuration or position to adapt to varying environmental conditions.
- Adjustable fluid flow systems: they control fluid flow and movement within the systems.
- Adjustable properties systems: they depend on changing properties.

Fig. 11 shows the system types and concepts discussed in this review.

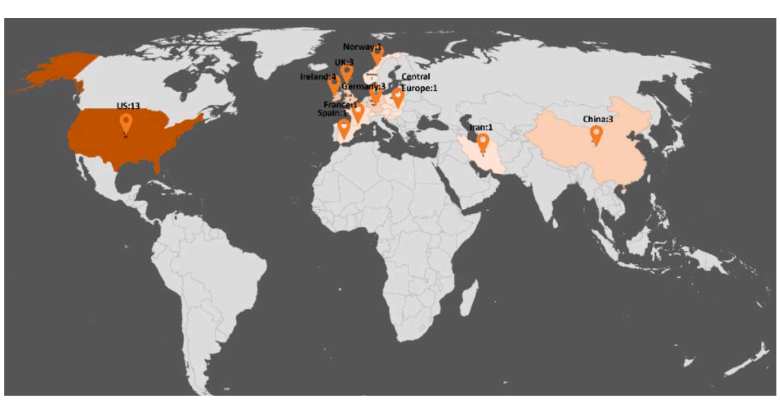

Fig. 8. The most related countries to the research topic.

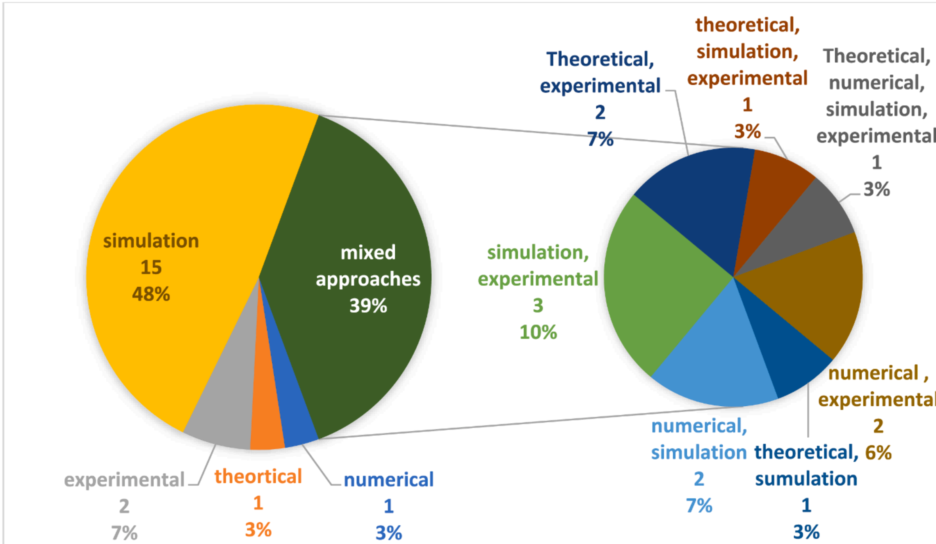

Fig. 9. Breakdown of articles according to research methodologies used in this research.

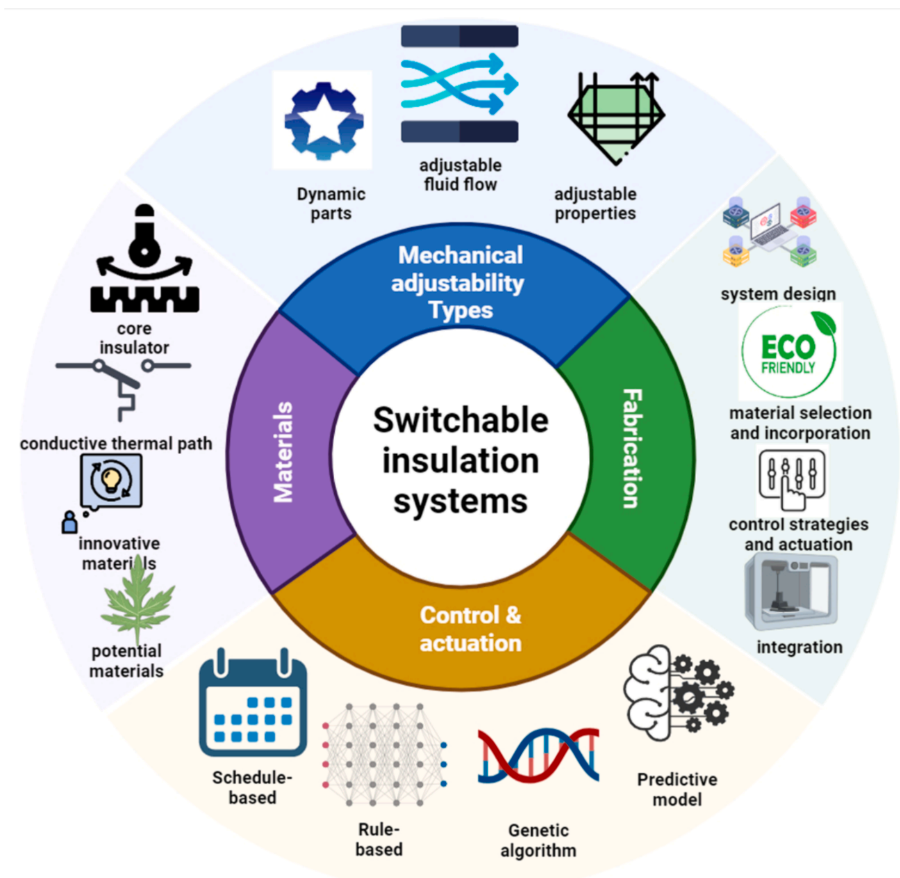

Fig. 10. Switchable insulation system focus.

4.1.1. Dynamic panels/parts

4.1.1.1. Movable insulation parts

4.1.1.1.1. Rotating panels. Krarti [73,29] proposed incorporating SISs into a building's thermal envelope. This involves the installation of two surfaces with a gas-filled cavity and insulating elongated fins attached to different rotational axes. These fins can rotate between closed and fully open positions (Fig. 13.A). Dehwah and Krarti [33] extended this concept to create dynamic window systems that combined switchable transparent insulation and smart glazing (Fig. 13.F). The window design optimizes performance by managing key factors such as the solar heat gain coefficient (SHGC), visible transmittance (VT), and thermal resistance (R-value). Smart glazing can be adjusted to high or low settings for SHGC and VT values, depending on the control strategy.

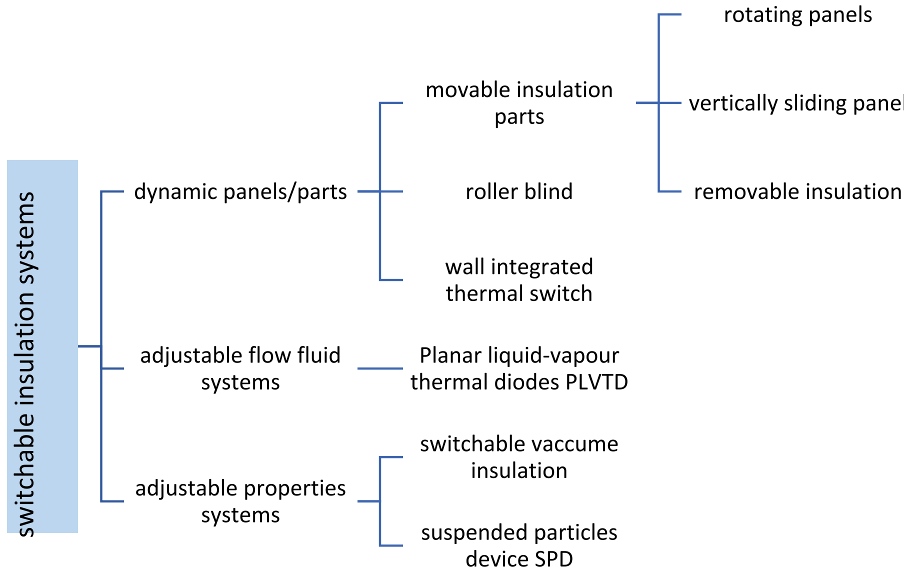

Fig. 11. Types of switchable insulation systems.

Furthermore, Rajabi et al. [37] assessed the energy efficiency of a similar SIS applied to a slab in residential buildings (Fig. 13.K).

4.1.1.1.2. Vertically sliding panel. Pflug et al. [58,74] introduced a translucent system that controls convection around a translucent insulation panel. This system features a switchable U-value and moves vertically within a double-glazing unit (Fig. 13.G). In its insulating state, the insulation panel is located at the top, minimizing convection around it. At this stage, the system comprised three insulating layers (two thin air layers and an insulation panel). However, when the system is configured to allow heat transfer, the insulation panel is centered vertically, creating air gaps at both the top and bottom to facilitate convection around it.

4.1.1.1.3. Removable insulation. Pflug et al. [30] developed a switchable facade component capable of altering its thermal and optical properties. The component features air-filled spaces separated by opaque films that can be rolled up or down between two fixed layers, enabling it to switch between a thermally insulating and a conductive state. This system can be applied to both windows and walls (Fig. 13.B and Fig. 13.H).

4.1.1.2. Roller blind. Alkhatib et al. [55] developed a dynamic insulating roller blind to control both heat transfer and daylight. The blind used a foldable, thermally insulating material installed inside the windowpane. It was equipped with side channels on the window frame to maintain its position close to the glass during operation. A cover at the top of the blind reduced air leaks between the insulated roller blind and the glass (Fig. 13.J). The roller blind was adjusted to four positions based on the internal temperature, preventing overheating in summer and reducing heat loss at night. The temperature thresholds for each position were 15°C for fully open, 18.4°C for quarter-height, 19.4°C for mid-height, and 21.4°C for fully closed positions.

4.1.1.3. Wall-integrated thermal switches. Miao et al. [28] developed a thermal switch that creates or disrupts a thermal path utilizing aluminum for heat conduction due to its high thermal conductivity, lightweight, and cost-effectiveness. The device frame was made of high-density polyethylene (HDPE) plastic with low thermal conductivity. Joule-heated shape memory alloy (SMA) wires activated the switch, controlling the gap opening and closing (Fig. 12). The device alternates between ON and OFF states using SMA wires and rotating blocks. When a voltage is applied to the outer SMA wire, it triggers the on state.

This state is maintained without further electricity consumption. To switch to the off state, the inner SMA wire is heated, rotating the pivot blocks and snapping the beam upward, creating an air gap that disrupts the thermal path and minimizes the heat flow. This system reduces the energy consumption for building envelope applications, requiring activation only once or twice daily, with each switch taking less than 10 s. The thermal switches were integrated into the building envelope wall (Fig. 13.C), with a layer of PCM placed between the two switches within the wall cavity center (switch-PCM-switch stack).

Kunwar et al. [26] presented a similar wall-integrated solid-state thermal switches (STS). It consists of flat pieces suspended in a steel wire clamped to a rotating shaft, which converts the rotary motion into linear motion. A DC motor controls the shaft based on the signal sent by a data acquisition system and sensors input from the thermistors. The system operates in two states (Fig. 13.D) R-low, where the flat pieces engage with the U-channels and create a thermal bridge and a higher heat flow, and R-high, where the thermal contact is broken, resulting in a lower heat flow.

4.1.2. *Adjustable fluid flow systems (thermal diodes)*

A thermal diode is a device that transfers heat with low resistance in

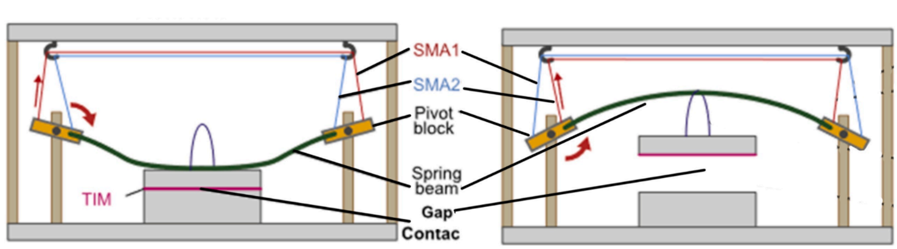

Fig. 12. Using joule-heated shape memory alloy (SMA) wires to control thermal switches.

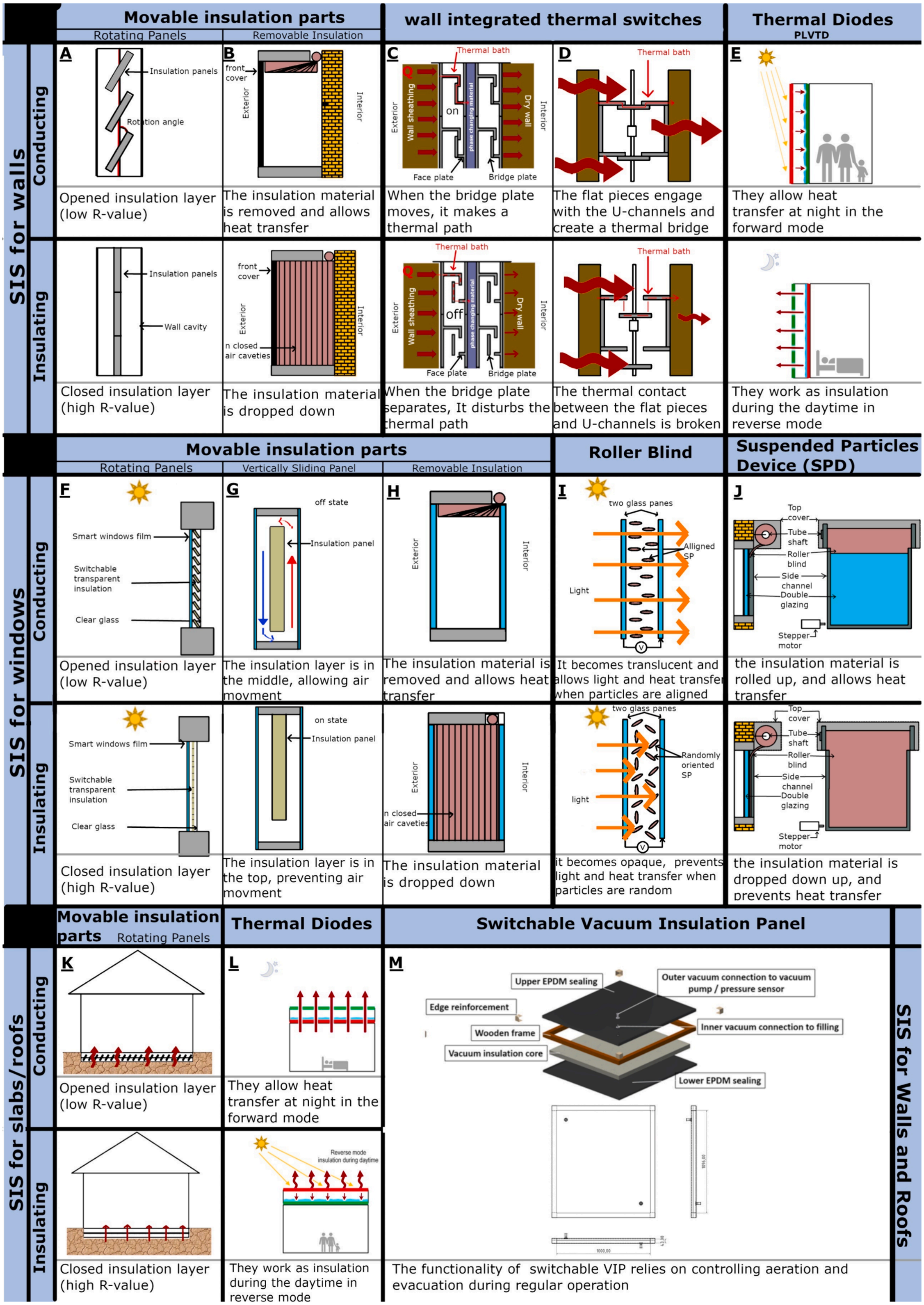

Fig. 13. Switchable insulation systems overview.

one direction and with high resistance in the other. It consists of two parallel plates separated by a cavity with a working fluid [56]. In the forward mode, the fluid wets the hottest plate, causing vaporization and subsequent condensation. By controlling the plate-wetting mechanisms, the device can reverse, initiate, or suppress its operation on demand, thus creating components with switchable thermal-insulation properties [75].

Pugsley et al. investigated the behavior of modified planar liquid–vapor thermal diodes PLVTD in horizontal (Fig. 13.L) [56], vertical, and tilted orientations (Fig. 13.E) [75]. The PLVTD facilitated heat transfer by using the temperature differences between the plates. In the forward mode, latent heat transfer occurred owing to phase changes in the working fluid and net transfer of the working fluid vapor mass. In reverse mode, thermal transmission occurred through various mechanisms, including convection, gaseous conduction, radiation, and conduction through the external envelope and internal structural elements. They discussed the application of PLVTDs in building envelopes as solar heat storage or switchable insulation in ceilings and walls between the day and night.

4.1.3. Adjustable properties systems

4.1.3.1. Switchable vacuum insulation. Owing to their low thermal conductivity, super-insulators, such as Vacuum Insulation Panels (VIPs), have gained popularity for energy saving in buildings, the cold-chain industry, and home appliances. VIP's effectiveness depends on the gas pressure level within the open-porous material [43]. It is vital to consider VIPs' physical characteristics, such as thermal conductivity, inner pressure, durability, and predicted service life [76]. The functionality of switchable VIP (Fig. 13.M) relies on controlling aeration and evacuation during regular operation [77].

4.1.3.2. Suspended particles device (SPD). Suspended particle glazing modifies the properties of the glazing material by introducing suspended particles into a fluid medium, adjusting the refractive index of the fluid, and the surface tension of the interface, thereby regulating the amount of light passing through a specific area [78]. Ghosh et al. [32] conducted experiments using an outdoor test cell to characterize the thermal properties of SPD switchable glazing and double-glazing systems. They depended on light to pass through the SPD glazing (Fig. 13.I). Tests demonstrated that SPD glazing effectively controlled the temperature increase inside the test cell, with a limited transmission of 55 % in transparent and 5 % in opaque conditions (compared with 78 % for double glazing). Furthermore, on sunny days, the solar heat gain can be controlled without any power requirement because the SPD remains opaque when unpowered [32].

4.2. Thermal insulation materials

It is crucial to select an appropriate material to enhance the performance of the SISs. This involves a deep understanding of the thermal conductivity parameters and the array of available material choices. Selecting suitable materials can significantly enhance the effectiveness of insulation systems and improve energy efficiency and cost savings (Table A2).

