sustainability

Review

A Comprehensive Review and Recent Trends in Thermal Insulation Materials for Energy Conservation in Buildings

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Abstract: In recent years, energy conservation became a strategic goal to preserve the environment, foster sustainability, and preserve valuable natural resources. The building sector is considered one of the largest energy consumers globally. Therefore, insulation plays a vital role in mitigating the energy consumption of the building sector. This study provides an overview of various organic and inorganic insulation materials, recent trends in insulation systems, and their applications, advantages, and disadvantages, particularly those suitable for extreme climates. Moreover, natural and composite materials that can be used as a low-cost, thermally efficient, and sustainable option for thermal insulation are discussed along with their thermal properties-associated problems, and potential solutions that could be adopted to utilize natural and sustainable options. Finally, the paper highlights factors affecting thermal performance and essential considerations for choosing a particular insulation system for a particular region. It is concluded that the most commonly used insulation materials are found to have several associated problems and there is a strong need to utilize sustainable materials along with advanced materials such as aerogels to develop novel composite insulation materials to overcome these deficiencies.

Keywords: thermal insulation; building energy conservation; sustainable materials; composite insulation; buildings

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1. Introduction

According to the International Energy Agency (IEA), global energy consumption is expected to rise by 53% over the next decade. This increase is attributed to the growth in industrial and rapid urbanization, which are a result of rapid infrastructure development and a significant increase in population size in recent decades [1]. Since 2000, the increase in the global energy consumption has been significant. According to the IEA report in 2022 [2], 34% of global energy consumption accounts for building operations, which indicates around one-third of global energy consumption [3]; where around 20% includes the energy consumption by electricity and heat used in the buildings, and around 10% indicates direct energy emission by the building [4]. Similarly, according to the US Energy Information Administration [5], Canada is the seventh-largest country with higher energy consumption per person. Figure 1 indicates the energy consumption per person in 2022 in various countries across the globe. Moreover, the Canadian Center for Energy Information (CCEI) states that 79% of the energy consumption in the residential sector accounts for space and water heating. Similarly, space and water heating utilize 63% of the energy in the commercial and institutional sectors [6]. Figure 2 indicates Canada's total residential and commercial energy consumption as per the energy fact book published by Natural Resource Canada in 2023 [6].

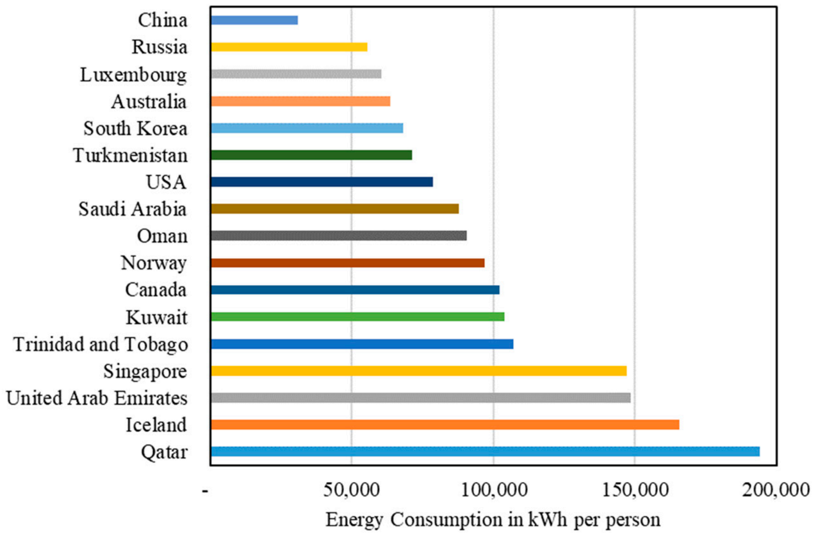


Figure 1. Energy consumption in various countries in kilo-watt hour per person in 2022 [5].

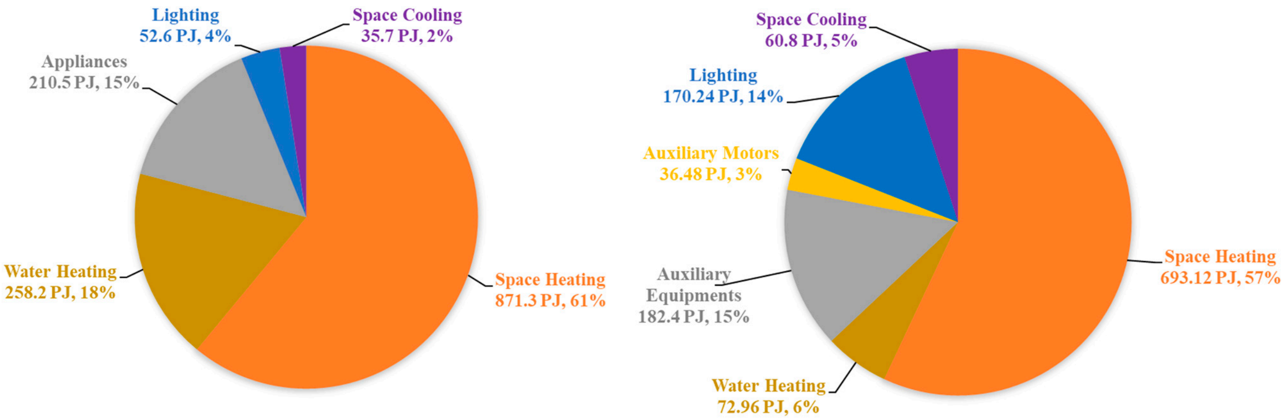


Figure 2. Total energy consumption in Canada: (**a**) residential; (**b**) commercial and institutional sector [6].

