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Review

Wall Insulation Materials in Different Climate Zones: A Review on Challenges and Opportunities of Available Alternatives

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Abstract: Buildings account for nearly one-third of overall energy consumption in today's world energy status, in which a considerable part is used for indoor conditioning. Energy efficiency enhancement of buildings components and technologies is a key priority, given the essential need for carbon neutrality and climate change mitigation around the world. Exterior wall insulation is considered as the most effective technology for protecting buildings against continual ambient fluctuations. Proper design and implementation of wall insulation would lead to performance enhancement, energy conservation as well as improved thermal comfort. They can also protect building structures against corrosion and heat fatigue, extending the life of buildings. There are many different types of thermal insulation materials currently on the market, each with its own set of thermal qualities and functionality. This paper aims to examine the qualities, benefits, and drawbacks of several exterior wall insulation technologies, and provide recommendations for how to use various forms of exterior wall insulation in different climates.

Keywords: exterior wall insulation; building material; climate zones; energy saving; energy efficiency; climate change

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1. Introduction

The building and construction sector is one of the top three energy consumers in the world, where a considerable portion of demand is due to space conditioning [1,2]. According to statistical data, the construction industry accounts for about 40 percent of global energy consumption and is expected to increase to 50 percent by 2050 [3,4]. Nations and countries all around the world have introduced various remedies centred on building energy conservation [5]. In March 2015, the European Union (EU) submitted a nationally determined contribution plan in response to the Paris climate agreement. The United Nations framework convention on climate change (UNFCCC) has also recommended a national plan that includes energy-saving strategies, like growing the use of renewable energy resources and enhancing the energy efficiency of buildings, industries, and household appliances [6].

As mentioned earlier, a significant amount of residential energy is consumed to provide occupants with an acceptable level of interior thermal comfort [7]. External wall insulation is an effective energy-saving approach [8] since it reduces regional heating and cooling demands [9] while also having a great impact on the surrounding microclimate [10]. However, the type and thickness of thermal insulation materials have to be carefully selected to ensure the optimal thermal performance of the building in a variety of climate zones [11]. Yuan et al. [12] compared the engineering test values of thermal insulation materials in six representative cities in six climate regions of Japan, utilising various combinations of four thermal insulation materials and four fuel sources. Their results showed that rock wool and liquefied natural gas (LNG) were the best combinations for each climate zone in Japan. Zhu et al. [13] also conducted a comparative study on the thickness of expanded polystyrene (EPS) external wall insulation boards used in Urumqi, Beijing, Shanghai, Guangzhou, and Kunming, which are representative cities in five climatic regions. It was concluded that the optimal EPS thickness was 175 mm, 216 mm, 205 mm, 116 mm and 163 mm, respectively. Rosas-Flores et al. [14] investigated the optimal insulation thickness of five insulation materials (i.e., expanded polystyrene, extruded polystyrene, glass wool, rock wool, and polyurethane) for different climate zones in Mexico, and concluded the recommended thickness of the five above-said insulations for tropical households (74, 63, 119, 89, and 45 mm) and optimal thickness for profiles (33, 29, 54, 40, and 20 mm). Huang et al. [11] developed a typical building model for China's humid subtropical climate zone and analysed the impacts of a new aerogel super insulation material plus four other commonly used insulation materials. Berardi [15] studied the effects of temperature on building thermal insulation and thermal conductivity in a Canadian climate, concluding that there is an approximately linear relationship between conductivity and temperature. Based on the IPCC Fourth Report (AR4), Emel et al. [16] evaluated the impacts of various thermal insulation materials on the indoor thermal comfort of residential buildings in central and western Brazil (Cuiaba). Rock wool and glass wool were finally recommended as ideal thermal insulating materials for tropical steppe climate areas in Brazil.

The selection of appropriate insulating materials is one of the primary methods for lowering a building's energy usage. The thermal performance of insulating materials can directly influence the shape of the building energy consumption and efficiently reduce internal and external heat transfers from building envelopes, assisting in the provision of more desired indoor thermal comfort provision for occupants. This study aims to review both commonly used and state-of-the-art exterior wall insulation materials and discuss their characteristics as well as application requirements to be applied in buildings located in different climate zones across the world. It highlights several new insulating materials that are suitable for various climate zones, which is beneficial for scientific researchers to conduct in-depth testing and research on. The authors also believe that this review will be valuable to professionals in the design and execution of exterior wall thermal insulation under various climate conditions to achieve the desired energy savings, emission reductions, and cost savings. The paper is divided into five sections; Section 2 presents various types of exterior wall thermal insulation materials and compares their technical features and key thermal properties. Section 3 looks at the performance of insulation materials in a variety of climate regions, including East Asia, the Middle East, Europe, North America, South America, and Australia, and provides recommendations for how to employ various forms of exterior wall insulations in each. Section 4 discusses the current challenges and opportunities. Eventually, in Section 5, the main conclusions are highlighted, and future outlook and research directions are presented.

2. Types of Insulation Materials

Here, insulation materials are classified into three main categories, as indicated in Figure 1, depending on material composition, material technology, and material sustainability index.

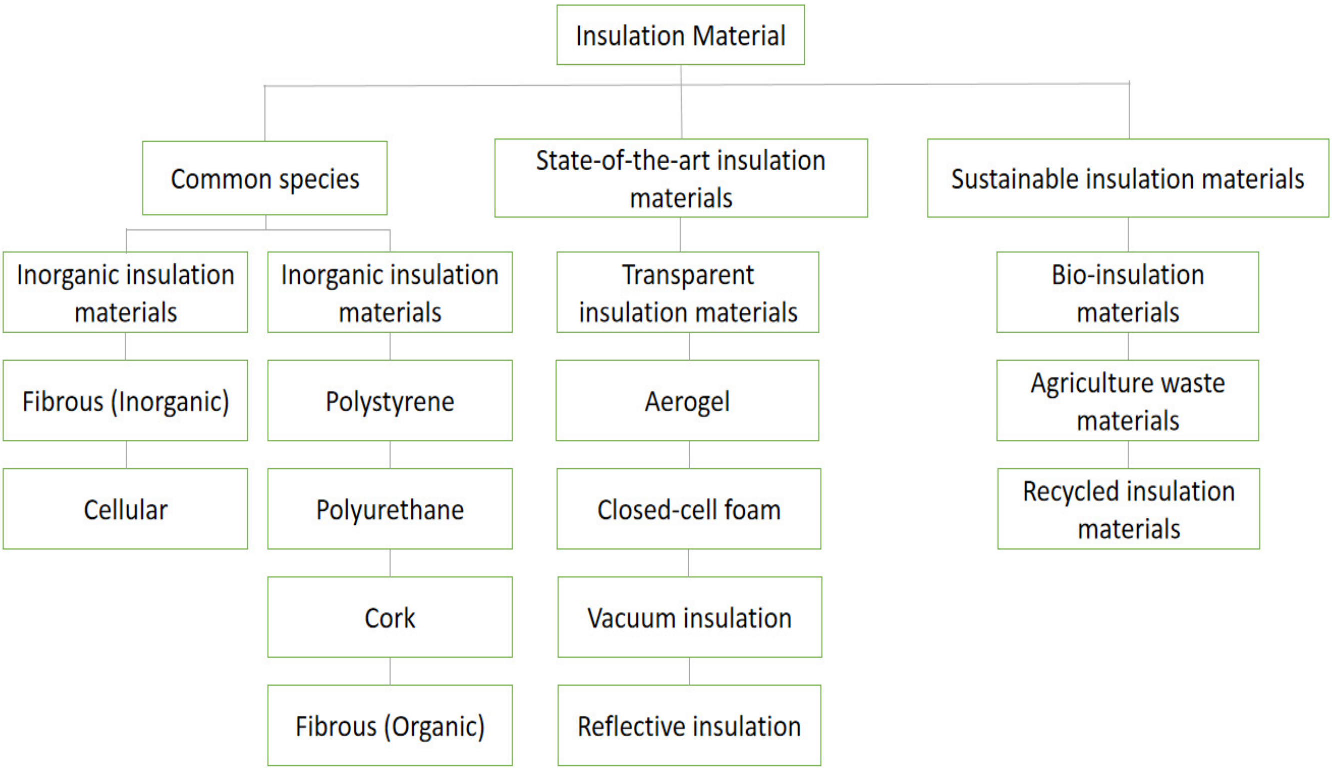

Figure 1. Classification of insulation materials for building applications.

2.1. Inorganic Insulation Materials

2.1.1. Inorganic Fibrous

Glass, rock, and slag wool are all fibrous elements that belong to mineral wool [17]. Fibrous insulation materials are made using crushed rock, quartz sand, diabase, and basalt [18]. Glass wool and rock wool are categorised as inorganic fibrous materials. Glass wool is made by mixing natural sand and (typically recycled) glass at temperatures ranging from 1300 °C to 1450 °C [5]. Fibre transformation then takes place through centrifugation and blowing. The fibres are finally held and stabilised using resin [5,19]. Rock wool is also formed using fibres made by melting stone (e.g., diabase and dolerite) at around 1500 °C and flinging the hot molten material out of a wheel or disc.

Figure 2 shows mineral wool in microscopic and close-up views. Mineral wool has a thermal conductivity of 0.030–0.040 W/m·K, while glass wool and rock wool offer a thermal conductivity of 0.030–0.046 and 0.033–0.046 W/m·K, respectively [20]. The thermal insulation performance of glass and rock wool materials will not be affected by ambient temperature and humidity [5,21]; however, these variables change mineral wool's thermal conductivity. If the moisture content of mineral wool is increased from 0% to 10%, the thermal conductivity is raised from 0.037 m·K to 0.055 m·K [1]. In real applications, mineral wool rods that are lighter and softer are used to frame cavities in other building structures [1], while denser, more complicated mineral wool panels are utilised for floors, walls, and roofs [18]. Glass wool can typically be used as thermal insulation material when the need for heat resistance is not great (for example, the roof of a factory building), but rock wool is usually a more sensible choice for large heat insulation requirements [1,18,22]. The literature reveals that the inorganic fibrous material is non-rotting, exhibits good high-temperature resilience, and has high levels of hygroscopicity. However, they are still quite expensive in the market today.