4.2.1. Thermal characterization and parameters influencing thermal conductivity of switchable insulation systems

4.2.1.1. Common characterization and factors of insulation materials. The thermal characterization of thermal insulation materials includes the thermal conductivity λ (for the steady state, which is affected by factors such as moisture content, bulk density, temperature, airflow velocity, aging, pressure, and thickness [39])., the thermal diffusivity D for the unsteady state, thermal transmittance (U-value), thermal resistance (R-value), specific heat, albedo (of the roof), periodic thermal transmittance, decrement factor (dimensionless), and Timeshift Δt (h) for a multilayer wall to define thermal insulation under unsteady conditions (the last three characterizations) [3,46,79]. Thermal insulation materials are characterized according to their thermal conductivities. Materials with the best performance have a thermal conductivity $(\lambda) < 0.05$ [W/(m·K)], whereas materials with poor performance have a thermal conductivity $(\lambda) > 0.08$ [W/(m·K)]. Materials with the remaining values are characterized as intermediate [39,44,79]. Understanding the relationship between effective thermal conductivity and influencing factors of insulation materials is critical for determining envelope heat transfer and building energy consumption [39].

4.2.1.2. Porosity, particle size, and gas pressure for the gas pressure-dependent materials. Porosity and particle size influence the thermal conductivity of gas pressure-dependent materials. Sonnick et al. [62] investigated the impact of porosity and particle size on gas pressure-dependent thermal conductivity of four materials: precipitated silica (PS), fumed silica (FS), silica gel (SG), and glass spheres (GS). For switchable vacuum insulation panels (Fig. 13.M), as illustrated in Table 4 and Table 5, silica gel had the most significant effect at a porosity of $\varphi = 0.84$ and maximum particle size. Natural convection within pores is undesirable because it increases the total heat transfer. Combining silica gel and helium as the filling gas produced the most favorable results because of the high thermal conductivity and small kinetic atomic diameter of silica gel and helium. Moreover, silica agglomerates reduce the time required for aeration and deaeration [77].

4.2.1.3. Rotating angle between panels and wall cavity thickness. The thermal conductivity of SIS with rotating panels is affected by the rotating angle between panels and wall thickness [29,73]. Dabbagh and Krarti [29] investigated this relationship and found that the width of the wall cavity, as illustrated in Fig. 14, and the size of the insulation layers affect the thermal performance. A 15-degree angle between the insulation layers resulted in over a 50 % reduction in the R-value of the wall, as illustrated in Fig. 15. Additionally, Pflug et al. [58] examined the effect of wall cavity thickness on the system's thermal conductivity, while the vertical air gap thickness, as in Fig. 13.A, influences the U-value ratio in conductive and insulating states.

4.2.1.4. The solar Heat-Gain coefficient (SHGC). The Solar Heat-Gain Coefficient (SHGC) is a key metric that measures the amount of solar radiation that enters a building through its windows. Several factors, including the window system's design, electrical performance, and operating conditions, determine SHGC values [80]. Advanced methods to enhance SHGC include the use of advanced glazing, shading devices, and water-filled glass [31]. Additionally, Switchable insulation integrated windows with rotating panels [59,81] (Fig. 13.F) can also switch between low and high SHGC values during cooling and heating modes, respectively, ensuring occupant comfort and creating a pleasant indoor environment.

4.2.1.5. Switching ratio. For all SISs, the switching ratio is a crucial parameter used to evaluate the performance of the systems. When it comes to conducting and insulating, the performances are distinct. Therefore, the thermal performance of SISs is characterized by the switching ratio (η) [82] as illustrated in the following equation:

Table 4
Selected domains for the parameter study on porosity and the decisive particle size [62].

	Ps	FS	SG	GS
Porosity	0.80 to 0.98	0.80 to 0.98	0.80 to 0.98	0.3 to 0.7
Particle size	Agglomerates 5 to 40 μm	Aggregates 50 to 225 μm	Aggregates 5 to 40 μm	Primary particles 1 to 100 μm

Table 5
Suitability of the different materials for switchable VIP [62].

Application	Value	Ps	FS	SG	GS
Switchable VIP	***Porosity***	Max.	Max.	Max.	Max.
	Particle size	Min.	0.90	0.84	Min.
$SW = \frac{\lambda(p=1000\,mbar)}{\lambda_{base}}$	***Switching ratio (SW)***	8.09	4.18	8.82	7.93

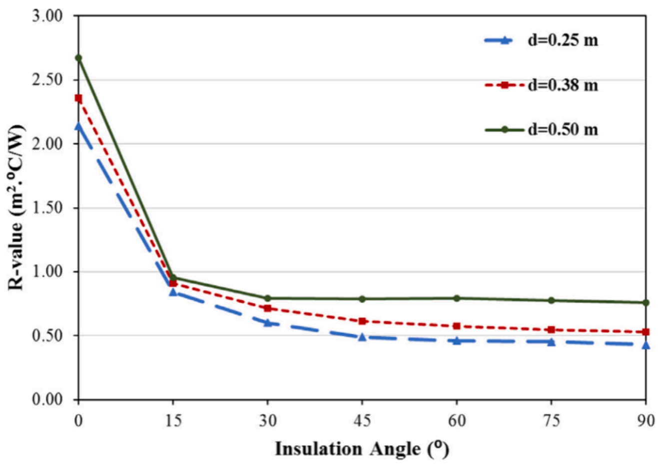

Fig. 14. Impact of wall cavity thickness within DIS on R-values for various insulation layers angles [29].

$\eta_{\lambda=}\lambda_{on}/\lambda_{off},\eta_R = R_{on}/R_{off},\eta_U = U_{on}/U_{off}$

Where $\lambda_{on}/\lambda_{off}$ is the thermal conductivity coefficient, R_{on}/R_{off} is the thermal resistance coefficient, and U_{on}/U_{off} is the heat transfer coefficient when the core layer is in insulating and conducting states.

4.2.2. Material types used

SISs can control heat flow by decreasing thermal conductivity using insulation materials or increasing it using conducting materials like metals. These approaches offer a flexible and efficient way to manage a material's thermal properties. As a result, SISs use diverse types of materials based on their concept and working principles. The materials can be classified into (Fig. 16):

1. Insulating materials that serve as a core insulator within the system.
2. Conducting materials used in systems that create or disturb thermal paths.
3. Materials integrated to enhance dynamic thermal performance.
4. Potential materials options

4.2.2.1. Insulating materials that serve as a core insulator within the system

4.2.2.1.1. Traditional insulation materials. Traditional insulation materials can serve as core insulation material. For instance, Mineral wool [81] and polyisocyanurate foam insulation [29] were used as core insulation materials in rotating panels. Another option is using Plexiglas® layers, which are a thin film made of polyethylene terephthalate (PET) with a thickness of only 12 μm, coated with aluminum on one side, that can be rolled up or down between two fixed layers to regulate the temperature and light transmission properties [30].

4.2.2.1.2. Translucent insulation material. For translucent façades and windows (Fig. 13.F and Fig. 13.G), Basotect® has been used as a translucent insulation material, a melamine foam with open pores and low density. At 20°C, it has a thermal conductivity of 0.035 [W/(m·K)], making it a good option for energy-efficient façades [58]. Another example of a translucent insulation material is monolithic silica aerogels (MSA), which offer high transmittance properties for light and solar radiation. MSAs have been utilized in Venetian blinds within smart glazing windows, where they can regulate their thermal resistance independent of the window's SHGC [59].

4.2.2.1.3. Silica and aerogel. Superinsulation applications often use silica and aerogel as insulation materials. Fumed silica, although the most common core material for vacuum insulation panels (VIPs) due to its high performance, is expensive [62]. Consequently, Researchers are exploring more cost-effective alternatives like precipitated silica, silica gel, and glass spheres to find affordable insulation solutions [62].

Aerogel is another lightweight insulation material, with a density ranging from 150-220 kg/m^3 and thermal conductivity between 0.024–0.027 [W/(m·K)], depending on the proportion of aerogel particles in the mixture. However, its major drawback is its lower heat storage capacity compared to conventional insulators [83]. It is often incorporated into fabrics for easy installation, as it is not used in pure form. Transparent aerogel with ultralow thermal conductivity (approximately 0.018 [W/(m·K)]) can improve the window's thermal resistance and reduce energy loss [61].

4.2.2.2. Materials used in systems that create or disturb thermal paths.

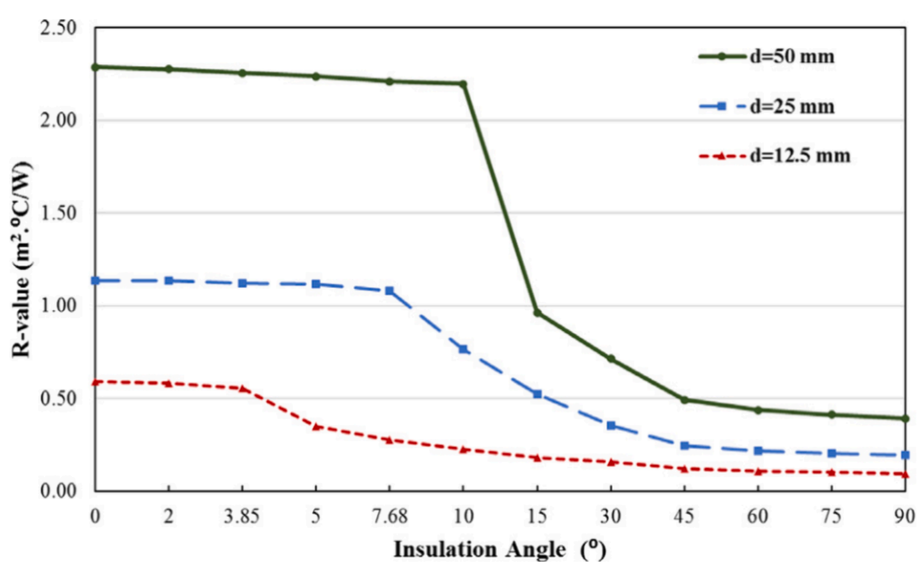

Fig. 15. R-value variations as a function of the rotating angle for various thicknesses of the insulation layers [29].

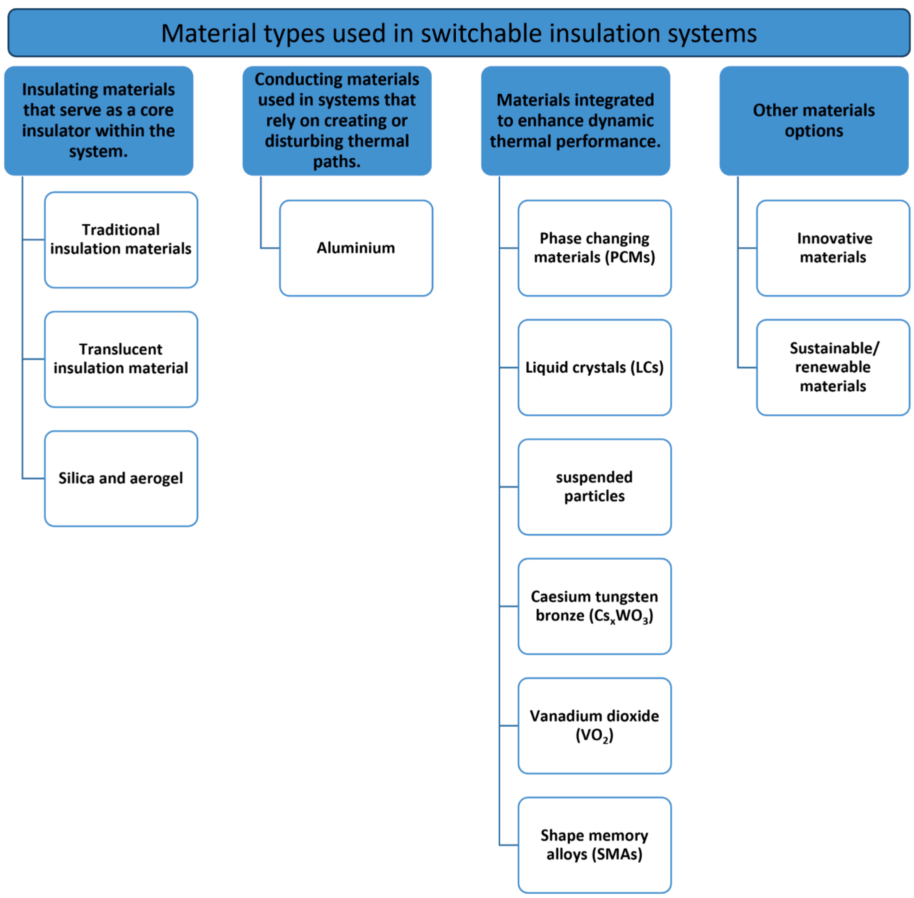

Fig. 16. Material types and options of SISs.

Aluminum is a good option for heat conductors due to its lightweight, high thermal conductivity, and low cost [21,25]. It was used within solid-state thermal switches (STSs) (Fig. 13.C and Fig. 13.D) by creating or disturbing thermal paths.

4.2.2.3. Innovative materials integrated to enhance dynamic thermal performance. Incorporating innovative materials is an effective strategy to enhance the performance of Switchable Insulation Systems (SISs). This can be achieved through various methods, such as increasing the thermal mass of materials and systems and regulating light and heat transmission.

4.2.2.3.1. Phase changing materials (PCMs). Phase-changing materials (PCMs) can significantly enhance thermal performance and energy efficiency in building insulation and promote sustainability [35,84]. PCMs can stabilize indoor temperature fluctuations, improving thermal comfort for building occupants [35]. The effectiveness of PCMs depends on factors like location, phase change temperature, and thermophysical properties [84]. The increasing thickness of the PCM layer only has a positive impact on the performance of the building in hot and severe cold climate zones [18]. Walls with PCM and dynamic insulation offer superior thermal adaptability, regulating R-values, dispersing peak loads, and improving indoor thermal comfort [24]. However, adding PCM can lead to summer overheating due to thermal barriers.

Integrating PCMs into SISs provides a significant thermal performance enhancement and more energy savings. To ensure the significance of adding PCM to such systems, Miao et al. [28] found that while incorporating a single layer of wall-integrated thermal switches can effectively enhance the use of ambient cooling and heating, adding a layer of phase change material (PCM) into the wall cavity, positioned between two thermal switches, provides additional benefits. This setup offers more flexibility and control to optimize natural cooling or heating and charge the PCM, leading to yearly energy savings ranging from 9 % to 55 % for heating and 17 % to 76 % for air cooling, depending on the climatic zone.

4.2.2.3.2. Liquid crystals (LCs). For smart windows with switchable characteristics, Liquid crystals (LCs) inhabit a unique state between solid and liquid. The contrast in their optical properties provides a promising solution for smart windows, as they can regulate both light and heat transmission [85,86]. LCs are known for their dual-field responsiveness, as they also react to electric fields [60].

4.2.2.3.3. Suspended particles. Liquid crystal windows and suspended particles, such as polymer particles, can switch between transparent and translucent states due to molecular or particle alignments [61]. Ghosh et al. [32] studied the characteristics of SPD glazing enclosed within double glazing (Fig. 13.E). They found that the mean U-value for SPD glazing was 5.9 [W/(m^2·K)], while the double glazing was 2.98 [W/(m^2·K)] When double glazing was combined with SPD switchable single glazing, the U-value was 1.99 [W/(m^2·K)].

4.2.2.3.4. Caesium tungsten bronze (Cs_xWO_3). He et al. [60] have developed a composite film that combines Polymer-dispersed liquid crystal (PDLC) and Cesium tungsten bronze (Cs_xWO_3) nanocrystals. The PDLC system enables switching between transparent and opaque states, improving indoor comfort and energy efficiency. Cs_xWO_3 nanoparticles block near-infrared light (NIR) irradiation, making them ideal NIR filters. The composite film can modulate light across the 400–2500 nm solar irradiation range, encompassing both visible and invisible NIR wavelengths. Transparency transitions occur when the temperature is below the phase transition temperature (45°C), remaining transparent at higher temperatures. Furthermore, the Cs_xWO_3 nanocrystals provide a protective effect in the 800–2500 nm range, screening 60 % to 95 % of NIR irradiation under thermal and electric fields.

4.2.2.3.5. Vanadium dioxide (VO_2). Vanadium dioxide (VO_2) is another material that can improve the performance of switchable windows. It has various physical and chemical properties, including the metal–insulator transition (MIT) temperature at 68°C [61,87], modulating its optical properties by transforming it from a semiconductor to a metal [88,89]. VO_2 also exhibits thermochromic properties, which regulate solar transmission in the NIR (780–2500 nm wavelength). Zhao et al. [61] developed an innovative film that combines thermal insulation and transparency by incorporating VO_2 nanoparticles into an aerogel film with low thermal conductivity. This thermochromic film enhances thermal insulation and dynamic solar transmission control, responding to ambient conditions. A thin 3.0 mm film can provide a low U-value of approximately 3.0 [W/(m^2·K)], high luminous transmittance of over 60 %, and solar modulation ability of roughly 20 %. Applying this film to single-pane windows can minimize energy loss, improve thermal comfort, and mitigate overheating in hot weather and moisture condensation in cold weather.

4.2.2.3.6. Shape memory alloys (SMAs). Shape memory alloys (SMAs) can remember their shape at low temperatures and recover from significant deformations when heated, known as the shape memory effect (SME). They can replace conventional actuators like electric and fuel-powered motors, performing complex behaviors while reducing weight and size [90,91]. Miao et al. [28] employed SMAs to control thermal pathways between open and closed states as required in wall-integrated thermal switches (Fig. 13.C) using Joule-heated SMA wires. This system's key feature is that an SMA wire undergoes a reversible transformation near its phase transition temperature, which can be reversed by applying a gentle external force.