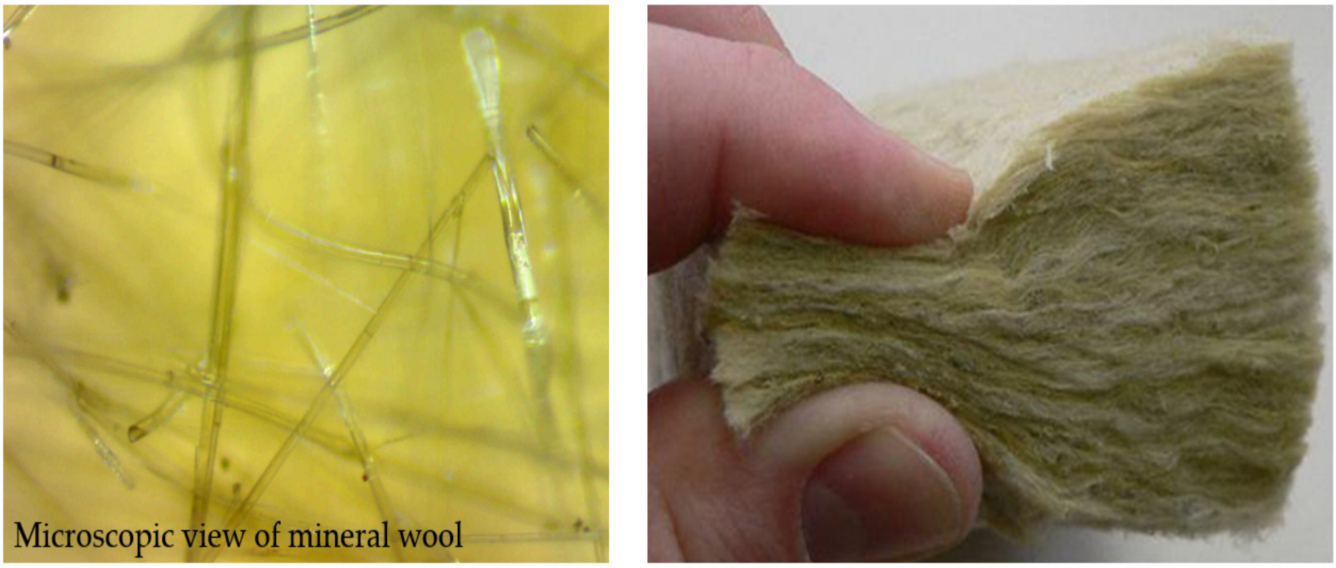

Figure 2. A microscopic view and close-up of mineral wool [23].

2.1.2. Cellular

Calcium silicate, foam glass, perlite, and vermiculite are examples of inorganic porous insulating materials [18]. The main components of these materials include sand, cellulose fibres, shattered glass, dolomite, oxides (e.g., aluminium and silicon), and magnesium–aluminium silicates. The large porosity of foam insulators reduces mechanical strength while increasing hygroscopicity, resulting in low heat conductivity [1].

At room temperature, the thermal conductivity of foam is around 0.12 W/m·K (with a density of 100 kg/m^3), which is larger than those of other fibre insulation materials [20]. Furthermore, this thermal conductivity is highly influenced by thermal radiation. According to results reported by Zukowski and Haese [24], incorporating perlite into the pores of porous insulating materials reduces heat conductivity. Gao et al. [25] introduced a new foam insulating material made of perlite/sodium silicate, H_2O_2, hexyl trimethyl ammonium bromide, and rock wool. Their foam insulator is lighter than conventional inorganic materials, has a low heat conductivity, and is mechanically durable. However, despite being a lightweight material, it lacks structural rigidity, making it unsuitable for use in enclosure structures that are subjected to vibration.

2.2. Organic Insulation Materials

2.2.1. Polystyrene

Polystyrene products are made from organic foam plastic. As an insulation material, polystyrene is commercially available in two forms: expanded polystyrene and extruded polystyrene [1].

- Expanded polystyrene (EPS)

Expanded polystyrene foam (EPS) is commonly made by evaporating pentane into polystyrene particles. This technique can produce white, rigid closed-cell foam. The specific heat of EPS materials is around 1.25 kJ/kg·K, and their thermal conductivity and density range from 0.031 to 0.037 W/m·K and 15 to 75 kg/m^3, respectively. The higher the density of EPS insulation material is, the better the insulation effect will be [19]. Additionally, as Lakatos et al. [26] confirmed, the thermal conductivity of EPS materials will be affected by humidity. They showed that if EPS material is kept dry for four hours in a climate chamber with a relative humidity of 90%, its thermal conductivity will decrease by 2.1%.

EPS material, on the other hand, is of closed porosity, low density, and no apparent acoustic qualities. Due to the high flammability of these materials, flame retardants are frequently added to their production process. EPS materials can be used for a variety of purposes, like packaging (Figure 3) and structure insulation [1,27]. The advantages of the EPS insulation board over commercially available inorganic active insulation mortar and foam glass include low thermal conductivity and a significant heat storage coefficient. However, because it is an organic material, the fireproof performance is a key point that needs to be paid attention to. Several manufacturers developed enhanced fireproof EPS boards, but the cost is relatively high. Moreover, EPS is extremely tough to degrade, and recycling EPS is problematic.

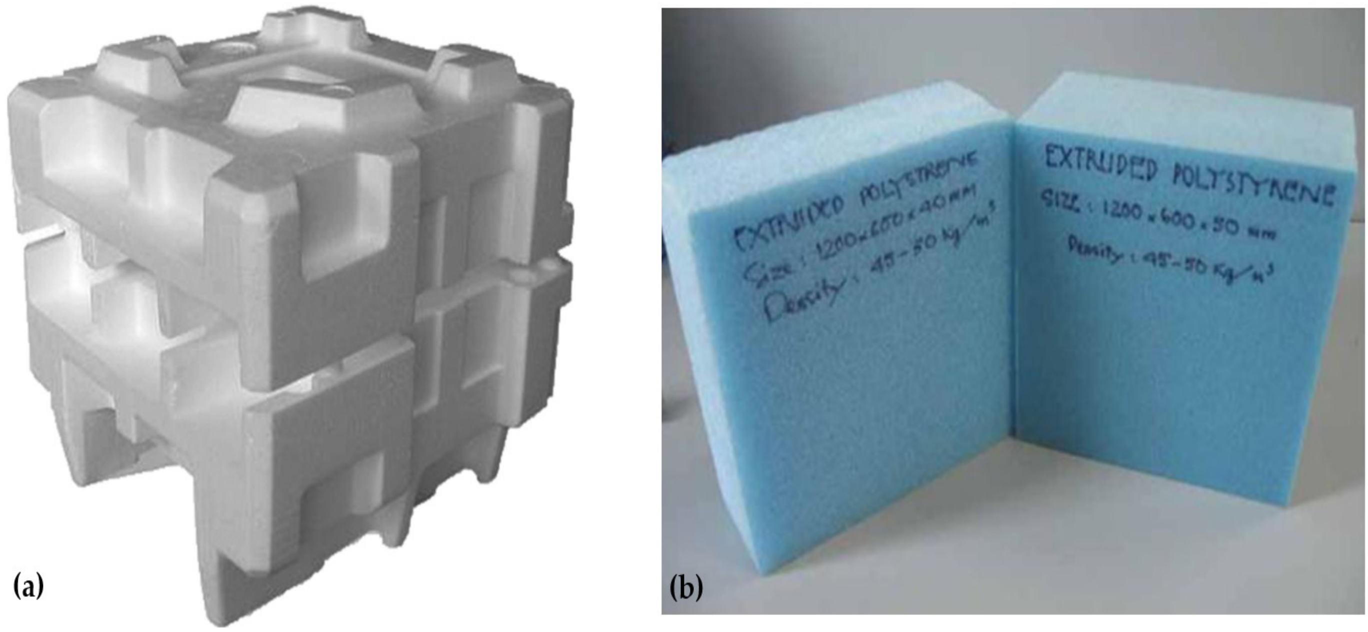

Figure 3. (**a**) EPS material used for packaging, and (**b**) XPS insulation material [23].

- Extruded polystyrene (XPS)

In the extrusion process, through which XPS is made, polystyrene particles are melted in an extruder and mixed with key additives, and the mixture then expands when cooling [28]. The thermal conductivity of XPS is typically between 0.025 and 0.035 W/m·K [20]. The thermal conductivity of XPS varies with temperature, moisture content, and density. It is shown that XPS thermal conductivity increases from 0.034 W/m·K to 0.044 W/m·K as the water content grows from 0% to 10% [1]. XPS insulation materials can be installed on and removed from a range of building structures without impacting their heat resistance [29]. While XPS has similar insulating qualities to EPS, it absorbs less moisture (0.3% vs. 2–4%) and poses a higher specific heat (1.3–1.7 kJ/kg·K). However, XPS usually costs 10–30% more than EPS [5]. XPS is practically identical to EPS, both of which are the most widely used insulation materials. However, they are not yet environmentally friendly materials, and planning a successful treatment strategy for recycling is challenging.

2.2.2. Polyurethane (PUR)

Polyurethane (PUR) and polyisocyanurates are produced when isocyanates and polyols react [18]. PUR has a thermal conductivity of 0.02 to 0.03 W/m·K, which is significantly lower than mineral wool, polystyrene, and cellulose products [29]. The thermal conductivity of PUR is affected by changes in temperature, moisture content, and mass density; The thermal conductivity is increased from 0.025 to 0.046 W/m·K as the moisture content grows from 0% to 10% [1]. In addition, PUR's thermal conductivity follows a decreasing trend when the cell size decreases [1,30].

Polyurethane can be employed to make panels and pipe fittings, as well as expanded into the foam to be used in buildings (for sealing doors and windows, and filling voids and spaces [1,5]. It is worth mentioning that even if PUR is safe in its intended applications, it can pose serious health concerns in the case of a fire. When PUR burns, highly hazardous hydrogen cyanide (HCN) and isocyanates are released [29]. Compared to other organic materials, the key benefit of PUR insulation boards (Figure 4) is their high structural strength. Yet, same as other organic material insulation boards, these have weak flame retardancy and low recycling rates.