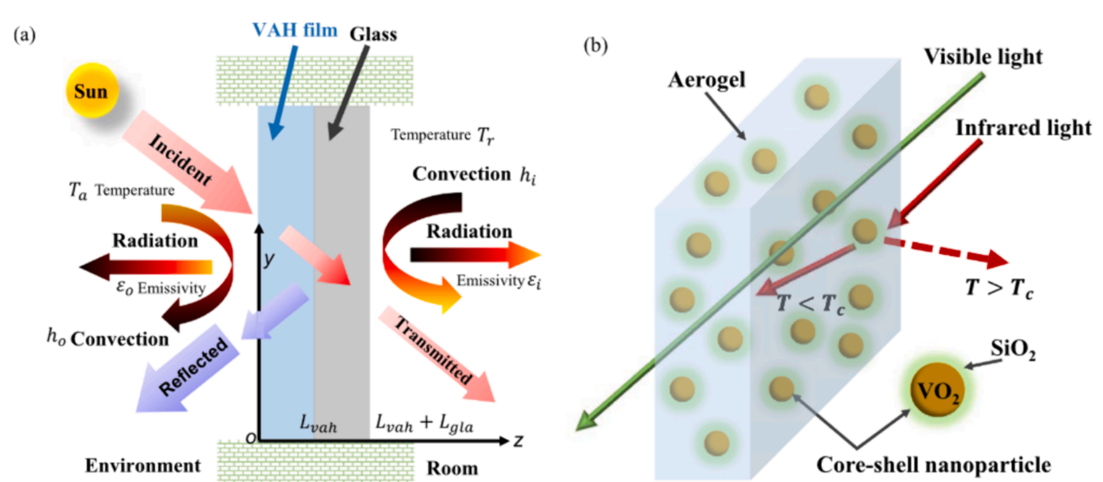

Fig. 17. (a) A single-pane window with a thermochromic VO2-aerogel hybrid (VAH) retrofitting film illustrates heat transfer and solar radiation transfer. (b) Structure of the VO_2-aerogel hybrid film. The transparent aerogel film reduces [61].

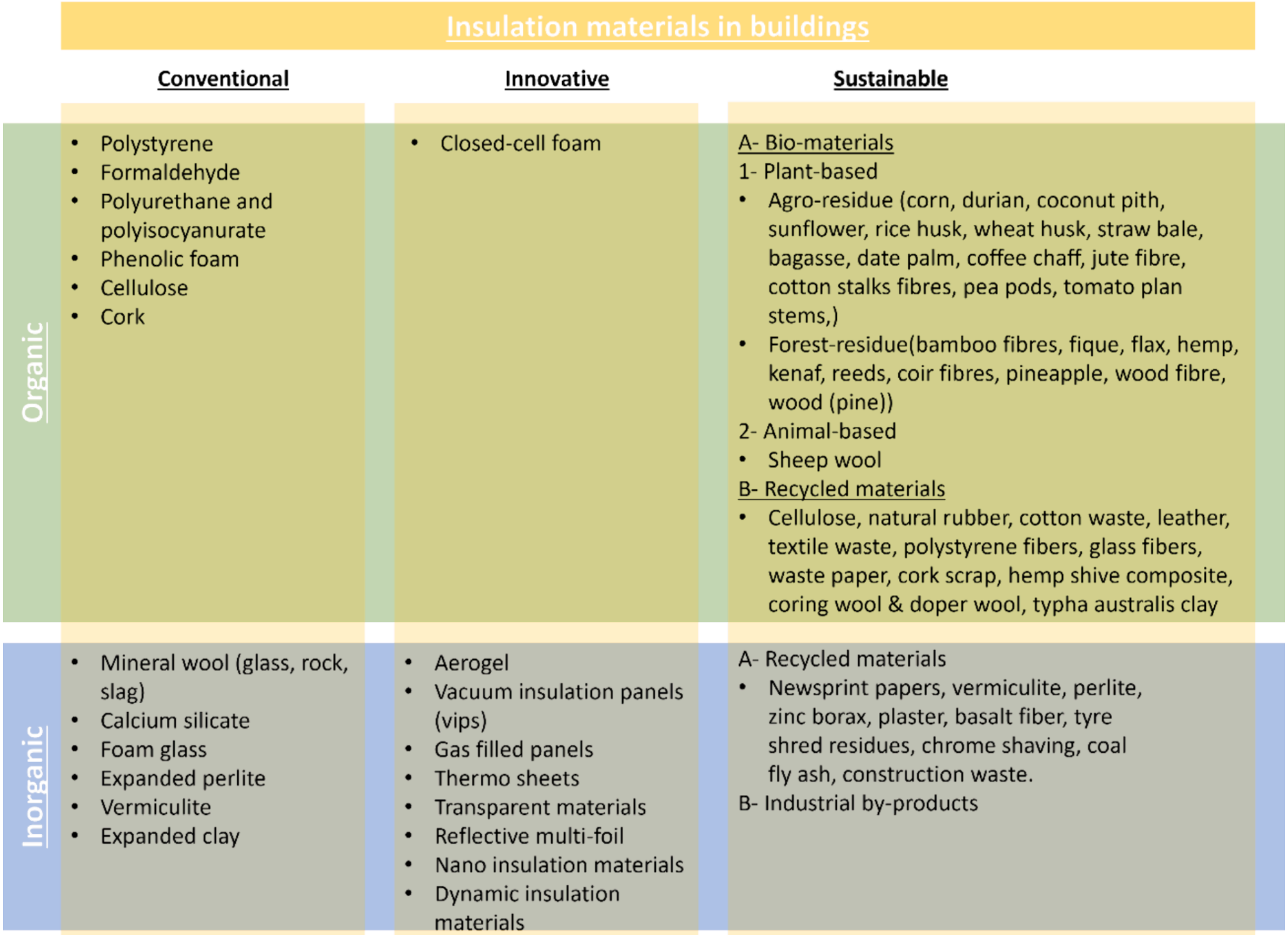

Fig. 18. Thermal insulation materials used in building [3,16,42,44,46,79,92].

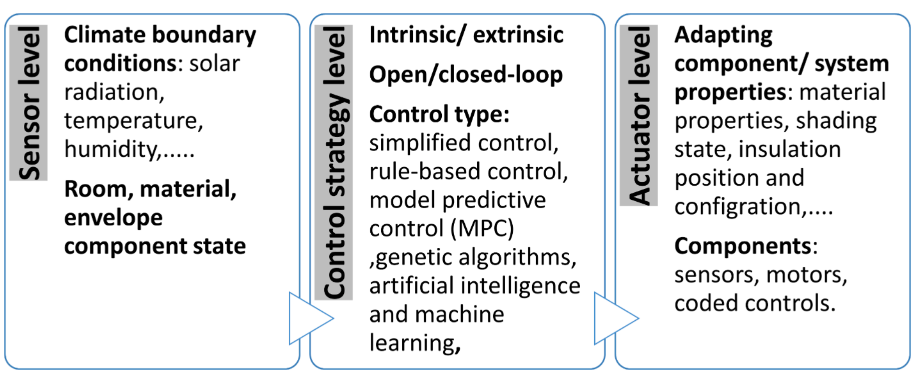

Fig. 19. Control architecture for switchable insulation systems (. adopted from [95])

4.2.2.4. Potential materials options. There are three main categories of thermal insulation materials used in building construction [16,42,92]: conventional, innovative, and sustainable/renewable, as presented in Fig. 18. Based on their origin, these materials are classified as organic and inorganic.

Conventional materials provide thermal comfort but require significant energy and non-renewable resources for their production. In contrast, Renewable materials offer similar performance in insulation, fire resistance, and cost-effectiveness [93]. Advanced insulation materials provide superior thermal insulation properties but have higher costs over their lifespan [16]. Sustainable insulation materials are better choices as they encourage eco-friendly practices, enhance energy efficiency, and reduce environmental impact [45]. Bio-based or recycled waste materials are commonly used in these materials. They are cost-effective, lightweight, and can be repurposed, recycled, or decomposed naturally at the end of their life cycle [94]. Selecting sustainable insulation materials promotes an eco-friendly and energy-efficient approach to thermal insulation in buildings while reducing carbon footprint.

4.3. Control strategies and actuation of switchable insulation systems

Control strategies and actuation methods are pivotal components in optimizing energy efficiency optimization and thermal performance of

Fig. 20. Concept of an intrinsic/open-loop system.

Fig. 21. Concept of an extrinsic/closed-loop system.

buildings. These systems are responsible for the adaptation process of SIS, which alters system configurations and insulation properties in response to varying climatic conditions. This includes adjustments to accommodate temperature differences between the internal and external surfaces of walls or windows and determining the heat flow direction [50]. Additionally, they regulate the impact of solar radiation on building surfaces (Fig. 17) [31,61].

The control architecture of SIS can be divided into three levels [95] (Fig. 19):

- Sensor level: Sensors monitor parameters like solar radiation, temperature, humidity, … etc. These sensors are set to the boundaries of external and internal climatic conditions, which serve as critical turning points in the system's behavior.
- Control strategy or control logic level: This allows for linking variables and data from sensors and actions by actuators after processing control logic.
- Actuator level: actuators are operated according to configurations from controls, switching between conducting and insulating states.

Control strategies are classified into:

1. intrinsic/open-loop, used in smart systems (e.g., thermochromic and PCMs) and directly triggered by a stimulus with no external interventions (Fig. 20).
2. extrinsic/closed-loop, which is used in adaptive systems (e.g., kinetic facades), needs external triggers to an external management system that makes decisions (Fig. 21) [96].

Control strategies for SISs can be classified into several categories based on their level of complexity: schedule-based control, rule-based control, Genetic algorithm control system, and Model-predictive control (MPC), (Table A3).

4.3.1. Scheduled-based control

Schedule-based control operates according to a preset timetable or seasonal schedule without any interventions related to environmental conditions [95]. In SISs, thermal resistance changes its value between two or multiple values based on the season or the time during the day [47]. For instance, Switchable roof insulation systems employing rotating panels can depend on seasonal-based control, switching their R-value between high and low depending on the season and building location [47]. Dynamic/switchable cool roofs switch their reflectance twice a year, transitioning between being reflective in summer and being absorptive in winter [33,97]. Yazdani and Baneshi [97] found that using dynamic cool roofs with seasonal control can save 0.7–45.3 % from annual energy consumption compared to conventional cool roofs in Iran. Despite its simplicity, this control type lacks flexibility as it cannot respond to real-time data regarding climatic changes.

4.3.2. Rule-based control

Rule-based control can manage SISs' adaptive behavior through predefined logical rules based on real-time data to change their state without complex algorithms [50], offering balanced simplicity, easy implementation, and effectiveness. Rule-based strategies vary in their complexity level from simplified to advanced rulesets, such as two-step control strategies [25,47] and multi-step control strategies [50]. These controls can be temperature-based [47], solar radiation-based, and illuminance-based [31], etc.

Temperature-based rule-based control, for instance, utilizes temperature sensors to adjust the R-value of the insulation system [25,47,50,98] based on temperature differences in indoor and outdoor environments, HVAC operation mode, surface temperatures, or a temperature set point [47].

The control mechanism of a two-step temperature-based strategy depends on determining the direction of heat flow within the wall (Fig. 22), typically assessed by measuring temperatures at interior and exterior surfaces and within the wall. In heating mode, the R-value is

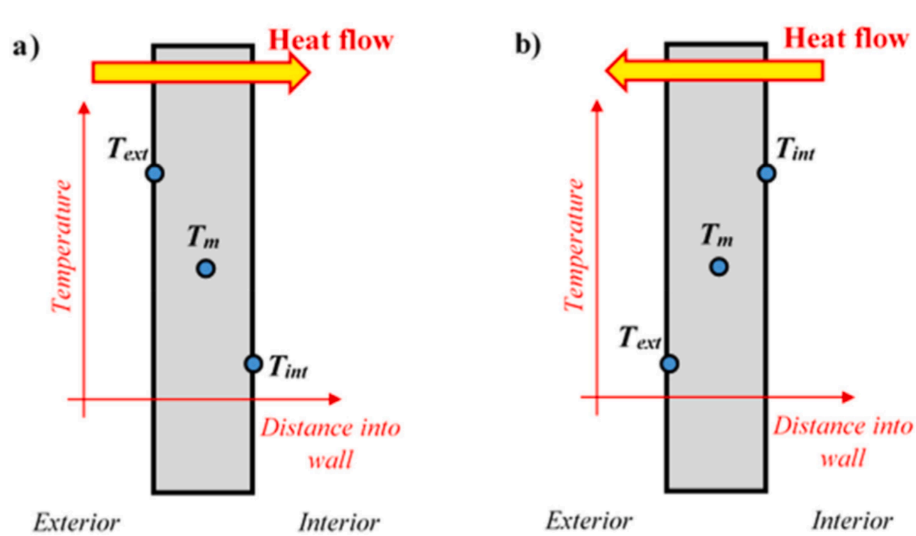

Fig. 22. Direction of heat flow (1) cold season and (2) hot season [50].

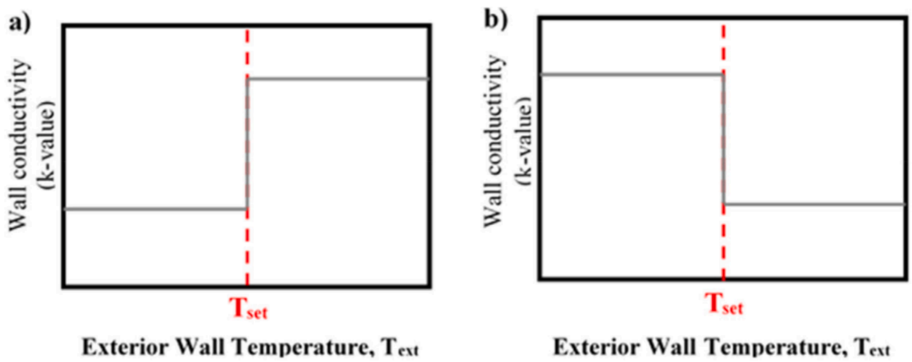

Fig. 23. Switching of the thermal conductivity in a two-step operation during (a) cold season and (b) hot season [50].

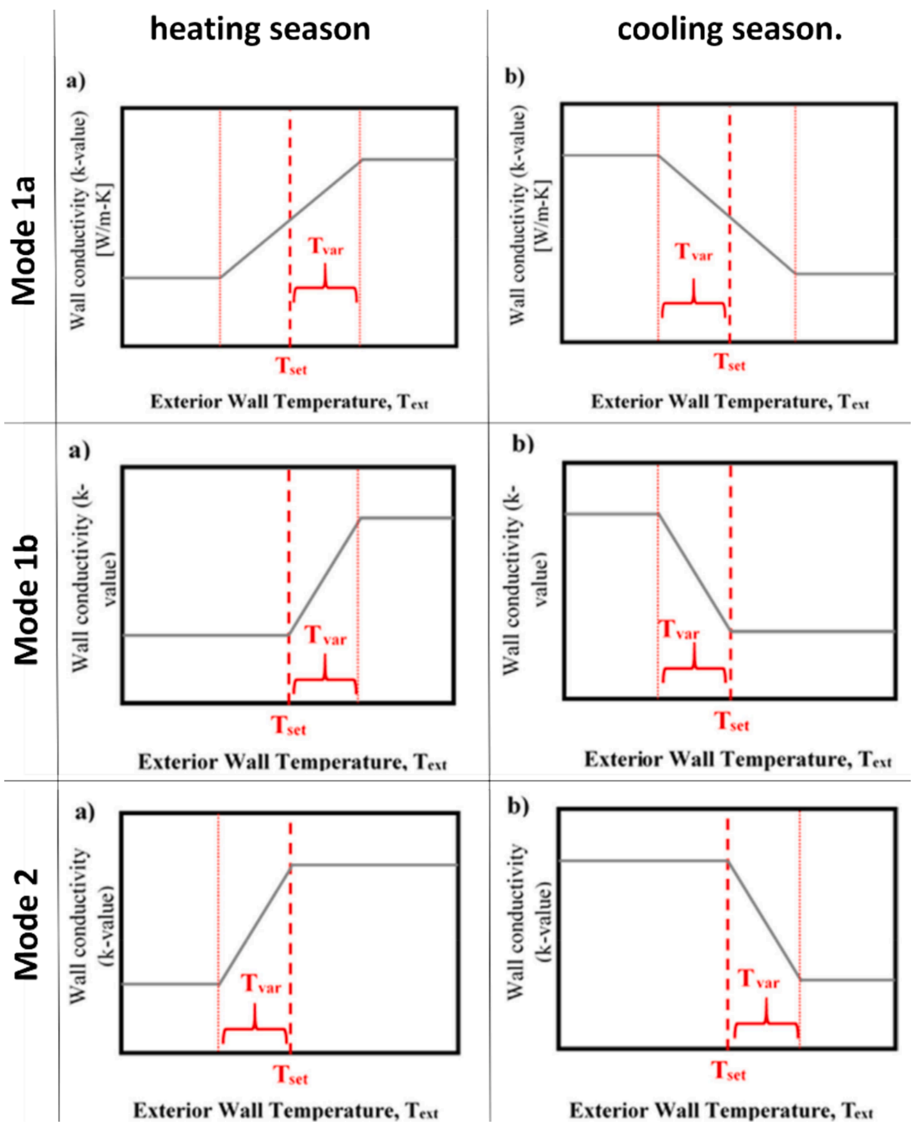

Fig. 24. Variation in wall conductivity under different operation modes in cold and hot seasons [50].

lowered when the temperature gradient within the wall indicates heat flow from the exterior to the interior, and the exterior surface temperature exceeds the setpoint temperature. In cooling mode, Conversely, the dynamic insulation material (DIM) switches to a low R-value when the direction of heat flow is from the inside to the outside [50] (Fig. 23).