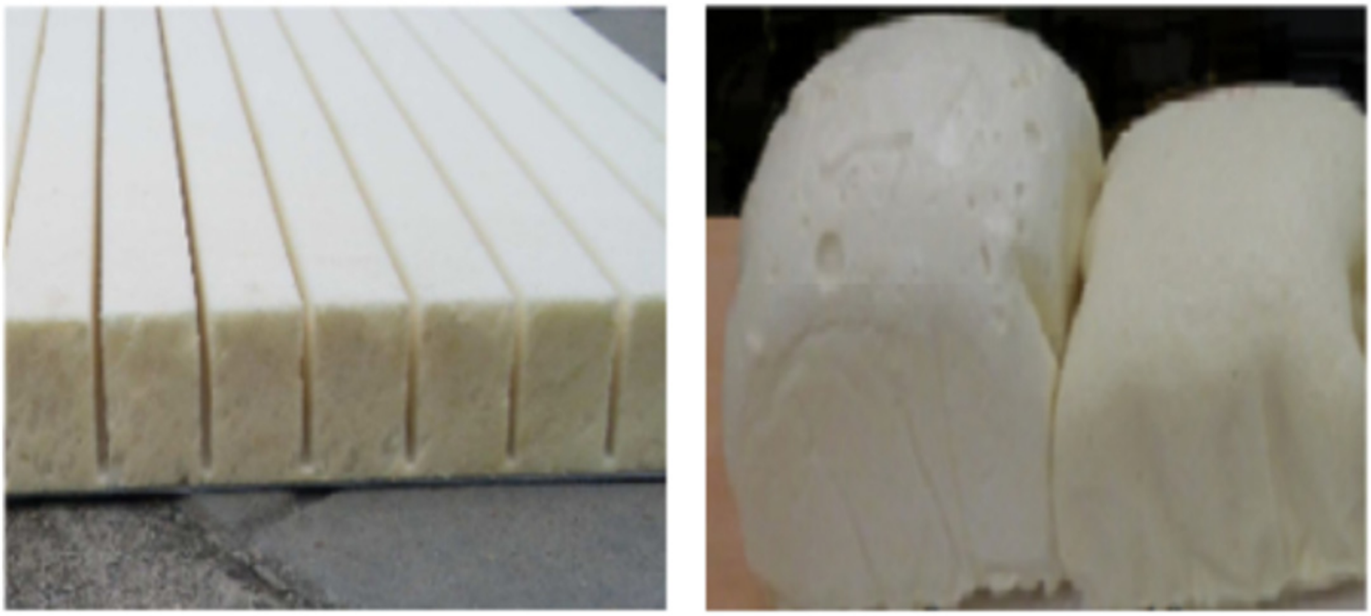

Figure 4. PUR insulation foam [1].

2.2.3. Cork

Cork thermal insulation is primarily made from cork oak. The thermal conductivity, density, and specific heat of cork material are in the range of 0.037–0.050 W/m·K, 110–170 kg/m^3, and 1.5–1.7 kJ/kg·K, respectively. Without affecting their thermal resistance, cork insulation products can be punctured, trimmed, and adjusted on the job site [29]. Materials consisting of cork particles are of good acoustic characteristics, like thermal shock insulation, air isolation, and sound absorption [31]. Softwood applications are ideal insulation materials under compression pressures due to their low thermal conductivity and high compressive strength. Cork oak is widely used in buildings because of its thermal and acoustic properties. It can be used either as a filler or a sheet [1]. Compared to the aforementioned organic materials, the recycling performance of cork materials is more effective. Considering the sustainable development of buildings, materials such as cork should gradually replace polymer materials that are difficult to degrade.

2.2.4. Organic Fibrous

- Cellulose

Cellulose is formulated using recycled paper, wood fibre, and boric acid to improve its thermal characteristics [32]. These components can also enhance its pest, fire, and corrosion resistance [5].

Cellulose has a thermal conductivity of 0.037 and 0.042 W/m·K, a density of 30 to 80 kg/m^3, and specific heat of between 1.3 and 1.6 kJ/kg·K. The thermal performance of cellulose can be influenced by the quality of the source newsprint [33]. Additionally, the thermal conductivity can be improved by increasing the moisture content from 0% to 5%, yielding 0.040 W/m·K and 0.066 W/m·K, respectively [1].

Cellulose insulation products can be perforated, trimmed, and modified on the job site without losing their thermal resistance [29]. Acoustically, if cellulose panels are utilised, their elasticity can be used as a floating floor elastic material, while the porosity and flow resistivity values are sufficient for sound absorption and cavity insulation [31]. Cellulose is commercially used to fill cavities, cardboard, and envelope liners [32]. Although cellulose panels and matting are produced by manufacturers, loose cellulose that can be blown into wall cavities is more widely available [5]. Cellulose can be used as a sustainable material when compared to organic polymer materials. Its improved workability should also be taken into consideration. However, more research is required on the durability aspect, since durability is the central argument against replacing EPS and XPS with new materials.

- Sheep Wool Insulation Materials

Sheep wool is a widely-used material in the garment and textile industries. However, a large amount of wool from coarse or semi-coarse sheep (dairy sheep) bred in southern Europe and Mediterranean countries is of poor textile quality. Therefore, it is recommended to use wools as sustainable insulation materials for buildings [34]. Figure 5 indicates sheep wool material and its applications in buildings.

Figure 5. Applications of sheep wool insulation in building constructions [1,23].

Semitekolos et al. [34] analysed a composite insulation that is made of epoxy resin and wool. Compared with pure epoxy resin, the thermal conductivity of their composite is reduced by 30%, demonstrating that wool fibre-epoxy resin composite might be considered a potential insulating material while also utilising natural waste. Iacob Florea et al. [35] investigated a new insulation material made of natural fibres, wool, and hemp. The experimental results showed that sheep wool materials provide better insulation than currently available materials, resulting in increased building energy efficiency. A study by Azra Korjenic et al. [36] found that the thermal insulation performance of pure wool as an internal insulation layer for façades is comparable to mineral wool and calcium silicate.

2.3. State-of-the-Art Insulation Materials

2.3.1. Transparent Insulation Materials (TIMs)

All transparent insulation materials (TIMs) can be categorised as solar collectors since they absorb solar energy while also providing insulation to prevent heat loss [37]. TIMS, which are usually assembled with a transparent cover and a double-glazing unit [38], can also control heat flow and transmit light, enhancing the building's thermal and visual comfort [18]. Based on different structural designs, TIMs are typically divided into four categories, i.e., vertical glass structure, parallel glass structure, composite glass structure, and homogeneous glass structure [38]. Homogeneous TIM has granular silica aerogel

(GSA) and single-piece silica aerogel (MSA). Figure 6 indicates silical aerogel granules used in glazing units. Although MSA-TIM is more important than GSA-TIM, its initial cost, as well as vulnerability, are substantial barriers to its commercialisation [39].

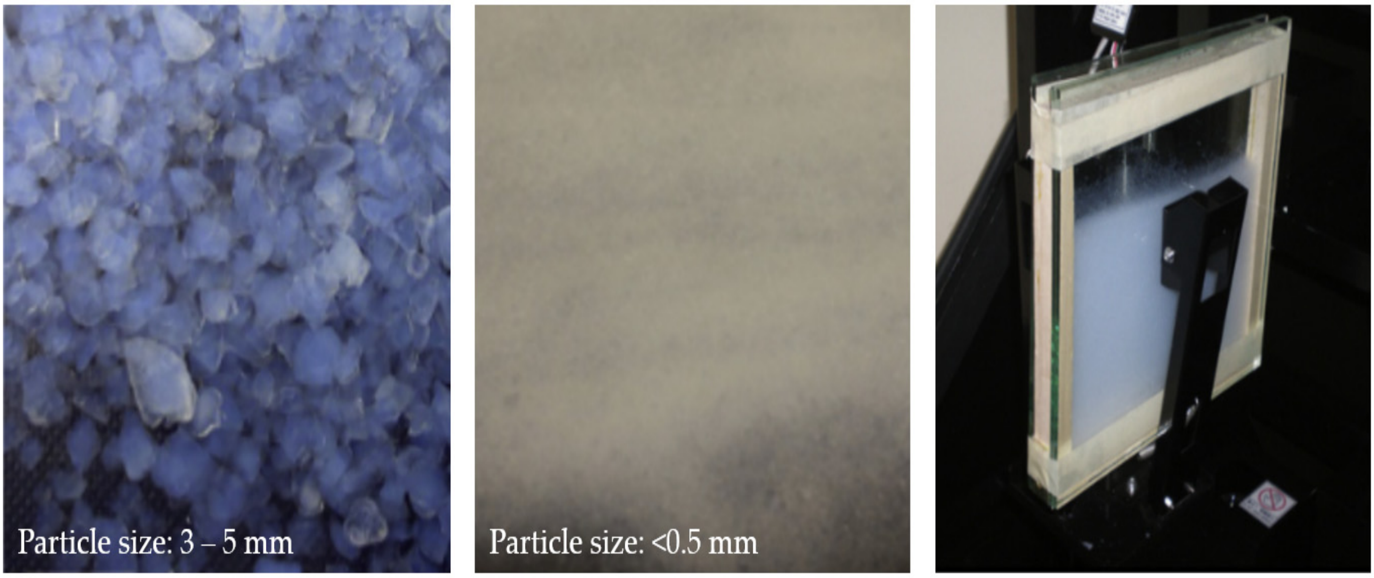

Figure 6. Silica aerogel granules used in glazing units [23,39].

TIMs are mostly used in transparent insulation (TI) systems in solar applications, namely TI solar collector systems and TI systems for buildings [37]. TI systems are also classified into two types of with and without aerogel. Compared to the TI system without aerogel, the aerogel-filled TI system is lighter and thinner, improving insulating performance [37]. Paneri et al. [37] confirmed that an aerogel-filled TI system shows superior insulating performance and g value when its weight and thickness are lowered. Therefore, aerogel-filled TI systems are ideally suited for energy conservation in both existing buildings (when retrofitted) and new constructions.