Instead of employing a binary switch between high and low insulation states, many systems allow for multiple levels of R-value within a predefined range, providing finer control and potentially maximizing energy savings. Rupp & Krarti [50] investigated five rules-based operation modes with a thermal conductivity that varies step-wise, developed by Park et al. [95] and Menyhart and Krarti [38]. Each mode adjusts the thermal conductivity based on specific conditions

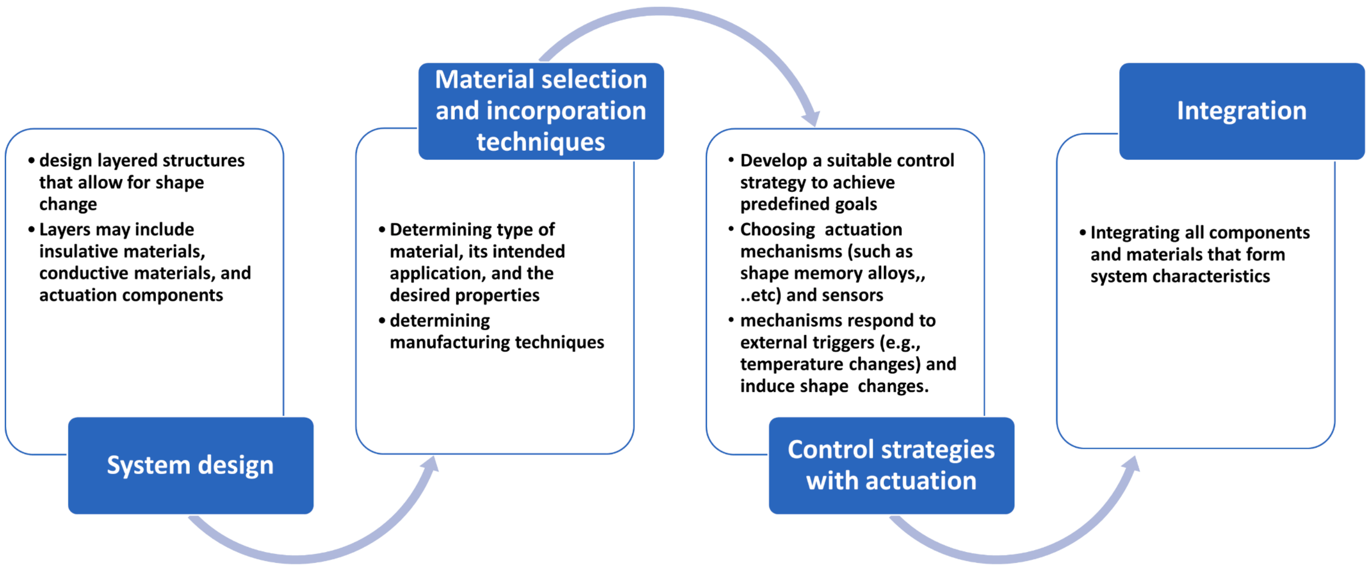

Fig. 25. Fabricating switchable insulation systems process.

during heating and cooling seasons (Fig. 24). The variations provide flexibility and control over the R-value, potentially leading to energy savings. The control mechanism successfully extends the duration while the insulation conductivity stays at its maximum, enabling the system to capitalize on favorable heat flow through the wall. Compared to the 2-step operation, this control mechanism reduced the cooling energy consumption by 1.20 % and the heating energy consumption by 1.50 % in Golden, Colorado.

4.3.3. Genetic algorithm (GA) control system

GA optimization can enhance simulation environments by identifying the most effective R-value settings for SISs to meet a specified objective function. This optimization strategy mimics biological evolution, employing a fixed, linear data structure that prioritizes the survival of the fittest solutions. It eliminates underperforming solutions from a collection of potential solutions and generates a new generation. MPC can formulate and solve multiple optimization functions, such as minimizing total energy consumption or operational cost or minimizing peak load demand [99].

Serale et al. [100] developed MPC control algorithms that use weather forecasts to determine the optimal location of PCM, whether oriented towards the interior or exterior relative to the insulation layer within the wall. Meanwhile, Cui et al. [99] developed a time-varying model predictive control (TV-MPC) to optimize mode selections of adaptive insulation system and HVAC system operation. Results indicated that setting the upper limit of the indoor air temperature to 25 °C during the summer can lead to more than 50 % energy savings and up to 38 % cost reduction. MPC can achieve superior performance compared to more straightforward control strategies, improving energy efficiency, comfort, and building cost savings.

4.4. Fabrication of switchable insulation systems

Fabricating SISs involves several steps. Fig. 25 illustrates the process of fabricating SISs, which includes designing the concept, selecting materials, incorporating them using suitable manufacturing techniques, and outlining control strategies and actuation mechanisms to integrate all components of the entire system.

Stevens et al. [23] highlighted the importance of manufacturing methods in topology morphing insulation research to assess its feasibility and scalability for real-world applications. Manufacturing methods can vary in complexity, cost-effectiveness, and compatibility with existing insulation manufacturing processes. They emphasized optimizing these parameters to develop efficient and reliable insulation solutions. Understanding manufacturing methods helps identify necessary materials and resources, assess their availability and environmental impact, and promote sustainable manufacturing techniques. This can help reduce the carbon footprint associated with topology morphing insulation production and encourage green building and sustainable design.

4.4.1. System design

SISs in buildings are innovative and sustainable methods for creating energy-efficient environments. They involve a holistic approach integrating advanced design principles and technological solutions using the latest materials, smart technologies, and strategies. The goal is to optimize energy efficiency while enhancing occupant comfort and well-being.

Planning and conceptualization are crucial to developing tailored solutions considering building typology, climate, and user requirements. Thorough research and analysis are necessary to understand challenges and opportunities. Interdisciplinary teams work together to propose solutions while addressing functional and performance requirements.

Refining design concepts and validating their feasibility is critical. Prototyping and iterative testing are essential for optimizing performance metrics like thermal efficiency, durability, and user-friendliness. Researchers can assess the performance of SISs under various scenarios and iterate on their designs accordingly. They can explore complex geometries, simulate different design scenarios, and optimize system performance using emerging technologies like computational design tools and parametric modeling.

4.4.2. Material selection and incorporation techniques

Insulation materials are produced in various forms based on their characteristics, intended uses, and desired properties [15]. Manufacturing techniques are determined by the type of material, its application, and desired properties. Examples include materials that can undergo reversible shape changes, [30,57,55] switch system states from insulative to conductive [26], or change optical properties [32]. So, various methods are employed to create diverse types of insulation materials with specific properties.

4.4.2.1. Traditional materials incorporation. Insulation materials in the construction industry, primarily polymers like polystyrene and

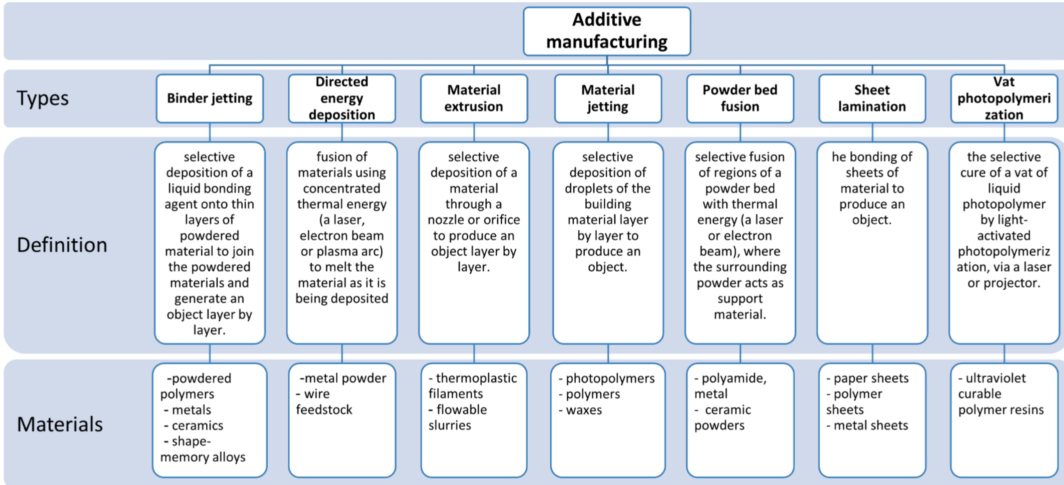

Fig. 26. Additive manufacturing with materials used (adopted from [102]).

polyurethane foam or fibrous materials like glass wool and rock wool [16], have negative environmental impacts due to resource consumption, high energy requirements, greenhouse gas emissions, and waste generation [17]. However, these materials are cost-effective in hotter climates, requiring less energy to maintain interior coolness [101].

4.4.2.2. PCM incorporation. Zhang et al. [24] presented various methods for incorporating PCM into building materials with the advantages and disadvantages of each method, making it essential to consider each method's specific needs and requirements. These methods are:

- Direct incorporation involves directly adding liquid or powdered PCM into the production process of materials like cement, gypsum, mortar, or concrete.
- Immersion involves immersing porous materials like wood board, gypsum board, bricks, or concrete into a container filled with liquid PCM.
- Vacuum impregnation technology follows a two-step process: Air and water are eliminated from the porous material, which is soaked in liquid PCM under vacuum conditions.
- Encapsulated PCMs come in various forms, such as tubes, spheres, or panels, and are considered core–shell materials. There are three primary categories of encapsulation methods: macro-encapsulation (with a diameter or thickness of 1 mm and more), micro-encapsulation (from 1 μm to 1 mm), and nano-encapsulation (less than 1 μm).
- Shape stabilization technology involves melting and combining support materials like high-density polyethylene, styrene, and butadiene with PCM at hot temperatures. The PCM is then cooled below the glass transition temperature of the support material until it solidifies completely. This method ensures that PCM is stable and does not leak from the material.

4.4.2.3. 3D printing. Pessoa et al. [102] explored the application of Additive Manufacturing (AM) in the construction sector, focusing on its potential to improve thermal efficiency in 3D-printed buildings. They highlighted the positive environmental impact of 3D printing, as it generates less waste and offers a promising solution for circularity. Fig. 26 summarizes the AM's process categories with materials used [102,103]. They discussed opportunities and challenges that need to be considered and suggested three ways to enhance the thermal performance of building walls through 3D printing technology, including:

1. using thermal insulation materials within the internal voids of the structural layers of the 3D-printed wall
2. simultaneously printing different layers with different extrusion nozzles
3. altering mortar composition, reusing construction waste, bio-insulations, and advanced insulators back into the production cycle

Jiang et al. [104] fabricated a 3D wall-cellulose structure using partially dissolved cellulose fibers in a NaOH/urea solvent system. The structure is lightweight, flexible, and ultra-strong, with remarkable elasticity and shape recovery properties. Once dried, it behaves as a rigid and strong material capable of supporting over 15,800 times its weight. The 3D-printed cellulose honeycomb can be used as a thermal insulation panel due to its high mechanical properties and porous structure. By freeze-drying, a 0.6 % TEMPO-oxidized cellulose nanofibrils (CNF) aerogel-filled honeycomb exhibited good interfacial adhesion between CNF aerogel and honeycomb cell walls to prevent heat loss from the honeycomb's open pores, CNF aerogel was used to fill them. They investigated the thermal insulating effects of the 3D printed honeycomb, CNF aerogel, and CNF aerogel-filled honeycomb on hot and cold surfaces using Infrared (IR) imaging.

4.4.2.4. Encapsulation. Material encapsulation involves applying a protective outer layer to a core material to protect its inherent properties from external factors. This method is used, for example, as thermal energy storage and VIPs [105]. Erlbeck et al. [77] described an encapsulation process used in building a switchable VIP. The process involves creating a wooden frame covered with ethylene propylene diene monomer (EPDM) and then filled with insulation material. The design is flexible enough to accommodate volume changes during gas aeration and deaeration.

4.4.2.5. Composite fabrication and lamination. Composite fabrication and lamination involve combining different materials for insulation properties, resulting in improved durability, flexibility, and thermal insulation [106,107]. Laminate composites, composed of fabric sheets

Table 6
SIS types according to their application location within the building envelope and the complexity in terms of concept and operation.

Envelope component	*Switchable insulation system*	*Complexity of system*	*Ref.*
Wall	Rotating panels	Simple	[73,29]
	Removable insulation	Simple	[30]
	Wall-integrated thermal switches.	Advanced	[26,28]
	Vertical planar liquid–vapor thermal diodes PLVTD	Advanced	[75]
	Switchable vacuum insulation	Advanced	[77]
	Dynamic insulation-phase change material system.	Simple	[35]
Window or translucent facade	Rotating panels	Simple	[33]
	Vertically sliding panel	Simple	[58,74]
	Removable insulation	Simple	[30]
	Roller blind	Simple	[55]
	Suspended particle glazing	Advanced	[32]
	Responsive film for smart window	Advanced	[60]
	Optically switchable thermally insulating vo2-aerogel hybrid film	Advanced	[61]
Roof or slabs	Rotating panels	Simple	[37]
	Horizontal planar liquid–vapor thermal diodes PLVTD	Advanced	[56]
	Switchable vacuum insulation	Advanced	[77]

embedded in a polymer matrix, offer advantages over traditional materials like increased stiffness, strength, mechanical damping, toughness, and resistance to corrosion and chemicals. The production process depends on matrix properties, reinforcement properties, item design, and intended purpose [108]. Composite laminates also enable the use of waste materials like buffing dust from the leather tanning industry and agricultural wastes, leading to resource recovery and reduced environmental pollution [109,110].

There are two primary categories of thermal insulation composite materials:

- Particle composites, which consist of a matrix or binder, usually a polymer, hold a dispersion of filler particles such as aerogels chosen for their low thermal conductivity [111]. The binder provides structural integrity and prevents moisture ingress [112].
- Fiber-reinforced composites, which are made up of a matrix, often a ceramic or polymer reinforced with fibers such as carbon, improve the composite's stiffness and strength while still providing thermal insulation [113,114].

Composite fabrication techniques for thermal insulation materials may vary depending on the materials used. Some of the commonly used methods are mixing [115], spraying [116], lay-up [117], and moldings like compression molding, vacuum infusion, injection molding, and more advanced methods like resin transfer molding (RTM), autoclave molding, filament winding and pultrusion [118].

4.4.3. Control strategies and actuation

Control algorithms play a significant role in managing the thermal characteristics of SISs by identifying the switching point between insulation states by employing control logic, optimization approaches, and real-time data to modify the insulation system's configurations. This process is performed by first monitoring interior and outdoor conditions and environmental factors, using sensors that provide controllers with required data. Secondly, the selected control strategy alters the insulation system configuration to the required adaptation. Thirdly, Actuators' dynamic response enables efficient thermal and energy management through heat transfer control. Actuation is significantly influenced by factors, including the needed adaptation actions, the level of complexity in movement, and the properties of used materials like dimensions and weight, considering durability and actuators' energy consumption. Fabrication involves incorporating sensors, actuators and controls into insulating panels or structural components.

5. Applicability of SIS to hot-climate developing regions

Developing countries in hot climates face energy efficiency, thermal comfort, and environmental impact challenges [119], making sustainable building practices crucial. SISs have shown promise in addressing these issues. However, successful implementation requires understanding the factors influencing adoption and effective resource utilization strategies. Future research can improve the adaptability and effectiveness of SISs in various environmental contexts to enhance SIS applicability in different climates. The focus should be on operational simplicity, cost-effectiveness, and sustainability potential.

5.1. Factors affecting adopting SIS in hot-climate developing regions

Adopting SIS in developing countries is influenced by multidimensional factors, including [120,121]:

- The motivation to adopt these technologies, which is driven by factors such as energy efficiency, cost savings, and environmental benefits.
- Adaptability to local Climatic conditions, which influence the effectiveness of switchable insulation by developing climate-specific materials and optimizing the thermal mass of systems to adapt to those regions' daily and seasonal temperature changes.
- Material and technology accessibility, that is locally available or easily transportable to minimize costs, facilitate maintenance, be sustainable, and have a low environmental impact.
- Cost considerations to achieve affordability, by using low-cost innovative materials and installation techniques, exploring new materials that are more cost-effective, and developing better installation methods. For instance, incorporating simpler-to-install materials such as prefabricated panels. Depending on local manufacturing can help bring down costs. Considering the initial cost when aiming for broader adoption in developing economies, despite the potential for long-term savings, makes it a worthy application.
- Potential limitations, like durability, maintenance, or compatibility with existing building systems, that hold back long-term use due to high maintenance costs or advanced technology.

Addressing these factors is essential to offer wider acceptance and use of switchable insulation systems in hot-climate developing countries.

To enhance the applicability and adaptability of switchable

Table 7
Examples of available local material in developing countries [3,16,79]. Green = best performance – λ < 0.05 [W/(m·K)], orange = intermediate performance – 0.05 [W/(m·K)] < λ < 0.08 [W/(m·K)], red = poor performance – λ > 0.08 [W/(m·K)].

Material category	*Examples*	*Thermal conductivity [W/(m·K)]*	*Density [Kg/m^3]*	*Specific heat [KJ/kg.k]*
Bio-based materials	Rice husk	*0.048–0.08*	*130–170*	–
	Sugarcane bagasse	*0.049–0.055*	*250–350*	*1.3–1.5*
	Straw boards	*0.038–0.067*	*50–150*	*0.6*
	Coconut Fiber	*0.040–0.045*	*75–125*	*1.3–1.6*
	Hemp fibers	*0.039–0.123*	*25–100*	*1.7–1.8*
	Date piths	*0.042–0.086*	*174–664*	*2.6*
	Reed	*0.045–0.056*	*130–190*	*1.2*
	Sheep wool	*0.038–0.043*	*10–25*	*1.3–1.7*
Recyclable materials	Waste glass	*0.031*	*450*	*0.83*
	Fly ash	*0.040*	*290–315*	*0.04–0.56*
	Recycled PET	*0.034–0.039*	*15–60*	*1.2*
	Shredded tires	*0.1663*	*313*	–
	Waste paper	*0.036–0.061*	*170–646*	–
advanced materials	Nanomaterials	*0.004–0.015*	*230*	*1*
	Vacuum insulation panels (VIPs)	*0.0035–0.008*	*160–230*	*0.8*
	Aerogel	*0.013–0.022*	*70–180*	*1*
Composite materials	Cellulose-reinforced silica aerogel nanocomposites [165]	*0.032–0.0355*	*245–275*	–
	Cardboard waste mixed with vegetable fibers [166]	*0.072–0.10*	*278.6–343.8*	*1.254–1.807*

insulation systems across hot climates, several key areas of research and development should be taken into consideration:

- Factors such as switching and response mechanisms, building typology, climate, and user requirements should be considered to determine the most appropriate systems for a building. Additionally, it is crucial to identify the building envelope's effective element that needs improvement in its insulation system, as it significantly impacts thermal comfort and energy consumption.
- optimizing thermal mass integration to enhance heat storage and release involves designing insulation systems that incorporate materials with high thermal mass [122], such as concrete [123], water [31,75], and PCMs [35] to absorb and release heat more efficiently. The design must also consider factors such as the building's orientation, insulation location, and shape to ensure optimal performance [124].
- choosing or developing materials specific to the climate and suitable properties, considering that materials should have a minimal environmental footprint. This involves exploring diverse materials to determine their suitability for different climatic conditions, including thermal conductivity, hygroscopic, acoustic, and fire retardancy properties, life cycle cost, and environmental impact [16]. Using materials with high reflectivity and low thermal conductivity is essential for reducing indoor overheating [125]. High reflectivity and low emissivity efficiently bounce back solar radiation to reduce the amount of heat absorbed [126]. Moreover, low thermal conductivity minimizes heat transfer. Additionally, insulation thickness significantly influences a building's thermal performance [127].
- developing control strategies tailored to building needs in different climatic contexts, optimizing the algorithms that dictate when and how the insulation system switches between its various modes [50,128,129] to achieve goals like energy savings [25,47,59], peak

Table 8
A matrix of integration potentials between SISs and examples of available materials options in developing countries.

		Simple					Advanced					
		Rotating panels	Removable insulation	Vertically sliding panel	Dynamic insulation-PCM system.	Roller blind	Suspended particle glazing	Wall-integrated thermal switches	PLVTD	Switchable VIPs	Responsive film for smart window	Optically switchable thermally insulating vo2-aerogel hybrid film
Best performance	VIPs									X		
	nanomaterials	X	X	X	X	X	X			X	X	X
	aerogel	X	X	X	X	X	X			X	X	X
	waste glass	X		X	X					X		
	cellulose-reinforced silica aerogel nanocomposites	X	X	X	X	X				X		
	recycled PET	X	X	X	X	X				X		
	fly ash	X	X	X	X	X				X		
	sheep wool	X	X	X	X	X				X		
	coconut fiber	X	X	X	X	X				X		
Intermediate performance	Sugarcane bagasse	X	X	X	X	X				X		
	Reed	X	X	X	X	X				X		
	Waste paper	X	X	X	X	X				X		
	Straw boards	X	X	X	X	X				X		
	Rice hulks	X	X	X	X	X				X		
	Date piths	X		X	X					X		
Poor performance	Cardboard waste mixed with vegetable fibers	X		X	X					X		
	Hemp fibers	X	X	X	X	X				X		
	Shredded tires	X		X	X					X		

demand reduction [26], and performance improvement of precooling strategies [27,130].

5.2. Development strategies

Exploring SIS types and concepts can help us understand how simple systems can ensure their components' maintenance, durability, cost, and availability. In Table 6, these types are categorized according to their application location within the building envelope and the complexity of the concept and operation. Some more straightforward examples of SISs include rotating panels, removable insulation, vertically sliding panels, roller blinds, and dynamic insulation-phase change material systems. On the other hand, more complex systems such as PLVTD, switchable vacuum insulation, and smart glazing rely on technologies such as suspended particle glazing, responsive film for smart windows, and optically switchable thermally insulating VO2-aerogel hybrid film.

Using Local Materials to develop switchable insulation systems offers several advantages, particularly in hot-climate developing countries where resources may be limited, and affordability is a significant concern. Various material options, available according to previous research conducted in that region, are proposed to address this issue.

- One approach is to use locally available materials such as *bio-based materials* like Agricultural By-products or residues [131] such as rice hulks [132,133], sugarcane bagasse [134,135], straw boards in Egypt [136], coconut husk in Malaysia [137,138], hemp fibers [139], date pits In Qatar and UAE [140,141], reed in Portugal [142] and pineapple by-product coming from the Mexican food industry [143]. Animal-based materials like sheep wool [92] are promising for using as bio-based materials. Earthen materials can be a suitable option, offering significant thermal mass and helping regulate indoor temperatures [144]. Thermal conductivity is typically the main focus of this material's investigated characterization. However, most research overlooks other crucial aspects of these materials, like their material certification, lifetime, thermal capacity, mechanical properties, and property degradation. Mechanical performance is significantly impacted by ancillary materials like binders and additives [101]. Furthermore, the shortcomings of bio-based insulation materials in buildings can be addressed by combining different types of biomaterials for insulation [145,146]. These limitations should be taken into consideration while using this approach.
- Another option is to promote the use of sustainable and recyclable materials like recycled waste glass [147], fly ash [148], plastic waste [149], sawdust [150], shredded used automobile tires [151], and waste paper [152]. However, using recyclable materials can enhance the circular economy [153], developing countries still have low recycling rates that need more attention to be more effective in an efficient circular economy. In low- and middle-income developing countries, the informal recycling sector (IRS) achieves 20–30 % recycling rates, reducing collection and disposal costs. The IRS plays a vital role in the value chain by reprocessing waste into secondary raw materials [154,155]. Developing countries in North Africa and the Middle East have a low rate of waste recovery (15 %) compared with developed countries (90 %) [156]. India has a complex scenario with a large IRS contributing to waste reuse and recycling, resulting in recycling rates of around 15 % at source and collection sites, while over 30 % of waste remains uncollected, with up to 70 % being dumped without control [157]. In La Paz, Bolivia, 56.1–71.1 % of inert aggregates from construction and demolition waste can be recycled [153].
- More *advanced innovative materials* that could be integrated into SISs might involve PCMs [158,159,160,161], nanomaterials such as Nanogel®Aerogel insulating material [162,163] and Nano-gel glass [164], and vacuum insulation panels (VIPs) [162]. Moreover, *composite materials* like cellulose-reinforced silica aerogel nanocomposites made of aerogel and straw composites [165], and cardboard waste mixed with vegetable fibers [166] have also been developed for eco-friendly insulation materials in developing countries, opening new opportunities to create more efficient ones. These materials and solutions enable cost-effective, eco-friendly, and sustainable manufacturing of SISs. They enhance thermal performance while contributing to environmental sustainability.

Several reviews presented characteristics of the previously mentioned available local materials in developing countries [3,16,79], as summarized in Table 7. It highlights that VIPs, nanomaterials, aerogel, waste glass, cellulose-reinforced silica aerogel nanocomposites, recycled PET, fly ash, sheep wool, and coconut fiber have the best performance, ranked in descending order of performance.

By analyzing previously mentioned SISs and examples of available materials options in developing countries, Table 8 presents a matrix showcasing integrations categorized into four areas, ranging from light green to darker shades, where lighter shades signify more effective integrations and darker shades denote less effective ones. Integrating all material options can be more effective with simple systems, which mostly can be applied to walls and roofs, than with advanced ones,

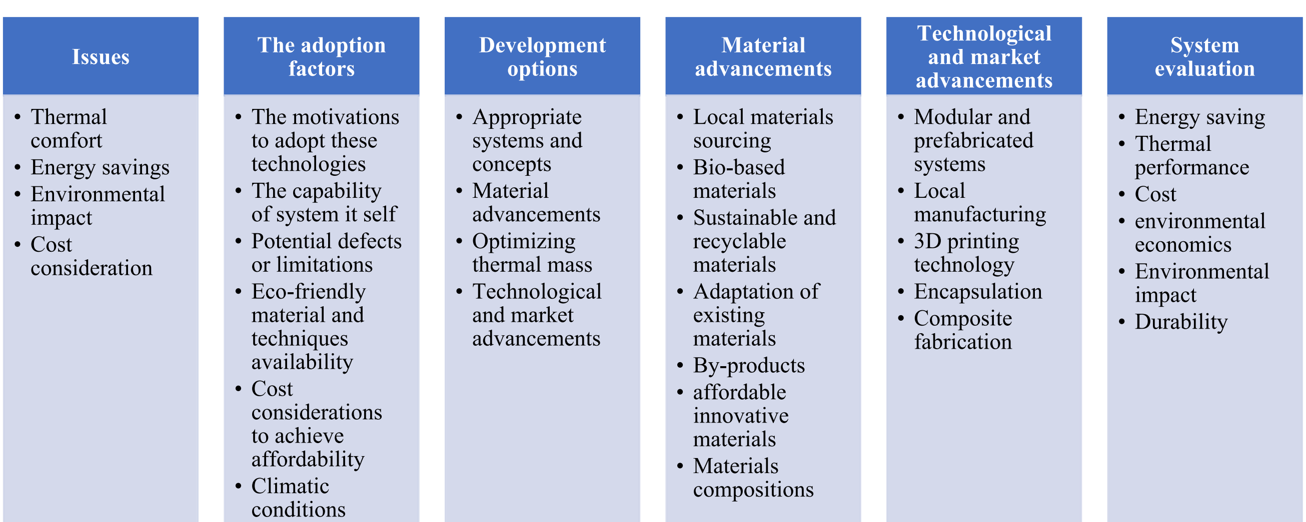

Fig. 27. The applicability framework for hot-climate developing regions.

which depend on innovative material compositions and more complicated mechanical movement. Particularly, the integration of high-performance materials is denoted by a red X. Taking affordability into account, integrating waste glass, recycled PET, fly ash, sheep wool, and coconut fiber into simple SISs (rotating panels, removable insulation, vertically sliding panel, Dynamic insulation-PCM system, and Roller blind) can offer a cost-effective and environmentally friendly SIS.

Technological advancements are vital in enhancing the applicability of affordable SISs. They can reduce costs and improve their sustainability for developing countries. Various strategies and solutions have been proposed to address this issue.

- *Moderate control technology* plays a vital role in determining the applicability of SISs depending on their level of complexity and sophistication. Rule-based control can be valuable in developing an affordable system, particularly where complexity is unnecessary or computational resources are limited.
- *Modular and Prefabricated* Systems allow for mass production of switchable insulation panels or coatings. These systems are easy to assemble and install, reducing labor costs and construction time. They can be customized to suit various building types and designs, making them compatible with existing structures and retrofit projects.
- *Local Manufacturing* can boost economic growth, reduce their reliance on imports, and reduce costs by encouraging the establishment of local manufacturing facilities for key components of SISs. Countries can reduce import dependence and strengthen their industrial base by investing in local production.
- *3D printing technology* allows customization of insulation components to meet specific building design needs, increasing energy efficiency and thermal performance. It also reduces waste during manufacturing by providing precise material control, contributing to resource conservation.
- *Encapsulation and composite fabrication* combine different materials to create insulation solutions with improved thermal insulation properties, flexibility, and durability. Composite materials can provide cost-effective and environmentally friendly alternatives to synthetic insulation using plant-based materials, agricultural and industrial by-products, and locally sourced resources.

Exploring appropriate SIS and incorporating technological advancements with locally available materials can help develop adaptive insulation systems designed to address specific challenges and requirements of hot-climate developing nations. Such strategies promote affordability, sustainability, and resilience in building construction, enhancing thermal comfort and energy efficiency in the built environment.

5.3. The applicability framework for developing an affordable, eco-friendly switchable insulation

Based on the abovementioned data analysis and literature review, the framework for adopting SISs in hot-climate developing countries is shown in Fig. 27. The framework shows issues, the adoption factors, development options, material advancements, technological and market advancements, and system evaluation to promote this concept locally.

6. Conclusion

Switchable insulation systems (SISs) are climate-adaptive building technologies that alter their thermal properties in response to environmental changes, leading to significant energy savings compared to static insulation. This paper presents a comprehensive review of SISs across three stages: a statistical analysis of existing literature, a systematic discussion of various SIS technologies, and an exploration of the feasibility of developing affordable, eco-friendly SISs for hot climate regions.

Key findings highlight the potential of SISs to enhance energy efficiency and thermal comfort in sustainable building envelopes. However, there is a notable gap in addressing SISs in developing countries, particularly in hot climates, necessitating further research to optimize these systems, reduce costs, and encourage widespread adoption. The study identifies essential factors for SIS implementation, including climatic adaptability, local material availability, cost, and technical advancement for installation and maintenance. The most significant development approach that has the potential to be followed to encourage SIS adoption in hot-climate developing countries includes integrating waste glass, recycled PET, fly ash, sheep wool, and coconut fiber into simple SISs (rotating panels, removable insulation, vertically sliding panel, insulation-PCM system, and Roller blind) to provide a low cost and environmentally friendly SIS, considering optimizing thermal mass and technological and market potentials (e.g., modular and prefabricated systems, local manufacturing, 3D printing technology, encapsulation, and composite fabrication) addressing energy saving, thermal performance, cost affordability, environmental impact, and durability.

In future work, it is recommended to focus on developing friendly environmental materials integrated within newly developed systems that align with the required adaptation needs in hot climate regions to enhance sustainability practices in developing countries, taking into consideration their long-term performance and resistance to environmental degradation. This will ensure that these materials can be reliably used in SIS systems, providing both sustainability and durability in building applications. Additionally, it is suggested to develop an optimization technique with low-cost and limited technologies. Furthermore, studying the sustainability performance of the new systems and investigating their effectiveness in the new context will influence advancing the adoption of SISs in developing countries.

CRediT authorship contribution statement

Alaa Salah: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis. **Sameh Nada:** Writing – review & editing, Supervision. **Hatem Mahmoud:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements The first author gratefully acknowledges the Egyptian Ministry of Higher Education and Scientific Research (MoHE) and the Cultural Affairs and Missions Sector for awarding the Ph.D. scholarship. Additionally, sincere appreciation is extended to Egypt-Japan University of Science and Technology (E-JUST) for its continuous support and for fostering a collaborative research environment.

Data availability

No data was used for the research described in the article.

Appendices

.

Table A1
Switchable Insulation Systems' articles focus on new concepts and systems.

Ref.	Type	Mech. Adjustability	Response mechanism	Research method	Simulation approach	Element type/ location	Prototype scale	Location	Applied building type	Time interval	Control type	Topology of movement	Actuation	Material	Performance enhancement	Solution approach
55	roller blind	dynamic insulation panels	Thermal responsive systems	simulation, experimental	IDA ICE software	windows	real scale	Dublin, Irland	test room	1 h	real-time	roller	"Nima 23" stepper motor, "Arduino" controller and motor driver, sensor (real-time)	foldable insulation material	a 15.3 % energy savings and a 7 % reduction in occupancy daylight discomfort compared with no blind.	A thermally insulated roller blind made of foldable material was mounted inside the windowpane. It uses a stepper motor, " controller, and motor driver. Side channels keep the blind close to the glass, while a top cover minimizes air leaks.
26	wall-integrated solid-state thermal switches	movable mechanical parts	Thermal responsive systems	experimental, simulation	EnergyPlus, COSMOL	opaque wall	bench-scale prototype	US, Los Angeles, California	residential	60 min	real-time	sliding	DC motor, sensors, thermistors (real-time)	insulation: off-the-shelf materials, core: Concrete as thermal storage	a reduction of energy consumption in HVAC by 3 % to 39 %, resulting in an estimated cost saving of $135 to $315.	using a concrete wall as thermal mass sandwiched between two solid-state thermal switches (STSs). These STSs change their thermal conductivity via an on/off metal switch to create/break a thermal bridge.
56	Horizontal planar Liquid-Vapour Thermal Diodes (PLVTD)	adjustable fluid flow system	Thermal responsive systems	Theoretical and experimental	——	ceiling	a lab scale of a large-scale prototype	Northern Ireland, UK	__	day and night	——	changing phase between fluid and vapor	condenser and evaporator (serpentine heat exchangers)	isothermal plates (stainless steel) & external isolation	——	thermal diodes
30	removable insulation	dynamic parts	for windows.: thermal, optical responsive system. For walls: thermal responsive system	theoretical, simulation, experimental	EnergyPlus & Energy Management System (EMS)	walls, windows	lab scale	Central Europe	office	24 h	simple and advanced control strategy	roller	motor to roll films	metalized PET films, Plexiglas® layers,	Switchable insulation reduces demands by 30 %. Reduce frame or edge losses for better performance.	A series of air-filled cavities separated by opaque films can be rolled up/down between two fixed layers, thus switching the thermal and optical properties

(*continued on next page*)

Table A1 (*continued*)

Ref.	Type	Mech. Adjustability	Response mechanism	Research method	Simulation approach	Element type/ location	Prototype scale	Location	Applied building type	Time interval	Control type	Topology of movement	Actuation	Material	Performance enhancement	Solution approach
																from a thermally insulating state to a conducting state.
57	multifunctional insulation	shapeshifting (may be adjustable properties)	thermal responsive systems	numerical	–——	wall	___	US	residential	–——	–——	filling polymers with air	–——	thin polymer membranes	_———	The wall has layers of air with membranes that reduce thermal convection. Heat transfers through the air layers via convection and radiation. The remaining resistance is due to conduction through the layers and membranes.
58,74	switchable insulation	dynamic insulation panels		simulation, experimental	TRNSYS	translucent facade	lab scale	Ludwigshafen, Germany.	office	biannual	__———	moving vertically	–——	Basotect	–——	The convection around a translucent insulation panel can be controlled by moving this panel vertically within the double-glazing unit.
28	switchable insulation	dynamic mechanical parts	Thermal responsive systems	numerical, experimental	COSMOL	wall	lab scale	US	residential	day and night	–——	movable blates with shape-changing	–——	Aluminum plates, shape memory alloy	annual energy savings of 9 %–55 % (heating) and 17 %–76 % (air conditioning), depending on the climate zone.	Device structure: The bridge plate connects two TIM rectangles in the "on" state and separates them in the "off" state.
29	rotating switchable insulation	dynamic panels	Thermal responsive systems	experimental, numerical	FLUENT	wall	lab scale	US	–——	–——	–——	rotating	DC voltage actuator	polyisocyanurate foam insulation	reduction of over 50 % of the wall R-value when the insulation layers no longer overlap	The dynamic insulation system comprises rotating layers that vary the R-value of a wall cavity between high and low levels depending on

(*continued on next page*)

Table A1 (*continued*)

Ref.	Type	Mech. Adjustability	Response mechanism	Research method	Simulation approach	Element type/ location	Prototype scale	Location	Applied building type	Time interval	Control type	Topology of movement	Actuation	Material	Performance enhancement	Solution approach
																its rotation angle. An actuator is used to control the position of the insulation layers based on a set of control strategies to achieve the desired R-value.
32	suspended particle device switchable glazing	dynamic parts	thermal for the application (window), electrical for the concept	experimental	–——	windows	lab scale	Dublin, Irland	–——	hourly	–——	optical properties changes	power switch connected to a power supply	polyhalide particles	SPD glazing in both “opaque (O)” and ”transparent (T)” conditions limits the temperature rise. The SPD transmission in” T” and “O” is 55 % and 5 %, respectively (double glazing was 78 %).	SPD glazing allows light to pass through. The switching voltage is proportionate to the glazing area and typically varies between 20–110 V. Transmission range of SPD in visible wavelength varies from usually 20–60 %, 10–50 %, and 0.1–10 %, for the “opaque and transparent” states while switching speed varies between 100–200 m s

Table A2
Switchable Insulation Systems' articles focus on materials.