Moreover, TIM needs the coordinated operation of electrical systems and is costly to be designed, manufactured, and implemented in buildings, making it uncommon in most city buildings but employed widely in public ones. To make TIM general, corresponding normative constraints should be developed to maximise cost savings and expand the scope of applications.

2.3.2. Aerogel

Aerogel is a translucent synthetic substance with a huge internal surface area, high porosity, and low density [1]. Commonly, aerogel is synthesized by the sol-gel method [1], which creates a highly porous nanostructure, reducing conduction and convection heat transfers through the material [18]. Synthetic materials exhibit the lowest thermal conductivity, refractive index, sound speed, and dielectric constant of any solid evaluated. These characteristics are attributed to their unique microstructure, which comprises particle diameters of 1–20 nm, pore widths of 2–50 nm, and porosity of up to 90%.

The other forms of aerogel include frozen smoke, solid air, and blue smoke [1]. Particulate aerogel can be placed in the cavity of a double-glazed window to reduce its U value considerably while having no negative impact on apparent transmittance [40]. Aerogels can also be employed as the core of vacuum insulation panels. Aerogel qualities have led to novel applications in a variety of fields, including solar collector covers, building envelopes (walls, floors, attics), windows, and coating applications (as a thickener) [23].

Aerogel, as shown in Figure 7, can also be classified as a new type of thermal insulation material. However, new materials have limited application possibilities and have issues with durability. Based on the literature, there is not much research in this area, and more research is needed if it is widely used in the future.

Figure 7. Aerogel-based plaster in building constructions [41].

2.3.3. Closed-Cell Foam

Closed-cell foam is a spray insulation with completely enclosed cells that are pressed together to prevent air and moisture entrapment within the foam [18]. The density and thermal conductivity of closed-cell foams are 16–55 kg/m^3 and 0.025–0.048 W/m·K, respectively [18]. The main weakness of these foams is that their thermal conductivity varies rapidly when they become moist [18,42]. Recent technological advancements have tended to manufacture thin insulating materials by limiting bubble size and foam gas injection, resulting in stiff and stable insulating materials that occupy 40% less occupied area than fibreglass at the same thermal resistance [43].

In building applications, closed-cell foam can be utilised as a hard surface material, and it is appropriate for exterior walls (but not cavity walls) in dry climates [42]. Closed-cell foam has no significant uncertainties about how well it performs as a surface spraying material. Thus, the focus of future studies should be on durability and fire resistance. Further investigation is required to determine whether cracking, performance deterioration, and fire risk exist in some severe circumstances.

2.3.4. Vacuum Insulation

Vacuum insulation board is a novel environmentally friendly, high-efficiency insulation material with thermal conductivity of one-fifth to one-tenth of that of traditional insulation materials. Vacuum insulations are gradually being employed in several applications, such as construction (Figure 8), refrigerators, cold storage, pipeline insulation, cold chain logistics, etc., due to their excellent properties [44]. Using expanded cork powder as an inexpensive substitute for fumed silica, Jiandong Zhuang et al. developed expanded cork/fumed silica composites with a hierarchical porous structure as the core of vacuum insulation panels with a thermal conductivity as low as 0.006 W/m·K [40].

In the most recent thermal insulation technology, vacuum insulation panels with super-layered glass fibre cores are produced by centrifugal spin blow moulding, and the thermal conductivity of a 3 mm vacuum insulation board reaches 1.25 mW/m·K, significantly improving the service life of the insulation board. Their further advantage is lower energy consumption as well as lower cost compared to traditional wet processes [45].

Vacuum insulation materials, on the other hand, can be used to replace vacuum glasses in building windows for improved thermal insulation. The results demonstrate that the insulating material with a vacuum pressure of 10 pa in the interlayer can provide a better insulation effect, but at a much higher cost [46]. Due to the instability of the vacuum environment, residual gases such as N_2, O_2, H_2O, and H_2 often appear in the vacuum space after the material is used for a certain period. Vacuum insulation products that often employ getters ensure that the material properties remain unchanged after long-term usage, which improves the service life of vacuum insulation materials [47]. A vacuum insulation board is an excellent insulation material; however, it is essential to ensure the structure of the insulation board is stable since its elements are insulated by vacuum. Reducing manufacturing cost and prolonging service life have always been major research topics [48,49].

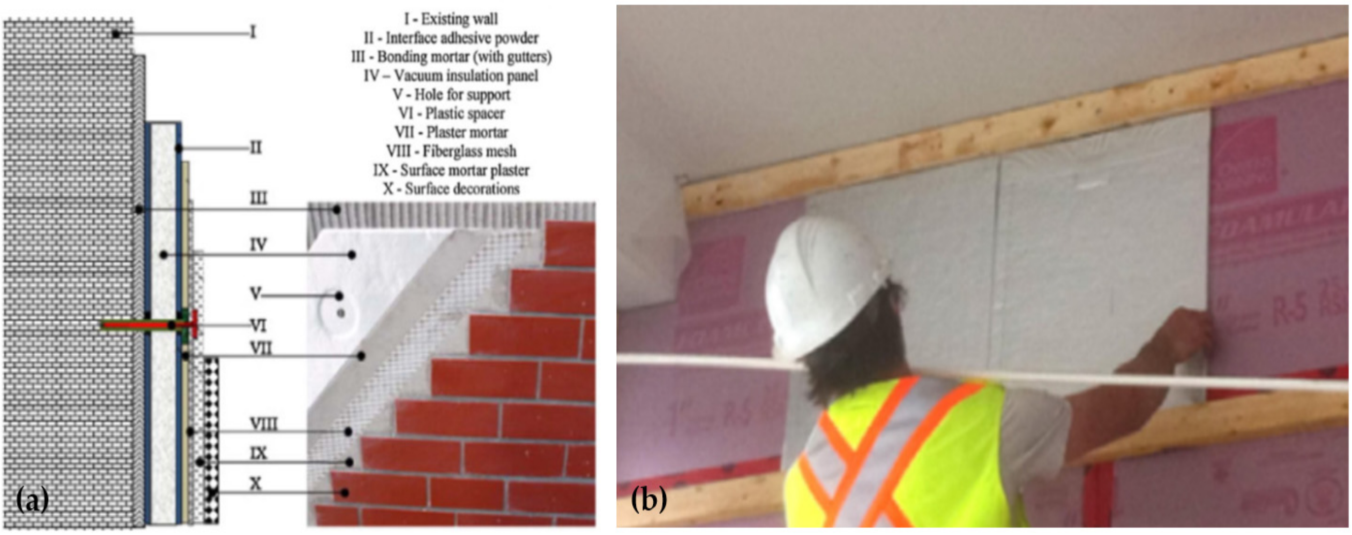

Figure 8. (**a**) Assembly of a vacuum insulation system, and (**b**) commercial vacuum insulation panels [50,51].

Theoretically, vacuum insulation should have the best thermal insulation performance, but more work is required to ensure durability in real-world applications. A strong and lightweight seal material is also required as the frame to maintain the vacuum inside the panel. Besides, the high cost is a barrier that must be solved for future developments.

2.3.5. Reflective Insulation

Thermal insulation systems commonly used in buildings reduce conductive and convective heat transfers between the interior and the outside of the building. Reducing the impact of indoor and outdoor radiative heat transfer in buildings is also a way to achieve building energy efficiency [52]. Reflective insulation systems, internal radiation control coatings, and inflatable panels are examples of building insulation technologies that use the reflective principle [53]. The performance of reflective insulation systems varies in different climates. As reported, reflective insulations can significantly reduce internal degree days and thermal energy in cold, temperate humid, hot arid, and hot humid climates [54].

By providing a reflective space interlayer in the middle of the insulation material, thermal insulation performance can be effectively improved. The latest reflective insulation technology incorporates wood fibreboard and an intermediate air layer with a highly reflective interface, which is used to reflect long-wave infrared radiation, with seven layers of multi-air layer insulation with thermal conductivity of about 0.033 W/m·K. Compared with the available building insulation materials in the market, reflective insulations pose a higher insulation potential [55].

In terms of the insulating concept, reflective insulation differs from conventional insulation materials. It reduces the heat radiation absorbed by the building via reflecting heat radiation, achieving the purpose of thermal insulation. The air wall is often covered with a layer of aluminium foil. This foil is also employed as an extra heat preservation mechanism, which functions in a variety of composite heat preservation boards and insulation membranes.

2.4. Sustainable Insulation Materials

As mentioned earlier, the building and construction sector has a number of undesirable environmental issues associated, like using 40% of the world's natural resources and producing over 45% of waste disposal [56]. Inorganic insulation materials, despite their widespread use in buildings for wall insulation due to their fire-resistant benefits, have major environmental impacts [57]. On the other side, organic insulation materials, such as EPS and XPS, are flammable and can emit large volumes of toxic gases when heated to around 80 °C [58]. Since building walls contain an extensive area in comparison to other components (floors, roofs, attics, etc.), it is essential to transition to safe, sustainable materials in order to address current safety issues and environmental concerns. In this section, a variety of sustainable insulation materials are reviewed and discussed.

2.4.1. Bio-Insulation Materials

Bio-insulation materials were first studied in 1974 [59]. Researchers and professionals have then widely invested in bio-insulation material development, especially after 2003. The materials studied mainly include coconut, wood (e.g., plywood [60], sawn timber [61], laminated wood [62], particleboard [63], and biocomposites [64,65]), hemp, sunflower, corn, flax fibre, straw, etc [66].