Ref.	Type	Mech. Adjustability	Response mechanism	Research method	Simulation approach	Element type/ location	Prototype scale	Location	Applied building type	Time interval	Control type	Topology of movement	Actuation	Material	Performance enhancement	Solution approach
35	dynamic insulation-phase change material system.	Adjustable properties systems	Thermal responsive systems	Theoretical, numerical, simulation, and experimental for validation	COSMOL	hollow wall	lab scale	China	———	———	———	phase changing	———	wallboard, brick, PCM	———	The PCM layer is surrounded by air on both sides to enhance the heat transfer of airflow. The PCM area is reduced, and two airstrips are created at the top and bottom. A forced turbulent PCM module is established by introducing an electric fan, which can increase the airflow magnitude and precisely control the airflow.
60	responsive film for smart window	Adjustable properties systems	Thermal, electrical responsive systems	experimental	———	window	lab scale	China	———	———	———	optical properties changes	———	CsxWO3 nanocrystals into the organic PDLC system.	———	The as-made cell can adjust the transmission of solar light to the temperature of the electric field. The transparent state obtained in an electric field's presence can satisfy the illumination demand. The transparent state due to the phase transition of the liquid crystal can act as a reminder of high temperatures, and people can actively lower their room temperature on hot days.
62	numerous applications, one of them being switchable vacuum insulation	Adjustable properties systems	Thermal responsive systems	numerical	———	wall	———	Germany	———	———	———	gas pressure differences	———	Precipitated silica, silica gel, and glass spheres	———	Vacuum Insulation Panels primarily use fumed silica as the core material, which is quite

(*continued on next page*)

Table A2 (*continued*)

Ref.	Type	Mech. Adjustability	Response mechanism	Research method	Simulation approach	Element type/ location	Prototype scale	Location	Applied building type	Time interval	Control type	Topology of movement	Actuation	Material	Performance enhancement	Solution approach
																expensive. To cut off costs, cheaper filler materials or waste materials can be added to the fumed silica. Additionally, alternative materials such as foams or fibers may also be used. Precipitated silica, for instance, is a cheaper core material that could be a viable alternative.
61	Optically switchable thermally insulating VO_2-aerogel hybrid film (thermochromic film)	adjustable properties systems	Thermal responsive systems	theoretical	–——	window	–——	Norway	___———	hourly	–—	optical properties changes	__———	VO2-aerogel	–——	By embedding insulator–metal phase transition vanadium dioxide (VO2) nanoparticles inside an ultralow thermal conductivity aerogel film
77	Switchable vacuum insulation panel	adjustable properties systems	Thermal responsive systems	Theoretical, experimental, and numerical	MATLAB	–——	Lab scale	–——	–——	–——	–——	gas pressure differences	pressure sensor, computer, vacuum pump, the storage of the gas, compressor	core materials (silica powder, silica agglomerates, silica gel), filling gases (air, nitrogen helium)	Silica gel and helium as filling gas yielded the best results with high heat conductivity difference between evacuated and aerated conditions.	Switching VIPs using filling gas to alter their state. The best alternative was tested for different core materials and filing gas combinations.

Table A3
Switchable Insulation Systems' articles focus on control strategies.

Ref.	Type	Mech. Adjustability	Response mechanism	Research method	Simulation approach	Element type/ location	Prototype scale	Location	Applied building type	Time interval	Control type	Topology of movement	Actuation	Material	Performance enhancement
59	rotating switchable insulation	dynamic insulation panels	thermal, optical responsive system.	simulation	MATLAB	smart windows	—	Golden, CO, US	residential	hour	GA algorithms	rotating	—	monolithic silica aerogels (MSA) with high transmittance properties for both light and solar radiation	that optimized controls of STISs can save up to 81.8 % in daily thermal loads compared to the simplified rule-set, especially in hot climates like Phoenix, AZ. optimally controlled STISs can reduce electrical peak demand by up to 49.8 % compared to the simplified rule-set.
25	rotating switchable insulation	dynamic insulation panels	Thermal responsive systems	simulation	—	roof or attic	—	US	residential	seasonal	2-step temperature rule-based control, GA-based optimal controls	—	—	—	GA-based optimal controls save between 3 % and 9 % in cooling energy end-use and 1 % to 18 % in peak cooling demand compared to 2-step rule sets, with monthly savings reaching up to 32 % in Golden, residential buildings.
47	rotating switchable insulation	dynamic insulation panels	Thermal responsive systems	simulation	EnergyPlus, EMS, MATLAB	attic	—	US	residential	hour	2-step time scheduled controls, step temperature-based controls, genetic algorithm (GA) optimization technique	rotating	—	—	Controls based on mean air and sol–air temperatures can save 8 % to 43 % in cooling energy for all US climates. Optimal controls for attic dynamic insulation systems can achieve up to 40 % additional savings in cooling energy compared to simplified controls

(*continued on next page*)

Table A3 (*continued*)

Ref.	Type	Mech. Adjustability	Response mechanism	Research method	Simulation approach	Element type/ location	Prototype scale	Location	Applied building type	Time interval	Control type	Topology of movement	Actuation	Material	Performance enhancement
50	Dynamic insulation material	Adjustable properties systems	Thermal responsive systems	simulation	EnergyPlus	wall	—	Golden, Colorado, USA	residential	—	temperature 2-step control & multi-step control	gas fill	—	static insulation assemblies (e.g., XPS, VIPs, GIPs),	Variable thermal resistance envelope materials (RSI-0.5/RSI-2.5) can cut cooling energy use by 15–39 % in US homes, regardless of the climate. Mild US climates can also lower annual heating energy use by up to 10 %, depending on window size and indoor heat.
218,219	Multiple options	Multiple options	—	theoretical, simulation	EnergyPlus	envelope	—	UK, China	office	—	MPC	—	—	Multiple options	yearly energy savings and thermal comfort improvements of up to 50 % could be achieved by adaptive insulation compared to an equivalent astatic insulation alternative.
130	rotating switchable insulation	dynamic insulation panels	Thermal responsive systems	simulation	EnergyPlus, MATLAB	roof	—	US	commercial	—	Hyperid control	rotating	—	—	optimal controls reduce total energy use by up to 19 % and electrical peak demand by up to 34 %.

Table A4
Switchable Insulation Systems' articles focus on building applications.

Ref.	Type	Mech. Adjustability	Response mechanism	Research method	Simulation approach	Element type/ location	Prototype scale	Location	Applied building type	Time interval	Control type	Topology of movement	Actuation	Material	Performance enhancement
37	rotating switchable insulation	dynamic insulation panels	Thermal responsive systems	numerical modeling and simulation	MATLAB and EnergyPlus	slab	—	US	residential	—	—	rotating	—	—	slab-integrated dynamic insulation can reduce heating energy by 10 % and cooling energy by 39 %, and total heating, ventilating, and air conditioning end-use by up to 12 %, especially for houses located in cold climates
98	rotating switchable insulation	dynamic insulation panels	Thermal responsive systems	simulation	EnergyPlus	attic	—	US	residential		2-Step temperature-based controls	—	—	—	the potential energy savings achieved by attic-integrated SIS insulation retrofit vary widely by climate ranging from 14 kWh/m2 to 51 kWh/m2 the annual energy cost savings when replacing the existing insulation with attic-integrated SIS range from $0.05/m2 to $1.57/m2 depending on the climate
167	rotating switchable insulation	dynamic insulation panels	thermal, optical responsive system.	simulation	MATLAB (for modeling), EnergyPlus (for validation)	exterior wall and windows	—	European countries, including Belgium and Spain	residential	seasonal	simple 2-step rule sets (for win)	rotating	—	not mentioned, just high and low R-value	SIS-integrated windows can save up to 44 % of heating energy end-use and eliminate mechanical cooling for all types of dwellings in Belgium.
75	Vertical Planar Liquid-Vapour Thermal Diodes (PLVTD)	adjustable fluid flow system	Thermal responsive systems	theoretical, experimental	—	wall	a lab scale of a large-scale prototype PLVTD	Northern Ireland, UK	—	day and night	—	changing phase between fluid and vapor	—	—	—

(*continued on next page*)

Table A4 (*continued*)

Ref.	Type	Mech. Adjustability	Response mechanism	Research method	Simulation approach	Element type/ location	Prototype scale	Location	Applied building type	Time interval	Control type	Topology of movement	Actuation	Material	Performance enhancement
27	rotating switchable insulation	dynamic insulation panels & thermal storage	Thermal responsive systems	simulation	Energyplusand EMS	roof, wall	—	US	commercial		temperature-based control & optimisation strategies	rotating	—	—	SIS saves annual heating and cooling energy end-uses reaching up to 65 % and 25 %, respectively
168	rotating switchable insulation	dynamic insulation panels	Thermal responsive systems	simulation	MATLAB, EnergyPlus	wall	—	Belgium, UN	residential	15 min	simple 2-step rule-based control	rotating	—	A layer of bricks or concrete with high thermal mass	The estimated potential energy savings range from 1.1 % to 3.7 % for space heating and 53.1 % to 98.7 % for cooling, depending on the dwelling type and location.
33	rotating switchable insulation	dynamic insulation panels	thermal, optical responsive system.	simulation	EnergyPlus, EMS	wall, roof, windows, opaque and translucent	—	US	office	seasonal,	—	rotating	manual & automatic	—	Advanced Energy Technologies (AETs) use in cold climates leads to the highest cooling energy savings (72 % and 70 %), followed by EL Paso and Tucson. However, in hot climates, AETs can achieve higher absolute savings (50,011 kWh) and reduce building electrical peak demand by up to 37 %.
34	rotating switchable insulation	dynamic insulation panels	Thermal responsive systems	simulation	EnergyPlus	roof/ ceiling	—	US	residential	60-min and 15-min	two-step control strategy	—	—	—	The deployment of 2-step control strategies operating SISs can reduce annual energy use by up to 44 % for space cooling and up to 17 % for space heating.
81	rotating switchable insulation	dynamic insulation panels	thermal, optical responsive system.	simulation	MATLAB, EnergyPlus	exterior wall and windows	—	France	residential	15 min	2-step control	rotating	—	mineral wool	63 % of annual energy savings associated to heating and cooling for a detached house and 82 % for an apartment unit.

References

[1] Á. Lakatos, Novel Thermal Insulation Materials for Buildings, Energies vol. 15, no. 18, Art. no. 18 (Jan. 2022), https://doi.org/10.3390/en15186713.

[2] D. Kaya, F. Çanka Kılıç, and H. H. Öztürk, "Energy Saving with Heat Insulation," in *Energy Management and Energy Efficiency in Industry: Practical Examples*, D. Kaya, F. Çanka Kılıç, and H. H. Öztürk, Eds., in Green Energy and Technology. , Cham: Springer International Publishing, 2021, pp. 443–462. doi: 10.1007/978-3-030-25995-2_16.

[3] S. Schiavoni, F. D'Alessandro, F. Bianchi, and F. Asdrubali, "Insulation materials for the building sector: A review and comparative analysis," *Renew. Sustain. Energy Rev.*, vol. 62, pp. 988–1011, Sep. 2016, doi: 10.1016/j.rser.2016.05.045.

[4] Ö. Agra, S. özgUr Atayilmaz, H. Demir, and I. Teke, "Environmental Impact of Optimum Insulation Thickness in Buildings", presented at the World Renewable Energy Congress – Sweden, 8–13 May, Linköping, Sweden, Nov. 2011 (2011) 1813–1820, https://doi.org/10.3384/ecp110571813.

[5] I. Nardi, S. Perilli, T. De Rubeis, S. Sfarra, D. Ambrosini, Influence of insulation defects on the thermal performance of walls. An experimental and numerical investigation, J. Build. Eng. 21 (Jan. 2019) 355–365, https://doi.org/10.1016/j.jobe.2018.10.029.

[6] V. Petránek, et al., "Thermal bridges in insulation systems", in *Adv*, Mater. Res. (2013) 182–185, https://doi.org/10.4028/www.scientific.net/AMR.732-733.182.

[7] J.-H. Song, S.-H. Park, M.-J. Park, J.-H. Lim, S.-Y. Song, Influence of Thermal Bridges on the Insulation Performance of Curtain Wall Panel Systems, J. Asian Archit. Build. Eng. 14 (3) (Sep. 2015) 741–748, https://doi.org/10.3130/jaabe.14.741.

[8] J.-H. Song, J.-H. Lim, S.-Y. Song, Evaluation of alternatives for reducing thermal bridges in metal panel curtain wall systems, Energy Build. 127 (Sep. 2016) 138–158, https://doi.org/10.1016/j.enbuild.2016.05.078.

[9] S. M. Cascone, S. Cascone, and M. Vitale, "Building Insulating Materials from Agricultural By-Products: A Review," in *Sustainability in Energy and Buildings*, vol. 163, J. Littlewood, R. J. Howlett, A. Capozzoli, and L. C. Jain, Eds., in Smart Innovation, Systems and Technologies, vol. 163. , Singapore: Springer Singapore, 2020, pp. 309–318. doi: 10.1007/978-981-32-9868-2_26.

[10] X. Li, Y. Zhang, D. Li, Y. Xu, R.D. Brown, Ameliorating cold stress in a hot climate: Effect of Winter Storm Uri on residents of subsidized housing neighborhoods, Build. Environ. 209 (Feb. 2022) 108646, https://doi.org/10.1016/j.buildenv.2021.108646.

[11] M.E. Abdalazeem, H. Hassan, T. Asawa, H. Mahmoud, Impact of windbreak design on microclimate in hot regions during cold waves: Numerical investigation, Int. J. Biometeorol. 68 (7) (Jul. 2024) 1315–1326, https://doi.org/10.1007/s00484-024-02668-8.

[12] X. Wang, Y. Fang, W. Cai, C. Ding, Y. Xie, Heating demand with heterogeneity in residential households in the hot summer and cold winter climate zone in China -A quantile regression approach, Energy 247 (May 2022) 123462, https://doi.org/10.1016/j.energy.2022.123462.

[13] X. Cao, et al., Energy-quota-based integrated solutions for heating and cooling of residential buildings in the Hot Summer and Cold Winter zone in China, Energy Build. 236 (Apr. 2021) 110767, https://doi.org/10.1016/j.enbuild.2021.110767.

[14] F. Stazi, E. Tomassoni, C. Di Perna, Super-insulated wooden envelopes in Mediterranean climate: Summer overheating, thermal comfort optimization, environmental impact on an Italian case study, Energy Build. 138 (Mar. 2017) 716–732, https://doi.org/10.1016/j.enbuild.2016.12.042.

[15] B. Abu-Jdayil, A.-H. Mourad, W. Hittini, M. Hassan, S. Hameedi, Traditional, state-of-the-art and renewable thermal building insulation materials: An overview, Constr. Build. Mater. 214 (Jul. 2019) 709–735, https://doi.org/10.1016/j.conbuildmat.2019.04.102.

[16] D. Kumar, M. Alam, P.X.W. Zou, J.G. Sanjayan, R.A. Memon, Comparative analysis of building insulation material properties and performance, Renew. Sustain. Energy Rev. 131 (Oct. 2020) 110038, https://doi.org/10.1016/j.rser.2020.110038.

[17] F. Balo, L.S. Sua, "Strategic Evaluation and Selection for Energy-Effective Natural Fibers as Alternative Sustainable Insulation Materials for Green Building Envelope", in *Handbook of Sustainable Materials: Modelling, Characterization, and Optimization*, CRC Press, 2023.

[18] J. Hu, X. Yu, Thermo and light-responsive building envelope: Energy analysis under different climate conditions, Sol. Energy 193 (Nov. 2019) 866–877, https://doi.org/10.1016/j.solener.2019.10.021.

[19] T. Yan, J. Gao, X. Xu, T. Xu, Z. Ling, J. Yu, Dynamic simplified PCM models for the pipe-encapsulated PCM wall system for self-activated heat removal, Int. J. Therm. Sci. 144 (Oct. 2019) 27–41, https://doi.org/10.1016/j.ijthermalsci.2019.05.015.

[20] M. Fawaier, B. Bokor, Dynamic insulation systems of building envelopes: A review, Energy Build. 270 (Sep. 2022) 112268, https://doi.org/10.1016/j.enbuild.2022.112268.

[21] S.J.M. Koenders, R.C.G.M. Loonen, J.L.M. Hensen, Investigating the potential of a closed-loop dynamic insulation system for opaque building elements, Energy Build. 173 (2018) 409–427, https://doi.org/10.1016/j.enbuild.2018.05.051.

[22] A. Karanafti, T. Theodosiou, K. Tsikaloudaki, Assessment of buildings' dynamic thermal insulation technologies-A review, Appl. Energy 326 (Nov. 2022) 119985, https://doi.org/10.1016/j.apenergy.2022.119985.

[23] T.R. Stevens, N.B. Crane, R.B. Mulford, Topology Morphing Insulation: A Review of Technologies and Energy Performance in Dynamic Building Insulation, Energies 16 (19) (Oct. 2023) 6978, https://doi.org/10.3390/en16196978.

[24] Y. Zhang, G. Ma, G. Wu, S. Liu, L. Gao, Thermally adaptive walls for buildings applications: A state of the art review, Energy Build. 271 (2022), https://doi.org/10.1016/j.enbuild.2022.112314.

[25] A.H.A. Dehwah, M. Krarti, "Optimal Control Strategies for Switchable Roof Insulation Systems Applied to US Residential Buildings", *J. Eng. Sustain. Build*, Cities 1 (4) (2020) pp, https://doi.org/10.1115/1.4048561.

[26] N. Kunwar, M. Salonvaara, E. Iffa, S. Shrestha, D. Hun, Performance assessment of active insulation systems in residential buildings for energy savings and peak demand reduction, Appl. Energy 348 (Oct. 2023) 121209, https://doi.org/10.1016/j.apenergy.2023.121209.

[27] A.H.A. Dehwah, M. Krarti, Performance of precooling strategies using switchable insulation systems for commercial buildings, Appl. Energy 303 (2021), https://doi.org/10.1016/j.apenergy.2021.117631.

[28] R. Miao, R. Kishore, S. Kaur, R. Prasher, C. Dames, A non-volatile thermal switch for building energy savings, Cell Rep. Phys. Sci. 3 (7) (2022) pp, https://doi.org/10.1016/j.xcrp.2022.100960.

[29] M. Dabbagh, M. Krarti, Evaluation of the performance for a dynamic insulation system suitable for switchable building envelope, Energy Build. 222 (2020), https://doi.org/10.1016/j.enbuild.2020.110025.

[30] T. Pflug, B. Bueno, M. Siroux, T.E. Kuhn, Potential analysis of a new removable insulation system, Energy Build. 154 (2017) 391–403, https://doi.org/10.1016/j.enbuild.2017.08.033.

[31] M. Gutai, A.G. Kheybari, Energy consumption of hybrid smart water-filled glass (SWFG) building envelope, Energy Build. 230 (2021), https://doi.org/10.1016/j.enbuild.2020.110508.

[32] A. Ghosh, B. Norton, A. Duffy, Measured overall heat transfer coefficient of a suspended particle device switchable glazing, Appl. Energy 159 (Dec. 2015) 362–369, https://doi.org/10.1016/j.apenergy.2015.09.019.

[33] A.H.A. Dehwah, M. Krarti, Energy performance of integrated adaptive envelope technologies for commercial buildings, J. Build. Eng. 63 (Jan. 2023) 105535, https://doi.org/10.1016/j.jobe.2022.105535.

[34] A.H.A. Dehwah, M. Krarti, Impact of switchable roof insulation on energy performance of US residential buildings, Build. Environ. 177 (Jun. 2020) 106882, https://doi.org/10.1016/j.buildenv.2020.106882.

[35] Z. Zhang, N. Zhang, Y. Yuan, P.E. Phelan, S. Attia, Thermal performance of a dynamic insulation-phase change material system and its application in multilayer hollow walls, J. Energy Storage 62 (2023), https://doi.org/10.1016/j.est.2023.106912.

[36] E. Iffa, D. Hun, M. Salonvaara, S. Shrestha, M. Lapsa, Performance evaluation of a dynamic wall integrated with active insulation and thermal energy storage systems, J. Energy Storage 46 (Feb. 2022) 103815, https://doi.org/10.1016/j.est.2021.103815.

[37] R. Rajabi, A.H.A. Dehwah, M. Krarti, "Impact of Dynamic Slab Insulation on Energy Performance of Residential Buildings", *J. Eng. Sustain. Build*, Cities 3 (4) (2022) pp, https://doi.org/10.1115/1.4056168.

[38] K. Menyhart, M. Krarti, Potential energy savings from deployment of Dynamic Insulation Materials for US residential buildings, Build. Environ. 114 (2017) 203–218, https://doi.org/10.1016/j.buildenv.2016.12.009.

[39] L.D. Hung Anh, Z. Pásztory, An overview of factors influencing thermal conductivity of building insulation materials, J. Build. Eng. 44 (Dec. 2021) 102604, https://doi.org/10.1016/j.jobe.2021.102604.

[40] S.W. Sharshir, et al., Thermal energy storage using phase change materials in building applications: A review of the recent development, Energy Build. 285 (Apr. 2023) 112908, https://doi.org/10.1016/j.enbuild.2023.112908.

[41] M. Sawadogo, M. Duquesne, R. Belarbi, A.E.A. Hamami, A. Godin, Review on the Integration of Phase Change Materials in Building Envelopes for Passive Latent Heat Storage, Appl. Sci. vol. 11, no. 19, Art. no. 19 (Jan. 2021), https://doi.org/10.3390/app11199305.

[42] W. Villasmil, L.J. Fischer, J. Worlitschek, A review and evaluation of thermal insulation materials and methods for thermal energy storage systems, Renew. Sustain. Energy Rev. 103 (Apr. 2019) 71–84, https://doi.org/10.1016/j.rser.2018.12.040.

[43] L. Aditya, et al., A review on insulation materials for energy conservation in buildings, Renew. Sustain. Energy Rev. 73 (Jun. 2017) 1352–1365, https://doi.org/10.1016/j.rser.2017.02.034.

[44] H. Ajabli, A. Zoubir, R. Elotmani, M. Louzazni, K. Kandoussi, A. Daya, Review on Eco-friendly insulation material used for indoor comfort in building, Renew. Sustain. Energy Rev. 185 (2023), https://doi.org/10.1016/j.rser.2023.113609.

[45] P. Raja, et al., A Review of Sustainable Bio-Based Insulation Materials for Energy-Efficient Buildings, Macromol. Mater. Eng. 308 (10) (2023) 2300086, https://doi.org/10.1002/mame.202300086.

[46] K.S.D. Chandhran, S. Elavenil, A comprehensive state-of-the-art review of sustainable thermal insulation system used in external walls for reduction in energy consumption in buildings, Int. J. Green Energy 20 (9) (Jul. 2023) 895–913, https://doi.org/10.1080/15435075.2022.2120769.

[47] A.H.A. Dehwah, M. Krarti, Control strategies for switchable roof insulation systems applied to US residential homes, Energy Build. 231 (Jan. 2021) 110649, https://doi.org/10.1016/j.enbuild.2020.110649.

[48] A. De Gracia, J. Tarragona, A. Crespo, C. Fernández, Smart control of dynamic phase change material wall system, Appl. Energy 279 (Dec. 2020) 115807, https://doi.org/10.1016/j.apenergy.2020.115807.

[49] V. Shekar, M. Krarti, Control strategies for dynamic insulation materials applied to commercial buildings, Energy Build. 154 (2017) 305–320, https://doi.org/10.1016/j.enbuild.2017.08.084.

[50] S. Rupp, M. Krarti, Analysis of multi-step control strategies for dynamic insulation systems, Energy Build. 204 (2019), https://doi.org/10.1016/j.enbuild.2019.109459.
[51] M.-S.-E. Imbabi, A passive–active dynamic insulation system for all climates, Int. J. Sustain. Built Environ. 1 (2) (2012) 247–258, https://doi.org/10.1016/j.ijsbe.2013.03.002.
[52] H. Cui, M. Overend, A review of heat transfer characteristics of switchable insulation technologies for thermally adaptive building envelopes, Energy Build. 199 (Sep. 2019) 427–444, https://doi.org/10.1016/j.enbuild.2019.07.004.
[53] H.-N. Su, P.-C. Lee, Mapping knowledge structure by keyword co-occurrence: a first look at journal papers in Technology Foresight, Scientometrics 85 (1) (Oct. 2010) 65–79, https://doi.org/10.1007/s11192-010-0259-8.
[54] "VOSviewer - Visualizing scientific landscapes," VOSviewer. Accessed: May 05, 2024. [Online]. Available: https://www.vosviewer.com//.
[55] H. Alkhatib, P. Lemarchand, B. Norton, D.T.J. O'Sullivan, Optimal temperature-actuated control of a thermally-insulated roller blind, Build. Environ. 244 (2023), https://doi.org/10.1016/j.buildenv.2023.110751.
[56] A. Pugsley, A. Zacharopoulos, J. Deb Mondol, and M. Smyth, "Theoretical and experimental analysis of a horizontal planar Liquid-Vapour Thermal Diode (PLVTD)," *Int. J. Heat Mass Transf.*, vol. 144, p. 118660, Dec. 2019, doi: 10.1016/j.ijheatmasstransfer.2019.118660.
[57] M. Kimber, W.W. Clark, L. Schaefer, Conceptual analysis and design of a partitioned multifunctional smart insulation, Appl. Energy 114 (2014) 310–319, https://doi.org/10.1016/j.apenergy.2013.09.067.
[58] T. Pflug, T.E. Kuhn, R. Nörenberg, A. Glück, N. Nestle, C. Maurer, Closed translucent façade elements with switchable U-value - A novel option for energy management via the facade, Energy Build. 86 (2015) 66–73, https://doi.org/10.1016/j.enbuild.2014.09.082.
[59] M. Dabbagh and M. Krarti, "Optimal control strategies for switchable transparent insulation systems applied to smart windows for us residential buildings," *Energies*, vol. 14, no. 10, 2021, doi: 10.3390/en14102917.
[60] Z. He, et al., A temperature and electric field responsive flexible hybrid composite film containing CsxWO3 nanocrystals for energy efficient smart window, Sol. Energy 265 (2023), https://doi.org/10.1016/j.solener.2023.112051.
[61] X. Zhao, S.A. Mofid, B.P. Jelle, G. Tan, X. Yin, R. Yang, Optically-switchable thermally-insulating VO2-aerogel hybrid film for window retrofits, Appl. Energy 278 (2020), https://doi.org/10.1016/j.apenergy.2020.115663.
[62] S. Sonnick, H. Nirschl, M. Rädle, Silica-based core materials for thermal superinsulations in various applications, Int. J. Energy Res. 46 (13) (2022) 18394–18409, https://doi.org/10.1002/er.8453.
[63] D. Reisman, "The developing countries," in *Global Political Economy*, Edward Elgar Publishing, 2023, pp. 113–132. Accessed: Jan. 21, 2024. [Online]. Available: https://www.elgaronline.com/monochap/book/9781035307418/book-part-9781035307418-11.xml.
[64] D. Kolokotsa, J. Yang, and L. Siew Eang, "5.20 Energy Management in University Campuses," in *Comprehensive Energy Systems*, I. Dincer, Ed., Oxford: Elsevier, 2018, pp. 808–826. doi: 10.1016/B978-0-12-809597-3.00540-X.
[65] S. Attaway, "Chapter 1 - Introduction to MATLAB," in *MATLAB (Fifth Edition)*, S. Attaway, Ed., Butterworth-Heinemann, 2019, pp. 3–35. doi: 10.1016/B978-0-12-815479-3.00001-5.
[66] "COMSOL: Multiphysics Software for Optimizing Designs," COMSOL. Accessed: Feb. 14, 2024. [Online]. Available: https://www.comsol.com/.
[67] A. Dahash, F. Ochs, and A. Tosatto, "Co-Simulation of Dynamic Energy System Simulation and COMSOL Multiphysics®".
[68] "DesignBuilder Software Ltd - Home." Accessed: Feb. 14, 2024. [Online]. Available: https://designbuilder.co.uk/.
[69] "Window Software Downloads | Windows & Daylighting." Accessed: Feb. 14, 2024. [Online]. Available: https://windows.lbl.gov/window-software-downloads.
[70] D.C. Curcija, et al., "Berkeley Lab WINDOW", Lawrence Berkeley National Laboratory (LBNL), Berkeley, CA (United States), BERKELEY LAB WINDOW (Mar. 2015), https://doi.org/10.11578/dc.20210416.62.
[71] "IDA ICE - Simulation Software | EQUA." Accessed: Feb. 14, 2024. [Online]. Available: https://www.equa.se/en/ida-ice.
[72] "Ansys Fluent | Fluid Simulation Software." Accessed: Feb. 15, 2024. [Online]. Available: https://www.ansys.com/products/fluids/ansys-fluent.
[73] M. KRARTI, "Dynamic insulation system for switchable building envelope," WO2021021884A2, Feb. 04, 2021 Accessed: Feb. 06, 2024. [Online]. Available: https://patents.google.com/patent/WO2021021884A2/en.
[74] T. Pflug, N. Nestle, T.E. Kuhn, M. Siroux, C. Maurer, Modeling of facade elements with switchable U-value, Energy Build. 164 (2018) 1–13, https://doi.org/10.1016/j.enbuild.2017.12.044.
[75] A. Pugsley, A. Zacharopoulos, J. Deb Mondol, and M. Smyth, "Vertical Planar Liquid-Vapour Thermal Diodes (PLVTD) and their application in building façade energy systems," *Appl. Therm. Eng.*, vol. 179, 2020, doi: 10.1016/j.applthermaleng.2020.115641.
[76] S. J. Chang, Y. Kim, G. Seok Choi, S. Wi, Y. Kang, and S. Kim, "Effective thermal performance analysis of vacuum insulation panel with metal-less film and infrared-dried core material," *Energy Build.*, vol. 233, p. 110684, Feb. 2021, doi: 10.1016/j.enbuild.2020.110684.
[77] L. Erlbeck, S. Sonnick, D. Wössner, H. Nirschl, M. Rädle, Impact of aeration and deaeration of switchable vacuum insulations on the overall heat conductivity using different core materials and filling gases, Int. J. Energy Environ. Eng. 11 (4) (2020) 395–404, https://doi.org/10.1007/s40095-020-00356-y.
[78] 卡拉姆雷蒙米勒, "Electrowetting devices with suspended particles 具有懸浮粒子的電潤濕設備," TW202011075A, Mar. 16, 2020 Accessed: Feb. 18, 2024. [Online]. Available: https://patents.google.com/patent/TW202011075A/en?q=(%22Electrowetting+devices+with+suspended+particles%22)&oq=%22Electrowetting+devices+with+suspended+particles%22.
[79] F. Asdrubali, F. D'Alessandro, S. Schiavoni, A review of unconventional sustainable building insulation materials, Sustain. Mater. Technol. 4 (Jul. 2015) 1–17, https://doi.org/10.1016/j.susmat.2015.05.002.
[80] A.R. Hassani, P. Domenighini, E. Belloni, T. Ihara, C. Buratti, Evaluation of the solar heat gain coefficient of innovative aerogel glazing systems: Experimental campaigns and numerical results, J. Build. Eng. 62 (Dec. 2022) 105354, https://doi.org/10.1016/j.jobe.2022.105354.
[81] L. Valentin, M. Dabbagh, M. Krarti, Benefits of switchable insulation systems for residential buildings in France, Energy Build. 259 (2022), https://doi.org/10.1016/j.enbuild.2022.111868.
[82] Y. Yang, S. Chen, Thermal insulation solutions for opaque envelope of low-energy buildings: A systematic review of methods and applications, Renew. Sustain. Energy Rev. 167 (Oct. 2022) 112738, https://doi.org/10.1016/j.rser.2022.112738.
[83] D. Kumar, M. Alam, J.G. Sanjayan, Retrofitting Building Envelope Using Phase Change Materials and Aerogel Render for Adaptation to Extreme Heatwave: A Multi-Objective Analysis Considering Heat Stress, Energy, Environment, and Cost, Sustainability 13 (19) (Sep. 2021) 10716, https://doi.org/10.3390/su131910716.
[84] R.A. Kishore, M.V.A. Bianchi, C. Booten, J. Vidal, R. Jackson, Enhancing building energy performance by effectively using phase change material and dynamic insulation in walls, Appl. Energy 283 (2021), https://doi.org/10.1016/j.apenergy.2020.116306.
[85] W. Shen, G. Li, Recent Progress in Liquid Crystal-Based Smart Windows: Materials, Structures, and Design, Laser Photonics Rev. 17 (1) (2023) 2200207, https://doi.org/10.1002/lpor.202200207.
[86] R. Zhang, et al., Advanced liquid crystal-based switchable optical devices for light protection applications: principles and strategies, Light Sci. Appl. 12 (1) (Jan. 2023) 11, https://doi.org/10.1038/s41377-022-01032-y.
[87] B.-S. Kim, et al., A Novel Process for Manufacturing Vanadium Dioxide(VO2) as a resource of Vanadium Electrolyte from Vanadium Pentoxide(V2O5), Geosystem Eng. 25 (3–4) (Jul. 2022) 202–207, https://doi.org/10.1080/12269328.2022.2156398.
[88] F. Scotognella, Vanadium oxide metal-insulator phase transition in different types of one-dimensional photonic microcavities, Front. Photonics 4 (Mar. 2023), https://doi.org/10.3389/fphot.2023.1081521.
[89] M. Qiu, T. Huang, W. Yang, R. Zhang, X. Chen, N. Dai, Polymorphous Dimer Chain-Dependent Structural Evolution and Phase-Change Electronic Switching in Triclinic Vanadium Dioxide, J. Phys. Chem. C 127 (16) (Apr. 2023) 7823–7828, https://doi.org/10.1021/acs.jpcc.3c00194.
[90] I. Chopra and J. Sirohi, Eds., "Shape Memory Alloys (SMAs)," in *Smart Structures Theory*, in Cambridge Aerospace Series. , Cambridge: Cambridge University Press, 2013, pp. 194–304. doi: 10.1017/CBO9781139025164.004.
[91] M.-S. Kim, et al., Shape Memory Alloy (SMA) Actuators: The Role of Material, Form, and Scaling Effects, Adv. Mater. 35 (33) (2023) 2208517, https://doi.org/10.1002/adma.202208517.
[92] S. Hetimy, N. Megahed, O.A. Eleinen, D. Elgheznawy, Exploring the potential of sheep wool as an eco-friendly insulation material: A comprehensive review and analytical ranking, Sustain. Mater. Technol. 39 (2024), https://doi.org/10.1016/j.susmat.2023.e00812.
[93] B. Conley, C. A. Cruickshank, and C. Baldwin, "2.24 Insulation Materials," in *Comprehensive Energy Systems*, I. Dincer, Ed., Oxford: Elsevier, 2018, pp. 760–795. doi: 10.1016/B978-0-12-809597-3.00252-2.
[94] Z. Cai, M. A. Al Faruque, A. Kiziltas, D. Mielewski, and M. Naebe, "Sustainable Lightweight Insulation Materials from Textile-Based Waste for the Automobile Industry," *Materials*, vol. 14, no. 5, Art. no. 5, Jan. 2021, doi: 10.3390/ma14051241.
[95] R. Loonen, F. Favoino, J. Hensen, M. Overend, Review of current status, requirements and opportunities for building performance simulation of adaptive facades, J. Build. Perform. Simul. 10 (Mar. 2016), https://doi.org/10.1080/19401493.2016.1152303.
[96] R.C.G.M. Loonen, M. Trčka, D. Cóstola, J.L.M. Hensen, Climate adaptive building shells: State-of-the-art and future challenges, Renew. Sustain. Energy Rev. 25 (Sep. 2013) 483–493, https://doi.org/10.1016/j.rser.2013.04.016.
[97] H. Yazdani, M. Baneshi, Building energy comparison for dynamic cool roofs and green roofs under various climates, Sol. Energy 230 (2021) 764–778, https://doi.org/10.1016/j.solener.2021.10.076.
[98] A.H.A. Dehwah, M. Krarti, Cost-benefit analysis of retrofitting attic-integrated switchable insulation systems of existing US residential buildings, Energy 221 (2021), https://doi.org/10.1016/j.energy.2021.119840.
[99] B. Cui, et al., Model predictive control for active insulation in building envelopes, Energy Build. 267 (Jul. 2022) 112108, https://doi.org/10.1016/j.enbuild.2022.112108.
[100] G. Serale, M. Fiorentini, A. Capozzoli, D. Bernardini, A. Bemporad, Model Predictive Control (MPC) for Enhancing Building and HVAC System Energy Efficiency: Problem Formulation, Applications and Opportunities, Energies 11 (3) (Mar. 2018) 631, https://doi.org/10.3390/en11030631.
[101] L. Cosentino, J. Fernandes, R. Mateus, A Review of Natural Bio-Based Insulation Materials, Energies vol. 16, no. 12, Art. no. 12 (Jan. 2023), https://doi.org/10.3390/en16124676.
[102] S. Pessoa, A.S. Guimarães, S.S. Lucas, N. Simões, 3D printing in the construction industry - A systematic review of the thermal performance in buildings, Renew. Sustain. Energy Rev. 141 (2021), https://doi.org/10.1016/j.rser.2021.110794.