Indra Mawardi et al. [67] recently conducted a research study on the insulating effectiveness of oil palm wood binderless panels. It is reported that such bio-insulation panels with a particle palm wood size of 0.42–0.84 mm offer good thermal insulation and sound absorption capabilities. Xuhao Zhang et al. [68] studied a thermal insulation cement made of magnesium phosphate cement and corn stalk, and based on their results, the walls with this material can better regulate temperature and relative humidity changes, improving the indoor environment's comfort. Shuang Wang et al. [69] experimentally investigated a rice husk/geopolymer foam composite. They showed that the new composite mixed with rice husk is of satisfactory performance to be used in buildings for energy-saving purposes. Lifang Liu et al. [66] assessed the thermal, mechanical, and hydraulic properties as well as the micromorphological effects of a bio-insulation material in which wheat straw and geopolymers were used as aggregate and binders, respectively. According to the findings, this new bio-insulation material has acceptable thermal and mechanical qualities and can be utilised in wall insulation applications, especially for prefabricated buildings. Dang Mao Nguyen et al. [70] carried out experiments on thermal insulation boards made of six different biological types of glue and bamboo fibres. They concluded that 70% bamboo fibre plus 30% bone and sodium lignosulfonate is an optimal ratio for their insulation boards to efficiently control the humidity and conserve building energy.

Although there have been many breakthroughs in bio-insulation thermal performance, the presence of organic components in biomass materials calls for additional research regarding durability, insect resistance, corrosion resistance, and flame retardancy.

As a sustainable building material, the use of bio-insulation materials in construction is highly encouraged.

2.4.2. Agriculture Waste Materials

Agricultural waste insulation materials, which are primarily natural or waste materials, abundant in resources, inexpensive, and free of complicated production processes, significantly contribute to achieving sustainable development goals in the building and construction sector.

Ana Ramos et al. [71] developed a particleboard using polyvinyl acetate and corncob and studied its thermal performance and environmental impacts. The experimental results revealed that agricultural waste and by-products are of desired thermal performance, allowing them to be used as promising eco-friendly building insulation materials. Nga et al. [72] applied a freeze-drying procedure to produce thermally insulating and flexible cellulose-based aerogel composites using pineapple leaves and cotton waste fibres. In this study, the authors investigated the material's density, porosity, morphology, durability, and thermal properties to ensure whether such developed biomass aerogel composites can be used for insulation purposes in real situations. Baiba Gaujena et al. [73] analysed the hydrothermal properties of hemp insulation boards in which the local agricultural residues can also be used. They found that the effect of binder powder on thermal conductivity is minimal, however, the value obtained using hemp is much higher than that of traditional insulation materials.

2.4.3. Recycled Insulation Materials

Converting available waste sources into high-value products is critical to promote sustainable development as well as to reduce production costs. Reviewing the literature, there is an increasing number of studies on the utilisation of recycled materials for wall insulations [74]. In a study conducted by Nga et al. [74], the biodegradable xanthan gum solution was mixed with the fibre skeleton as a binder and freeze-dried, leaving a hollow porous structure. This material is reported as an environmentally benign and cost-effective insulation for building applications. Moghaddam Fard et al. [75] developed a new thermal insulation material out of recycled plastic and polystyrene, sandwiching recycled plastic bags between polystyrene insulation boards for improved thermal insulation performance as well as fire and water resistance; however, compressive strength was sacrificed. Reynoso et al. [76] developed a new type of recycled insulation material with thermal insulation properties comparable to commercial insulation materials using expanded polystyrene waste, cementitious adhesives, plastic additives, and water. Jensen et al. [77] investigated the properties of regenerated cellulose building materials and concluded that insulating materials consisting of regenerated fibres are low-cost, have good thermal and acoustic insulation capabilities, and can be used to replace traditional insulating materials. Overall, the use of recycled materials can provide novel thermal and acoustic insulators with high performance and low cost, which is the future path of insulating material research.

Table 1 summarises the main characteristics and production processes of commonly used building insulation materials based on their category.

Table 1. Main characteristics and production process of building thermal insulation materials.

Category	Thermal Insulation Material	Thermal Conductivity (W/m·K)	Density (kg/m^3)	Specific Heat (kJ/kg·K)	Installation Position in Wall Structures	Production Method	Refs.
Inorganic insulation material	Fibrous (Glass wool)	0.030–0.046	10–100	0.9–1.0	Interior and exterior	Glass wool is made by mixing natural sand and typically recycled glass at temperatures ranging from 1300 to 1450 °C. Centrifugation and blowing procedures are used to convert fibres, which are subsequently linked together via resin.	[5,19]
	Fibrous (Rock wool)	0.033–0.046	40–200	0.8–1.0	Interior and exterior	Rock wool is made by melting stone (diabase, dolerite) at around 1500 °C and hurling the molten material out of a wheel or disc, resulting in fibres.	[18,33]
	Cellular (Foamed glass)	0.038–0.055	100–200	0.21	Exterior	Porous foam glass is a porous glass material filled with bubbles after softening, foaming, and annealing by adding a foaming agent, modifier, accelerator, and other ingredients based on ordinary glass.	[78,79]
	Cellular (Perlite)	0.040–0.060	32–176	0.2	Interior and exterior	Polystyrene foam is turned into polystyrene emulsion with water, then heated and combined with expanded perlite in a rotary drum.	[80,81]
	Cellular (Calcium Silicate)	0.059–0.065	200–240	1.3	Usually for interior	Calcium silicate slurry is made by breaking calcium silicate and mixing it with water. The hard calcium silicate slurry is synthesised and prepared by adding fibre-reinforced raw materials and sodium silicate at 190–250 °C and 1.3–4.0 MPa.	[82]
	Cellular (Vermiculite)	0.040–0.064	64–130	0.84–1.08	Exterior	Vermiculite with a diameter greater than 2 mm is screened and put into the crucible. The expanded vermiculite is then made by calcining the crucible containing vermiculite at high temperatures in a muffle furnace.	[83,84]

Table 1. *Cont.*

Category	Thermal Insulation Material	Thermal Conductivity (W/m·K)	Density (kg/m^3)	Specific Heat (kJ/kg·K)	Installation Position in Wall Structures	Production Method	Refs.
Organic insulation material	Polystyrene (EPS)	0.031–0.037	15–75	1.25	Interior and exterior	EPS is typically made by evaporating pentane into polystyrene particles. This method may produce closed-cell foam that is white and stiff.	[5,20]
	Polystyrene (XPS)	0.025–0.035	32–40	1.3–1.7	Interior and exterior	XPS is made by feeding molten polystyrene (like hydrofluorocarbons (HFC)), CO_2, or C_6H_6 through a nozzle, relieving pressure, expanding, and adding a foaming ingredient.	[18,20,28]
	Polyurethane (PUR)	0.020–0.030	30–160	1.3–1.45	Interior and exterior	Polyurethane (PUR) and polyisocyanurates are made when isocyanates and polyols react. During expansion, the closed pores are filled with expanding gases, CO_2, or C_6H_6.	[1,18,29]
	Cork	0.037–0.050	100–120	1.5–1.7	Exterior	Cork thermal insulation is primarily made from cork oak.	[18,29]
	Fibrous (Cellulose)	0.037–0.042	30–80	1.3–1.6	Interior and exterior	Cellulose is made using recycled paper, wood fibre and boric acid to improve thermal characteristics.	[5,18,32,33]
	Fibrous (Sheep wool fibre-epoxy composites)	0.32–0.3	-	-	Exterior	The epoxy resin and hardener are mixed at a ratio of 100 and 58 parts/weight, respectively. The wool samples are taken from two different Greek sheep breeds, i.e., Kalarritiko and Katsika. The composite is finally made using a hydraulic heat press.	[34]
	Fibrous (Sheep wool and gypsum composites)	0.046	415	-	Exterior	After equally mixing the gypsum and water, it is poured on the sheep wool and dried to form the composite. Composites containing 35 g sheep wool, 250 g gypsum, and 160 g water are in high demand.	[35]

Table 1. *Cont.*

Category	Thermal Insulation Material	Thermal Conductivity (W/m·K)	Density (kg/m^3)	Specific Heat (kJ/kg·K)	Installation Position in Wall Structures	Production Method	Refs.
	Fibrous (Sheep wool inner wall insulation layer)	0.04	-	-	Interior	Sheep wool is directly used inside the wall. To achieve the insulating function, using gypsum cement is also utilised as a binder to form a 0.08 m thick inner wall insulation layer.	[36]
State-of-the-art insulation material	TIM (without aerogel)	0.22×10^{-3} –1.3×10^{-3}	-	-	Interior	TIMs are assembled using a transparent cover and double-pane glazing unit with an air cavity.	[18,38,85]
	Aerogel	0.013–0.021	70–150	1.0	Exterior	Aerogel is synthesised using the sol-gel process to remove liquid from the gel.	[18,86]
	Closed-cell foam	0.025–0.048	16–55	-	Exterior	Closed-cell foam is spray insulation in which the cells are entirely enclosed and pushed together to avoid air and moisture traps within the foam.	[87]
Sustainable insulation material	Bio-insulation (Oil palm wood)	0.050–0.143	0.58–0.70	-	Interior and exterior	Using heat, the oil palm wood is pelletised, boiled, dried, and pressed into insulation boards.	[67]
	Bio-insulation (Magnesium phosphate cement and large corn stalk)	0.087–0.165	0.060–0.131	0.101	Interior and exterior	MgO, fly ash, and $NH_4H_2PO_4$ are combined in a 3:1:2 weight ratio to prepare the MPC binder. Corn stover thermal insulation concrete, in which corn stover makes up a third of the total weight of all solid materials, is obtained after stirring and curing.	[68]
	Bio-insulation (Rice husk/ geopolymer foam composite)	0.082–0.184	174–813	-	Interior and exterior	The rice husk is combined with a stabiliser, a foaming agent, and a mixture of alkaline activator and metakaolin before being moulded.	[69]

Table 1. *Cont.*

Category	Thermal Insulation Material	Thermal Conductivity (W/m·K)	Density (kg/m^3)	Specific Heat (kJ/kg·K)	Installation Position in Wall Structures	Production Method	Refs.
	Bio-insulation (Wheat straw)	0.092–0.186	235–894.1	-	Interior and exterior	After the wheat straw has been pre-wetted, the mixed water and NaOH solid particles are added to the sodium silicate solution to make the alkali activator. The mineral binder, metakaolin and the alkali activator are mixed, followed by the surfactant and the H_2O_2 solution. The pre-wetted wheat straw is finally added to the foam geopolymer slurry.	[66]
	Bio-insulation (Bamboo fibres)	0.077–0.088	311–538	-	Interior and exterior	Bamboo fibres and glue are manually mixed and dried in an oven at 100 °C for 24 h. Fibreboards are then prepared after pressing via a hydraulic press.	[70]
	Agriculture waste (Corncob particleboards)	0.052–1.33	-	-	Interior and exterior	After the corncob is punched into a board, the surface is coated with 15% (w/v) polystyrene to fill the voids between the fibres and strengthen the bond between the particles, resulting in particleboard.	[71]
	Agriculture waste (Pineapple leaf and cotton waste fibres)	0.039–0.043	19–46	-	Interior and exterior	Fibres were cut into smaller sample sizes and blended with sonication dilute polyvinyl alcohol solution. They are then baked in an oven at 70 °C for 2 h. The samples are eventually vacuumed and freeze-dried after being pre-cooled at −5 °C for 24 h to form cellulose aerogels.	[72]
	Agriculture waste (Hemp fibre)	0.054–0.059	200–300	-	Interior and exterior	After final grinding with a disc mill, drying at 150 °C, and adding binder moulding, insulation panels are stabilised by mixing the pre-moistened stem fibre mixture with chopped stems of dried hemp.	[73]

3. Suitable Insulation Materials for Different Climates

3.1. East Asia

3.1.1. Japan

According to meteorological data obtained over 35 years (1981–2015), Japan has six distinct climate zones with six typical representative cities, see Table 2 [12,88]. Yuan et al. [12] carried out a comparative study on various types of thermal insulation materials used in the abovementioned six typical cities in Japan (Figure 9). In this study, they analysed different combinations of EPS, foam board, rock wool, and XPS insulation materials, as well as four fuel sources. The results revealed that the optimal thermal resistance (OTR) of thermal insulation material is maximum when liquefied natural gas (LNG) is used as a fuel source. It is also found that the combination of rock wool and LNG works well in Japan's various climatic zones. The maximum OTR is around 2.5 $m^2 \cdot K/W$ for Sapporo (climate zone I), 2.1 $m^2 \cdot K/W$ for Akita (climate zone II), 1.8 $m^2 \cdot K/W$ for Fukushima (climate zone III), 1.3 $m^2 \cdot K/W$ for Osaka (climate zone IV), and 0.9 $m^2 \cdot K/W$ for Kagoshima (climate zone V), and there is no need to adopt thermal insulation for Naha (climate zone VI). From climate zone I to VI, the OTR of thermal insulation materials clearly decreases (from low latitude to high latitude). Additionally, regarding the total potential energy cost saving (ECS), the highest ECS is reached by adopting the ideal mix of rock wool and LNG for all climate zones in Japan. Furthermore, the payback period (PP) tends to increase from climate zone I to VI, which corresponds to low latitude to high latitude; The shortest PP is about 0.4 years in Sapporo (climate zone I), 0.5 years in Akita (climate zone II), 0.6 years in Fukushima (climate zone III), 0.8 years in Osaka (climate zone IV), and 1.2 years in Kagoshima (climate zone V).

3.1.2. China

The climate zones of China are classified into five groups. As Zhu et al. [13] reported, Urumqi, Beijing, Shanghai, Guangzhou, and Kunming are typical cities in China's various climate zones, with optimal EPS thicknesses of 175 mm, 216 mm, 205 mm, 116 mm, and 163 mm, respectively. Furthermore, increasing the EPS thickness from the required to the optimal value can reduce the average annual cost of Urumqi, Beijing, and Shanghai by 18%, 37%, and 52%, respectively. In addition, it is found that instead of EPS, XPS can provide better insulation and has a lower average annual cost during the life cycle. Huang et al. [11] developed a typical building model in China's humid subtropical climate zone and compared the performance of a new aerogel super insulation material to four other commonly used insulation materials. Using degree days and P1-P2 methodologies, the appropriate thermal insulation thickness, recovery period, and energy-saving effect of thermal insulation materials across their entire life cycle were determined. The results demonstrate that the optimum insulating thickness of aerogel in an aerated concrete wall is the shortest 3.7 mm), when compared to XPS (44 mm), EPS (70 mm), polyurethane (38 mm), and glass fibre (45 mm). They also found that the corresponding greenhouse gas emissions of aerogel are reduced more rapidly as its thickness is increased. The new aerogel material has the potential to decrease CO_2 emissions by up to 8.169 $kg/(m^2$ year). It is also found that the thickness of the insulating layer has a greater impact on the thermal load of the buildings than on the cooling load. When different cities (representative cities of the five climate regions) adopt the same external thermal insulation technologies for the same type of buildings, Harbin saves the most energy, followed by Xi'an, Shanghai, Kunming, and Guangzhou. Increased thermal insulation thickness has a negligible effect on energy savings in Guangzhou constructions. Zhang et al. [8] showed that increasing the insulating thickness of external walls can reduce the annual cooling and heating load. When the insulation layer reaches a specific thickness, further increases in thickness result in a slight rise in the annual cooling and heating load.

Table 2. Details of Japan's six climatic regions [12].

Climate Zones	Representative Cities	HDD18 (°C-day)	CDD28 (°C-Day)	Location (Lat., Long.)
I	Sapporo	3530.1	0.0	43.1° N, 141.3° E
II	Akita	2746.3	0.0	39.2° N, 140.1° E
III	Fukushima	2362.2	0.0	37.8° N, 140.5° E
IV	Osaka	1485.5	28.6	34.7° N, 135.5° E
V	Kagoshima	1024.3	25.4	31.6° N, 130.6° E
VI	Naha	60.0	52.8	26.2° N, 127.7° E

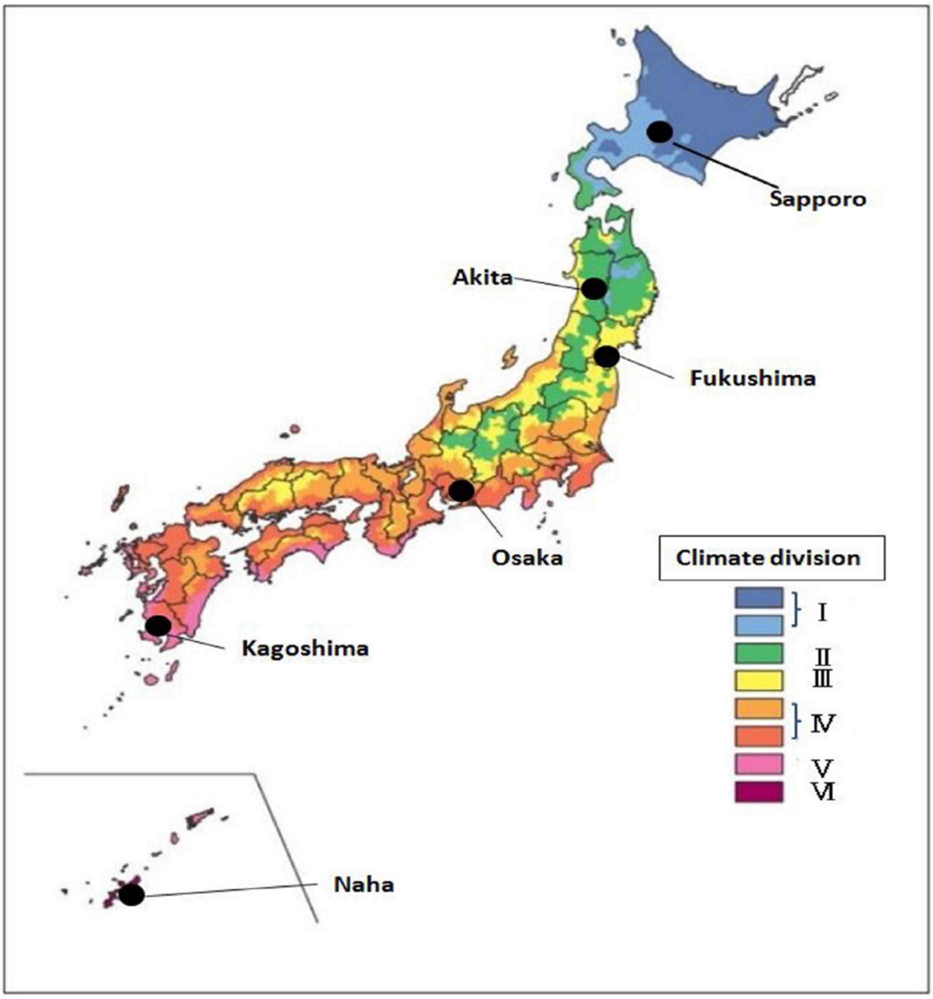

Figure 9. Six climate zones of Japan and representative cities in different climate zones [12].

3.2. The Middle East

The Middle East has a hot climate, with the summer months of June and August being particularly scorching. Rehman [89] studied solar calorimeters by conducting open-air outdoor testing at Lak city, United Arab Emirates, to investigate the energy-saving advantages of solar insulation materials. The findings showed that by refurbishing building facades with polyisocyanurate and reflective coatings, or high energy-efficient dry insulation walls, an average of 7.6–25.3% energy savings can be realised. Reflective insulation materials are a viable option in the Middle East, where the sun is more abundant. Synnefa et al. [90] investigated how increasing roof reflectivity might reduce energy usage in a warm area, and the results demonstrate that it is able to significantly decrease building energy consumption.

3.2.1. Iran

Iran is one of the few countries in the world that can build and preserve a variety of vernacular structures in different regions to accommodate varying climatic and geographical conditions [91]. In general, Iran is divided into three climate types: (1) hot, arid and semi-arid, including the central desert, east of the country, and the northern Persian Gulf, (2) cold and dry, including the western and north-western areas, as well as the Zagros mountains, and (3) the Mediterranean or mild climate, including south of the Caspian Sea and north of the Alborz mountains [92]. Since the climatic conditions differ from city to city in Iran, Iranians use a range of architectural elements and strategies to develop their national architecture. Buildings in Iran often manage indoor temperature through extraordinary measures, such as very thick walls, cellars, passive ventilation, unique building designs, etc., and rarely use external wall insulation materials [91]. In modern buildings, however, due to the heat and ample sunlight, more reflective insulation materials and some bio-insulation materials can be explored to reduce building energy consumption.