[103] "ISO/ASTM 52900:2015(en), Additive manufacturing — General principles — Terminology." Accessed: Mar. 01, 2024. [Online]. Available: https://www.iso.org/obp/ui/#iso:std:iso-astm:52900:ed-1:v1:en.
[104] J. Jiang, H. Oguzlu, F. Jiang, 3D printing of lightweight, super-strong yet flexible all-cellulose structure, Chem. Eng. J. 405 (2021), https://doi.org/10.1016/j.cej.2020.126668.
[105] F. Ahangaran, A.H. Navarchian, F. Picchioni, Material encapsulation in poly (methyl methacrylate) shell: A review, J. Appl. Polym. Sci. 136 (41) (2019) 48039, https://doi.org/10.1002/app.48039.
[106] H. Er-rradi, et al., Experimental study of composite materials based on ecological wastes, J. Compos. Mater. 56 (21) (Sep. 2022) 3295–3306, https://doi.org/10.1177/00219983221113029.
[107] R. Kumar, Experimental investigation of heat characteristics of composite material for thermal insulation application, Int. J. Ambient Energy 42 (5) (Apr. 2021) 546–549, https://doi.org/10.1080/01430750.2018.1557555.
[108] S. Biswas, J. Anurag, "Fabrication of Composite Laminates", in *Reinforced Polymer Composites*, John Wiley & Sons Ltd (2019) 39–53, https://doi.org/10.1002/9783527820979.ch3.
[109] W. Ulfat, et al., Reuse of Buffing Dust-Laden Tanning Waste Hybridized with Poly-Styrene for Fabrication of Thermal Insulation Materials, Sustainability vol. 15, no. 3, Art. no. 3 (Jan. 2023), https://doi.org/10.3390/su15031958.
[110] H. Serin, G. Güzel, U. Kumlu, M.A. Akar, Potential of Using Agricultural Waste Composites as Thermal Insulation Material, Macromol. Symp. 404 (1) (2022) 2100409, https://doi.org/10.1002/masy.202100409.
[111] T. Zhang, D. Yu, F. Xu, Y. Kong, X. Shen, Flexible Silica Aerogel Composites for Thermal Insulation under High-Temperature and Thermal-Force Coupling Conditions, ACS Appl. Nano Mater. 7 (6) (Mar. 2024) 6326–6338, https://doi.org/10.1021/acsanm.3c06127.
[112] J. Sharma, G. Polizos, C.J. Jafta, Y. Bai, D. Hun, X. Lyu, A lightweight thermally insulating and moisture-stable composite made of hollow silica particles, RSC Adv. 12 (24) (May 2022) 15373–15377, https://doi.org/10.1039/D2RA01561G.
[113] L. Li, J. Feng, F. Liu, L. Li, Y. Jiang, J. Feng, Mechanical and thermal insulation properties of carbon fibre-reinforced carbon aerogel composites, Adv. Appl. Ceram. 121 (5–8) (Nov. 2022) 222–230, https://doi.org/10.1080/17436753.2022.2156163.
[114] J. Feng, et al., Thermal insulation and mechanical properties of carbon fiber-reinforced thermoplastic polyphthalazine ether sulfone ketone composites reinforced by hollow glass beads, Polym. Compos. 44 (11) (2023) 7941–7952, https://doi.org/10.1002/pc.27677.
[115] Z. Jiao and W. He, "Fabrication of PVC Based Composites and Nanocomposites by Mechanical Mixing," in *Poly(Vinyl Chloride) Based Composites and Nanocomposites*, A. H and T. Sabu, Eds., Cham: Springer International Publishing, 2024, pp. 1–29. doi: 10.1007/978-3-031-45375-5_1.
[116] A. Contreras Cuevas, E. Bedolla Becerril, M. S. Martínez, and J. Lemus Ruiz, "Fabrication Processes for Metal Matrix Composites," in *Metal Matrix Composites: Wetting and Infiltration*, A. Contreras Cuevas, E. Bedolla Becerril, M. S. Martínez, and J. Lemus Ruiz, Eds., Cham: Springer International Publishing, 2018, pp. 83–114. doi: 10.1007/978-3-319-91854-9_3.
[117] M. Elkington, D. Bloom, C. Ward, A. Chatzimichali, K. Potter, Hand layup: understanding the manual process, Adv. Manuf. Polym. Compos. Sci. 1 (3) (Jul. 2015) 138–151, https://doi.org/10.1080/20550340.2015.1114801.
[118] N. S. Karaduman and Y. Karaduman, "2 - Various fabrication methods employed in fiber reinforced composites," in *Fiber Reinforced Composites*, K. Joseph, K. Oksman, G. George, R. Wilson, and S. Appukuttan, Eds., in Woodhead Publishing Series in Composites Science and Engineering. , Woodhead Publishing, 2021, pp. 25–45. doi: 10.1016/B978-0-12-821090-1.00016-8.
[119] U. N. Environment, "Renewable Energy and Energy Efficiency in Developing Countries: Contributions to Reducing Global Emissions," second report, Nov. 2016. Accessed: Apr. 18, 2024. [Online]. Available: http://www.unep.org/resources/report/renewable-energy-and-energy-efficiency-developing-countries-contributions-reducing.
[120] C. Amoah, J. Smith, Barriers to the green retrofitting of existing residential buildings, J. Facil. Manag. 22 (2) (Jan. 2022) 194–209, https://doi.org/10.1108/JFM-12-2021-0155.
[121] W. Wang, S. Zhang, Y. Su, X. Deng, Key Factors to Green Building Technologies Adoption in Developing Countries: The Perspective of Chinese Designers, Sustainability vol. 10, no. 11, Art. no. 11 (Nov. 2018), https://doi.org/10.3390/su10114135.
[122] A. Madhumathi and M. C. Sundarraja, "Energy Efficiency in Buildings in Hot Humid Climatic Regions Using Phase Change Materials as Thermal Mass in Building Envelope," *Energy Environ.*, vol. 25, no. 8, pp. 1405–1421, 2014, Accessed: Apr. 21, 2024. [Online]. Available: https://www.jstor.org/stable/43735610.
[123] S. Rbihi, H. Neggaoui, L. Laallam, A. Jouaiti, Cellulose waste for making sustainable cellulose/concrete bio-composite: functional and environmental value for the thermal insulation, Biomass Convers. Biorefinery (2022), https://doi.org/10.1007/s13399-022-02347-x.
[124] M. Alyami, The Impact of the Composition and Location of Thermal Insulation in the Building Envelope on Energy Consumption in Low-Rise Residential Buildings in Hot Climate Regions, Arab. J. Sci. Eng. 49 (4) (Apr. 2024) 5305–5351, https://doi.org/10.1007/s13369-023-08366-8.
[125] D.R. Clarke, Materials selection guidelines for low thermal conductivity thermal barrier coatings, Surf. Coat. Technol. 163–164 (Jan. 2003) 67–74, https://doi.org/10.1016/S0257-8972(02)00593-5.
[126] J. Torres-Quezada, H. Coch, A. Isalgué, Assessment of the reflectivity and emissivity impact on light metal roofs thermal behaviour, in warm and humid climate, Energy Build. 188–189 (Apr. 2019) 200–208, https://doi.org/10.1016/j.enbuild.2019.02.022.
[127] I. Neya, D. Yamegueu, Y. Coulibaly, A. Messan, A.-L.-S.-N. Ouedraogo, Impact of insulation and wall thickness in compressed earth buildings in hot and dry tropical regions, J. Build. Eng. 33 (Jan. 2021) 101612, https://doi.org/10.1016/j.jobe.2020.101612.
[128] F. Favoino, Q. Jin, M. Overend, Design and control optimisation of adaptive insulation systems for office buildings. Part 1: Adaptive technologies and simulation framework, Energy 127 (May 2017) 301–309, https://doi.org/10.1016/j.energy.2017.03.083.
[129] Q. Jin, F. Favoino, M. Overend, Design and control optimisation of adaptive insulation systems for office buildings. Part 2: A parametric study for a temperate climate, Energy 127 (May 2017) 634–649, https://doi.org/10.1016/j.energy.2017.03.096.
[130] A.H.A. Dehwah, M. Krarti, Optimal controls of precooling strategies using switchable insulation systems for commercial buildings, Appl. Energy 320 (Aug. 2022) 119298, https://doi.org/10.1016/j.apenergy.2022.119298.
[131] L. Liu, et al., The development history and prospects of biomass-based insulation materials for buildings, Renew. Sustain. Energy Rev. 69 (Mar. 2017) 912–932, https://doi.org/10.1016/j.rser.2016.11.140.
[132] Y.G. Frómeta, F.R. Rivera, V.G. Holguín, J. Cuadrado, Experimental Investigation of Thermal Conductivity from Insulation Based on Rice Hulks: Guarded and Calibrated Hot Box Method, Mater. Sci. Forum 1046 (2021) 71–76, https://doi.org/10.4028/www.scientific.net/MSF.1046.71.
[133] G. Garas, M. Allam, Thermal performance of plastered rice straw bales and walls: a case study, Int. J. Sustain. Dev. Plan. 6 (2) (Jun. 2011) 226–237, https://doi.org/10.2495/SDP-V6-N2-226-237.
[134] M.N. Guirguis, Z. Farahat, A. Micheal, Developing an interior cladding fiberboard by utilizing sugarcane bagasse as a local agro-waste in Egypt, Sci. Rep. 13 (1) (Aug. 2023) 12870, https://doi.org/10.1038/s41598-023-39860-6.
[135] K. Manohar, J. Ramroopsingh, and D. W. Yarbrough, "Use of Sugarcane Fiber as Building Insulation," pp. 299–313, doi: 10.1520/STP11020S.
[136] R. Elawadly, A. Abdel-Rehim, Performance and Economical Analysis of Different Insulating Materials Used to Reduce the Heat Load of an Existing Residential Building, WSEAS Trans. Environ. Dev. 17 (Feb. 2021) 155–166, https://doi.org/10.37394/232015.2021.17.16.
[137] R. Deraman, et al., "Production of Roof Board Insulation Using Agricultural Wastes Towards Sustainable Building Material", *J. Adv. Res. Fluid Mech*, Therm. Sci. vol. 99, no. 1, Art. no. 1 (Aug. 2022), https://doi.org/10.37934/arfmts.99.1.6689.
[138] J. Iwaro, A. Mwasha, Effects of Using Coconut Fiber-Insulated Masonry Walls to Achieve Energy Efficiency and Thermal Comfort in Residential Dwellings, J. Archit. Eng. 25 (1) (Mar. 2019) 04019001, https://doi.org/10.1061/(ASCE)AE.1943-5568.0000341.
[139] M. Charai, H. Sghiouri, A. Mezrhab, M. Karkri, Thermal insulation potential of non-industrial hemp (*Moroccan cannabis sativa L.*) fibers for green plaster-based building materials, J. Clean. Prod. 292 (Apr. 2021) 126064, https://doi.org/10.1016/j.jclepro.2021.126064.
[140] M.G.A. Marri, M.A. Al-Ghouti, V.C. Shunmugasamy, N. Zouari, Date pits based nanomaterials for thermal insulation applications—Towards energy efficient buildings in Qatar, PLOS ONE 16 (3) (Mar. 2021) e0247608.
[141] B. Abu-Jdayil, W. Hittini, A.-H. Mourad, Development of Date Pit-Polystyrene Thermoplastic Heat Insulator Material: Physical and Thermal Properties, Int. J. Polym. Sci. 2019 (Mar. 2019) e1697627.
[142] R. Malheiro, A. Morilla, A. Ansolin, J. Fernandes, S. Silva, R. Mateus, The potential use of giant reed from Portugal as a thermal insulation material, Acta Polytech. CTU Proc. 38 (Dec. 2022) 235–240, https://doi.org/10.14311/APP.2022.38.0235.
[143] D.A.A. Vázquez, L. Moreschi, G.J.I. Valverde, M. Gallo, A.D. Borghi, J.C.A. Arcos, Evaluation of By-products' Potentiality for the Reincorporation in New Building Materials, IOP Conf. Ser. Earth Environ. Sci. 544 (1) (Jul. 2020) 012007, https://doi.org/10.1088/1755-1315/544/1/012007.
[144] A. Farouk Mohamed, "Comparative study of traditional and modern building techniques in Siwa Oasis, Egypt: Case study: Affordable residential building using appropriate building technique", *Case Stud*, Constr. Mater. 12 (Jun. 2020) e00311.
[145] A. Torres-Rivas, C. Pozo, M. Palumbo, A. Ewertowska, L. Jiménez, D. Boer, Systematic combination of insulation biomaterials to enhance energy and environmental efficiency in buildings, Constr. Build. Mater. 267 (Jan. 2021) 120973, https://doi.org/10.1016/j.conbuildmat.2020.120973.
[146] Y.A. Basyouni, H. Mahmoud, Affordable green materials for developed cool roof applications: A review, Renew. Sustain. Energy Rev. 202 (Sep. 2024) 114722, https://doi.org/10.1016/j.rser.2024.114722.
[147] M.G. Eisa, H. Sameh, M.M.A. El-Razik, Development of Architectural Green Mortar Incorporating Waste Glass and its Impact on Energy Saving in Buildings, Key Eng. Mater. 945 (2023) 157–164, https://doi.org/10.4028/p-qyuz0v.
[148] R. Niyazbekova, et al., The Influence of Addition of Fly Ash from Astana Heat and Power Plants on the Properties of the Polystyrene Concrete, Energies vol. 16, no. 10, Art. no. 10 (Jan. 2023), https://doi.org/10.3390/en16104092.
[149] P. Balcom, V.P. Carey, Exergy-Based Sustainability Analysis for Tile Production From Waste Plastics in Uganda, in: Presented at the ASME 2019 13th International Conference on Energy Sustainability Collocated with the ASME 2019 Heat Transfer Summer Conference, American Society of Mechanical Engineers Digital Collection, Dec. 2019, https://doi.org/10.1115/ES2019-3897.
[150] U.W. Robert, S.E. Etuk, O.E. Agbasi, U.S. Okorie, A. Lashin, Hygrothermal properties of sandcrete blocks produced with raw and hydrothermally-treated

sawdust as partial substitution materials for sand, J. King Saud Univ. - Eng. Sci. (Oct. 2021), https://doi.org/10.1016/j.jksues.2021.10.005.
[151] F. Zakaria, M.A. Radwan, M.A. Sadek, H.A. Elazab, Insulating material based on shredded used tires and inexpensive polymers for different roofs, Int. J. Eng. Technol. vol. 7, no. 4, Art. no. 4 (Sep. 2018), https://doi.org/10.14419/ijet.v7i4.14081.
[152] U.W. Robert, S.E. Etuk, O.E. Agbasi, G.P. Umoren, S.S. Akpan, L.A. Nnanna, Hydrothermally-calcined waste paper ash nanomaterial as an alternative to cement for clay soil modification for building purposes, Acta Polytech. vol. 61, no. 6, Art. no. 6 (Dec. 2021), https://doi.org/10.14311/AP.2021.61.0749.
[153] N. Ferronato, R.C. Fuentes Sirpa, E.G. Guisbert Lizarazu, F. Conti, V. Torretta, Construction and demolition waste recycling in developing cities: management and cost analysis, Environ. Sci. Pollut. Res. 30 (9) (Feb. 2023) 24377–24397, https://doi.org/10.1007/s11356-022-23502-x.
[154] C.A. Velis, D.C. Wilson, O. Rocca, S.R. Smith, A. Mavropoulos, C.R. Cheeseman, An analytical framework and tool (' *InteRa* ') for integrating the informal recycling sector in waste and resource management systems in developing countries, Waste Manag. Res. J. Sustain. Circ. Econ. vol. 30, no. 9_suppl (Sep. 2012) 43–66, https://doi.org/10.1177/0734242X12454934.
[155] Accessed: Aug. 03 (2024) [Online]. Available: https://www.worldbank.org/en/topic/urbandevelopment/brief/solid-waste-management.
[156] N. Ghaboun, Significant guidance for the effective management of construction waste in North Africa and the Middle East countries, Smart Tour. 4 (1) (Sep. 2023) 2195, https://doi.org/10.54517/st.v4i1.2195.
[157] F. Di Maria, R.L. Mersky, S. Daskal, O. Ayalon, S.K. Ghosh, Preliminary Comparison Among Recycling Rates for Developed and Developing Countries: The Case of India, Israel, Italy and USA, in: S.K. Ghosh (Ed.), Sustainable Waste Management: Policies and Case Studies, Springer, Singapore, 2020, pp. 1–13, https://doi.org/10.1007/978-981-13-7071-7_1.
[158] S. Hasan, S. Khan, S. Uddin, Impact of Phase Change Material (Butyl Stearate) and other insulation material on thermal performance of building envelope in different climates of India, Mater. Today Proc. 43 (Jan. 2021) 706–713, https://doi.org/10.1016/j.matpr.2020.12.764.
[159] A.C. Rai, Energy performance of phase change materials integrated into brick masonry walls for cooling load management in residential buildings, Build. Environ. 199 (Jul. 2021) 107930, https://doi.org/10.1016/j.buildenv.2021.107930.
[160] J. Kosny, E. Kossecka, A. Brzezinski, A. Tleoubaev, D. Yarbrough, Dynamic thermal performance analysis of fiber insulations containing bio-based phase change materials (PCMs), Energy Build. 52 (Sep. 2012) 122–131, https://doi.org/10.1016/j.enbuild.2012.05.021.
[161] S.K. Jaiswal, D. Kumar, "An experimental assessment of bio-mixed-phase change material in a lightweight compartment and its potential as latent energy storage in north-east climate of India", *Energy Sources Part Recovery Util*, Environ. Eff. (2020) 1–14, https://doi.org/10.1080/15567036.2020.1850928.
[162] H. F. Salem, M. A. Ibrahim, and Z. El-Sayad, "IMPACT OF NANO INSULATING MATERIALS ON ENERGY RETROFIT OF BUILDINGS," presented at the ECO-ARCHITECTURE 2022, Lisbon, Portugal, Sep. 2022, pp. 49–60. doi: 10.2495/ARC220051.
[163] M. Hussain, E.A. Sabour, S.M. Mansour, Nanomaterials in facades A Tool Towards Environmental Sustainability in Egypt, IOP Conf. Ser. Earth Environ. Sci. 1113 (1) (Dec. 2022) 012019, https://doi.org/10.1088/1755-1315/1113/1/012019.
[164] G. Nagy, H. Adnan, A Guideline for Developing Resilient Office Buildings using Nanotechnology Applications, IOP Conf. Ser. Earth Environ. Sci. 1056 (1) (Aug. 2022) 012015, https://doi.org/10.1088/1755-1315/1056/1/012015.
[165] P.S. Jadhav, A. Sarkar, S. Pasupathy, S. Ren, Biogenic Straw Aerogel Thermal Insulation Materials, Adv. Eng. Mater. 25 (13) (2023) 2300037, https://doi.org/10.1002/adem.202300037.
[166] M. Ouakarrouch, et al., Sustainable thermo-acoustical insulation material from cardboard waste and natural fibers: Elaboration and performance evaluation, J. Build. Phys. 46 (3) (Nov. 2022) 372–392, https://doi.org/10.1177/17442591221121924.