3.2.2. Turkey

As shown in Figure 10, Turkey is divided into four distinct climate zones as defined by TS825 (Turkish Standard 825), and the hottest and coldest cities are considered as Regions 1 and 2, respectively. The difference in monthly mean temperature between regions 3 and 4 is small, but the two climatic regions are distinguished according to the maximum energy consumption per unit volume of buildings defined in TS825. Yigit et al. [93] reported that although three materials are available for exterior walls and suspended ceilings, EPS is commonly utilised for external walls, and stone wool insulation is used for suspended ceilings in all regions of Turkey The total cost of the materials is also between \$25,000 and \$30,000.

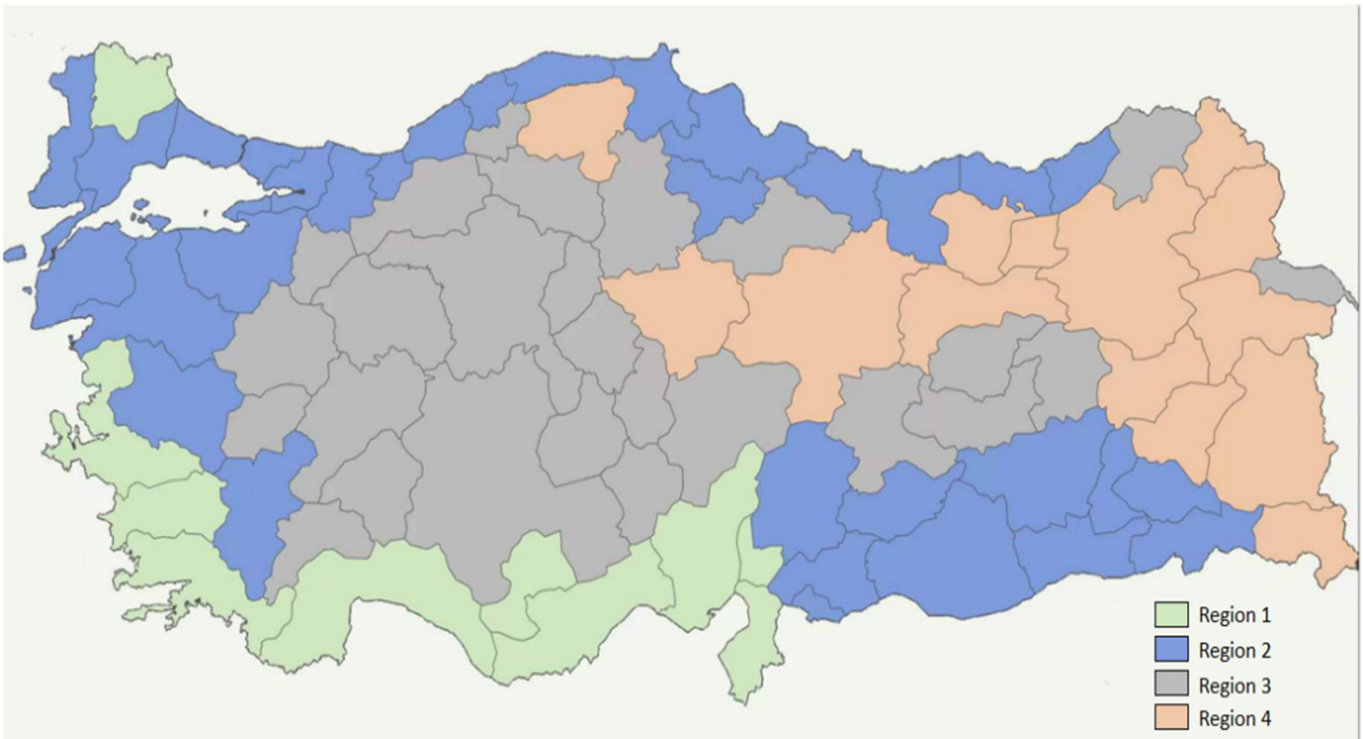

Figure 10. The four climate regions in Turkey [93].

3.3. North America

3.3.1. Canada

As Berardi [15] concluded, the relationship between temperature and insulations' thermal conductivity in the Canadian climate is mostly linear. Low temperatures reduce the thermal conductivity of inorganic insulation materials like glass fibre and asbestos, as well as petrochemical insulation materials such as polystyrene. Some compounds, however, have their own thermal conductivity and temperature correlations, such as foam insulating materials like polyisocyanurate. Furthermore, Awad et al. [94] reported that wood fibre (Type A) multi-functional panel (MFP) is recommended for south-facing external wall constructions in temperate climates like Vancouver. In cold climates, such as Edmonton, particularly in north-facing wall assemblies, XPS (Type B) MFP is recommended for better thermal resistance. Besides, when both MFPS are added to a normal wall assembly, the thermal performance and the temperature distribution within the wall are considerably improved.

3.3.2. Mexico

As indicated in Figure 11, Mexico is of numerous microclimates, which are classified into three broad macroclimatic regions: warm-dry, temperate, and tropical-humid. Reyes-Barajas et al. [95] indicated that Mexico's hot, arid climate zone has the highest percentage of insulation applications in the country, where almost 90% of houses have roof insulation. Rosas et al. [14] assessed the optimal thickness of adiabatic materials in several climate zones across Mexico, finding that the optimal thickness of expanded polystyrene, extruded polystyrene, glass wool, rock wool, and polyurethane insulation materials are 89 mm, 75 mm, 142 mm, 106 mm, and 53 mm, respectively. The recommended thickness of the five above-said insulations for tropical households are 74, 63, 119, 89, and 45 mm, while their optimal thicknesses for profiles are 33, 29, 54, 40, and 20 mm, respectively. These findings can be used to help decision-makers comply with the Energy Reform and Energy Conversion Act, whose goal is to implement strategies to supply fuel at lower prices, and increase the use of clean energies, thereby reducing the corresponding environmental impacts.

3.4. South America

Brazil

Emeli et al. [16] investigated the thermal comfort and discomfort periods of various insulation materials used in houses located at the Brazilian plateau, which is influenced by equatorial low pressure and low latitude trade winds with dry and wet characteristics (i.e., a typical savanna climate). As they found, by 2080, the average annual temperature will be 32.48 °C, with an annual relative humidity of 53.67%. Furthermore, in Brazil's Midwest, the use of rock wool and glass cotton can provide the highest comfort and satisfaction for occupants. The service life of these two types of insulation materials accounts for 50.2%, which is higher than the average time spent using EPS (47.8%).

3.5. Europe

Europe has a Mediterranean climate, which means hot, dry summers and mild, rainy winters. Considering sustainable development goals, recycled materials should be used as much as feasible instead of traditional insulation materials. The great hydrophilicity and water absorption of the regenerative bio-insulation material will result in low dimensional stability and excessive expansion [96–98]. Therefore, under the rainy climate conditions of Europe in winter, the use of regenerated bio-insulations has to address the materials' water absorption difficulties. Other recycled materials, such as recycled plastics and recycled foam boards, show better hydrophilicity, fire resistance, and stability than recycled biomass materials, and are more suited to Europe's Mediterranean environment. For a residential building in Berlin, Germany, Urbikain [99] proposed using vacuum insulation panels and triple-glazed low-E argon-filled windows to be used instead of traditional insulation panels (such as mineral wool and foam) and typical windows. According to the simulation results, the building's energy consumption is reduced by 66%. However, there are certain drawbacks to vacuum insulation panels, such as their high cost, short service life, and poor stability, which should be researched and addressed in future studies.

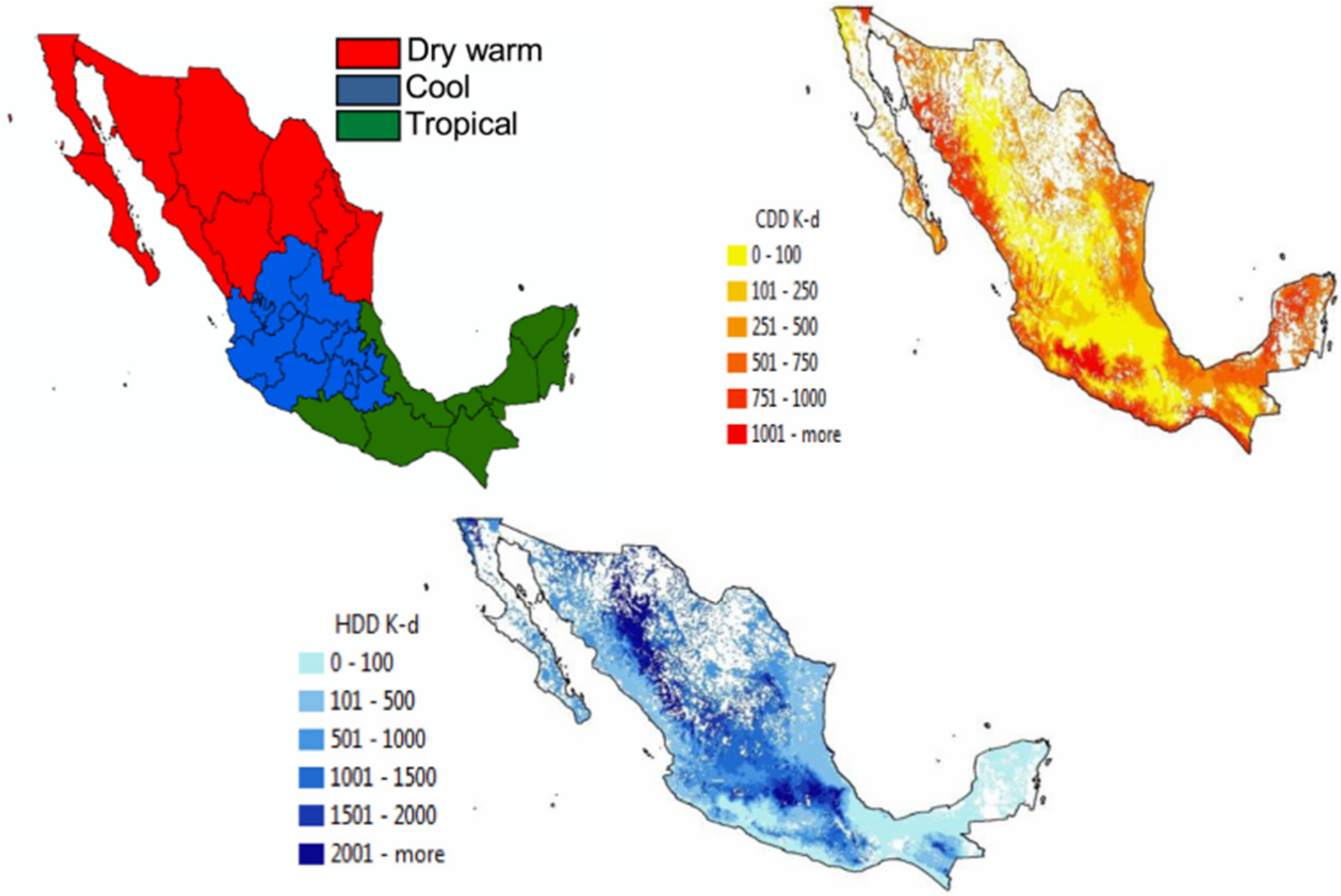

Figure 11. Mexican climatic zones [14].

3.6. Australia

Australia covers a broad range of latitudes and climates. The central and western regions are uninhabited deserts, arid and less rainy, with high temperatures and significant temperature differences, while the coastal areas have abundant rainfall and a humid climate. Dileep Kumar et al. [100] investigated the use of aerogels and phase change materials (PCMs) as insulations in a typical single-story dwelling in Melbourne with a temperate oceanic climate. By applying aerogel paint and PCM on the exterior walls, as well as adding PCM to the ceiling, the time of indoor discomfort is reduced by 82%, and the overall energy consumption is lowered by 40%. In the study conducted by Mostafa and Morteza Razzaghmanesh [101], a new thermal insulation strategy in Australia, called a living wall, is described, which leverages the growth of plants on the wall to provide thermal insulation. Using this strategy, the surface of the wall is cooler in the summer and warmer during the fall.

3.7. Summary

Following is a summary of the abovementioned discussions of proper insulating materials for various climatic types in different regions:

- The OTR of thermal insulating materials drops substantially in climates where the temperature range between summer and winter is higher, but their payback period will be shorter. The effect of saving energy will be more noticeable as the thermal insulation layer thickness rises.

- Reflective insulation can be utilised in hot, sunny climates to further reduce energy use, as is already the case in Iran and the Middle East. Additionally, roof insulation is frequently used in hotter, more arid climates.
- Researchers have frequently examined the optimum insulation material thickness for the commonly used insulation materials in various climatic zones within a specific country or region. Chinese scientists, for instance, tested the optimum EPS of representative cities in temperate continental climate (Urumqi), temperate monsoon climate (Beijing), and subtropical monsoon climate (Shanghai), and found that the best EPS thickness in these areas is 216 mm, 205 mm, and 175 mm, respectively. The average annual cost can be significantly decreased while also enhancing the economy and environmental protection by designing the optimal thickness for various climatic types.
- In temperate areas, wood-fibre multifunctional panels can be utilised for south-facing external walls for enhanced heat resistance, whereas north-facing exterior walls in cold climates can use XPS multifunctional panels.
- Due to the wide temperature range between climate zones, it is essential to consider the linear relationship between temperature and thermal conductivity when designing external wall insulation materials. Low temperatures will decrease the thermal conductivity of inorganic and petrochemical insulation materials.
- In savannah climate regions, such as the central and western parts of Brazil, rock wool and glass wool insulation materials are typically used. This increases individual thermal comfort and satisfaction. Additionally, the service life of these two types of insulation materials is generally higher than that of EPS in these climate regions.
- Some European countries prefer to use recycled plastic, foam board, and other insulating materials that have superior hydrophilicity, fire resistance, and stability due to the Mediterranean climate, which is typically hot and dry in the summer and mild and rainy in the winter.
- Aerogel and PCMS are being used as exterior wall insulation materials in countries with predominantly temperate marine climates to save energy and improve indoor comfort levels. These countries also use wall plants as insulation, keeping the interior cool in the summer and warm in the winter.
- Different types and thicknesses of insulation materials are normally not selected in areas that experience slight climatic variations. Instead, these countries frequently focus on past design practices and the cost-effectiveness of insulation when designing insulated facades.

4. Current Challenges and Opportunities

There are still certain concerns on this topic that require further research based on what has already been discussed about the thermal performance and optimal design of various commonly used thermal insulation materials in different climates. The following are potential future research avenues:

- Studies have revealed that conventional lightweight building envelopes often disregard the characteristics of heat capacity, which can increase the risk of interior overheating in mild and warm climates. In such cases, specific ventilation techniques as well as high thermal resistance façades are recommended to manage indoor air temperature [102,103].
- Following the relevant building energy conservation design standards, finding the proper thermal insulation materials in various climate zones and promoting the innovation of external wall thermal insulation structure technology can ensure the realisation of building energy conservation goals. This is because the requirements for building energy conservation around the world are rising.
- As the thermo-physical characteristics of dynamic insulations will vary with environmental circumstances, they should be developed and used in building envelopes in the future to prevent the adverse impacts of diurnal and seasonal variations.

- Phase change material (PCM) exterior wall insulations are excellent for usage in mild and warm regions because they absorb and store heat in large quantities, preventing overheating [104,105]. The prior studies indicate that, however, there is still a lack of applicable research on how to introduce PCM into exterior wall insulation materials and ensure their rigidity and durability.
- Although previous studies have conducted lots of research on exterior wall insulation materials in various climate zones, it should go through the whole process of the planning layout as well as the design of buildings' components. In order to obtain the best outcomes from the architectural envelope design, it is still required to test and refine the current approaches.
- Future research should prioritise the volume heat capacity of wall insulation materials in addition to their durability, thermal resistance, thermal conductivity, as well as sustainability-related concerns.
- In addition to providing superior insulating performance, insulation materials also need to focus on other qualities like affordability and environmental issues, especially carbon emissions. To replace non-renewable energy sources in various climate zones, it is also possible to introduce solar energy as a renewable energy source; for instance, building envelopes in building integrated photovoltaics (BIPV) [106–108].
- More new advanced technologies can be offered by the developed countries for the development of thermal insulation materials due to the better economic status of these industrialised countries. Developing countries are also encouraged to focus on thermal insulation materials are encouraged to assist in updating the relevant policies to facilitate the promotion of energy conservation and emission reduction targets in the building and construction sector.

5. Conclusions

Insulation materials play an essential role in building energy efficiency, and all insulation materials have a number of specific characteristics. The main findings of the current review can be summarised as follows:

- Thermal conductivity is the most crucial factor since it influences the thermal insulation effect of materials. Using materials with lower thermal conductivity can help reduce the thickness of the external wall insulation layer while still providing the same energy saving. At the end of the life cycle, recycling rates should also be improved.
- The second key factor is the durability of the material. Bio-insulations and recycled insulating materials have varying degrees of durability; In high-humidity climates, mildew and insects may harm biomass materials used as insulation. The review has shown that traditional thermal insulation materials, such as EPS and XPS, typically are of acceptable durability. However, new sustainable materials, such as recycled materials, wool, bio-mass materials, etc., contain organic components, which are prone to mildew, corrosion and insects. Vacuum insulation panels also need improved materials to prevent air leakage. Future research on durability aspects is required as a result.
- The service life and the thermal insulation effects can also make users unsatisfied. For arid environments, the fire resistance property cannot be ignored. Some traditional thermal insulation materials, like EPS, glass wool, rock wool, and polyurethane, offer much better fire resistance than sustainable materials. Sustainable insulations, however, can be used in combination with other materials to improve refractory performance, although they may lose their economic advantage.
- Temperature, humidity, and sunlight intensity are three factors affecting the suitability of insulation materials in various climates. When the temperature fluctuates, the thermal conductivity of some compounds changes. Foam insulation materials like polyisocyanurate, for instance, have a particular conductivity; they are not recommended to be used if the temperature difference between day and night is high, or the temperature variation between seasons is large. Insulation materials, like bio-insulations and

recycled materials, are also more sensitive to humidity. In high-humidity conditions, mildew is easily formed, affecting the material's performance. Such sensitive materials are not recommended for external wall insulation in high-humidity environments. It is also suggested that in severe sunlight and high-temperature areas, reflective materials should be employed on buildings' roofs and walls to isolate the radiant heat transfer to the interior space.

- A new form of phase-change thermal insulation material has recently emerged. PCM thermal insulation materials are used to self-adapt to the indoor temperature in order to achieve a more comfortable indoor ambient temperature due to the indoor overheating problem caused by traditional building materials with low heat transfer coefficients.
- Future developments should be directed towards sustainable and high-performance insulation materials. At this stage, recycled materials still have a lot of issues, like unstable performance, insufficient strength, and short life, that must be addressed. The overall cost of high-performance materials needs to be reduced while their service life is extended. The utilization of phase change exterior thermal insulation materials will also be the future development trend. Besides, efforts should be continued to develop materials with lower thermal conductivity while also focusing on sustainability aspects. From the literature, it has been found that some sustainable materials have the same thermal insulation effect as traditional thermal insulation materials, indicating that it is essential to investigate how to improve the durability and suitability of sustainable insulation materials so that they can be widely used in buildings.

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Abbreviations

ASTM	American society for testing and materials
BIPV	Building integrated photovoltaics
CED	Cumulative energy demand
ECS	Energy cost saving
EP	Eutrophication
EPS	Expanded polystyrene
EU	European Union
GSA	Granular silica aerogel
GWP	Global warming potential
HCN	Hydrogen cyanide
ISO	International organisation for standardisation
LCA	Life cycle assessment
LNG	Liquefied natural gas
OTR	Optimal thermal resistance
PCM	Phase change material
POCP	Photochemical oxidant formation
PP	Payback period
PSi	Polyimide-silica
PUR	Polyurethane
TIM	Transparent insulation material
UNFCCC	United Nations framework convention on climate change
XPS	Extruded polystyrene

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