The corresponding environmental problems are more apparent daily with the continuous increase in energy demands. Among others, the emission of carbon dioxide (CO_2), which is known as a harmful substance to human health, is continuously increasing. During the year 2022, the global emission of CO_2 increased by 0.9% or 321 Mt, reaching a new peak value of 36.8 Gt. Moreover, out of 321 Mt, 60 Mt of CO_2 emissions are the results of building heating and cooling during extreme weather. CO_2 emission, which is prominent in urban areas, considerably contributes to the greenhouse gas effect, which results in the average rise of global temperature and significant climate change [2,7,8].

According to NASA's and the Wisconsin Department of Natural Resources' (DNR) reports in 2020, the average temperature across the globe increased by approximately 1.1 °C since 1880 [9,10]. Similarly, according to the Intergovernmental Panel on Climate Change (IPCC) and DNR, if proper measures are not taken to tackle the continuous increase in CO_2 and other greenhouse emissions, it is predicted that the average temperature of the earth will rise approximately between 2.0 and 4.0 °C by the end of the 21st century [10,11]. Similarly, the World Wildlife Organization [12] stated that an increase of 2 °C in average global temperature would result in unprecedented and irreversible impacts. Some of the serious highlighted problems could be rising sea levels, disturbances in natural ecosystems, global warming, ice-free arctic, heat waves, and flooding.

The urban heat island (UHI) [13] effect is a phenomenon associated with climate change characterized by significantly higher temperatures in urban areas compared to their surrounding rural regions. This is also the main reason for extremely hot weather in the Gulf countries, as deserts mostly surround them with very limited vegetation, resulting in extremely high energy demand as mentioned in Figure 1. The insulation not only plays a role in cold climates, but also reduces the energy demand in hot climates. However, the reduction in the heating energy demand is higher compared to the cooling energy demand.

On the other hand, the extremely cold weather in various parts of the world, such as Canada, the US, Russia, China, Finland, Norway, etc., increases the demand for energy consumption to achieve a suitable indoor environment [14]. According to the government of Canada [15], recently, in December 2021, on Christmas Eve, a temperature of −45 °C was observed in the northwest territories. Yakutsk City in Russia was the only place at that time with a temperature of −48 °C. Such a harsh environment increases the energy demand required for indoor thermal comfort. The National Energy Code of Canada (NECB) 2020 [16] sets specific requirements for insulation in buildings, including R-value and U-value requirements. The northern Indigenous communities of Canada are severely affected by climate change, as these communities mostly live in remote regions. These communities are facing threats to their traditional ways of life, housing, food security, and cultural practices due to climate change, extreme temperature, and ecological shifts. Considering the unique challenges faced by these communities due to their geographical location and severe weather conditions, there is a serious need for sustainable housing with suitable thermal insulation systems. Thermal insulation plays a critical role in building sustainability and thermal comfort in these communities, where winter temperatures often plummet to significantly lower values, reaching below −40 °C. Effective insulation is paramount to mitigate heat loss from buildings and ensure energy efficiency. It also enhances indoor comfort in such harsh climates and significantly reduces heating costs and energy consumption. Therefore, selecting appropriate insulation materials and techniques is essential to ensure optimal performance in such extreme conditions.

The building sector is considered one of the major consumers of energy, where the major consumption accounts for the heating and cooling of the building. Using novel insulation strategies, energy consumption could be reduced, and the building would be energy-efficient in this scenario as it would require less heating in winter and less cooling in summer to maintain the desired internal temperature. To mitigate energy consumption, it is crucial to promote the adoption of passive techniques to reduce the energy requirements of buildings. Specifically, the designs of walls and roofs should prioritize their functionality as long-term passive systems. This is because a significant proportion of heating and cooling demands within a given area arise from heat transfer through the building envelope. Passive systems encompass a combination of natural and architectural elements, such as insulation materials, shading devices, optimal orientation, and the incorporation of thermal mass in the building structure. Collectively, these components diminish the energy consumed for cooling and heating purposes in buildings [17,18].

As the energy demand continues to rise daily, implementing thermal insulation materials in buildings gained significant interest in the past few decades. Thermal insulation consists of materials or combinations of materials that effectively impede heat flow through conduction, convection, and radiation when applied correctly. Using thermal insulation products reduces the dependency on heating, ventilation, and air conditioning systems for maintaining comfortable indoor environments, thereby conserving energy and minimizing the consumption of natural resources. Additional benefits of thermal insulation materials include cost savings, environmentally friendly properties, extended periods of indoor thermal comfort, noise reduction, and fire protection. The insulation also facilitates energy efficiency in various other sectors, such as food cold storage, refrigeration, and petroleum and liquefied natural gas pipelines. According to the Joint Research Centre (JRC) of the European Commission [19], the global thermal insulation market accounted for USD 22.73 billion in 2015 and is expected to rise to USD 38.69 billion by 2027. The

European Union has the largest thermal insulation market, followed by North America, as mentioned in Figure 3 [19]. The popularity of sustainable insulation products with lower embodied energy and reduced environmental emissions is also trending nowadays, with a wide range of innovative and sustainable insulation types continually entering the market. The use of insulation not only results in energy efficiency, but also reduces greenhouse gas emissions as it reduces the use of naturally available resources such as gas and petroleum reserves used for power generation and energy conservation.

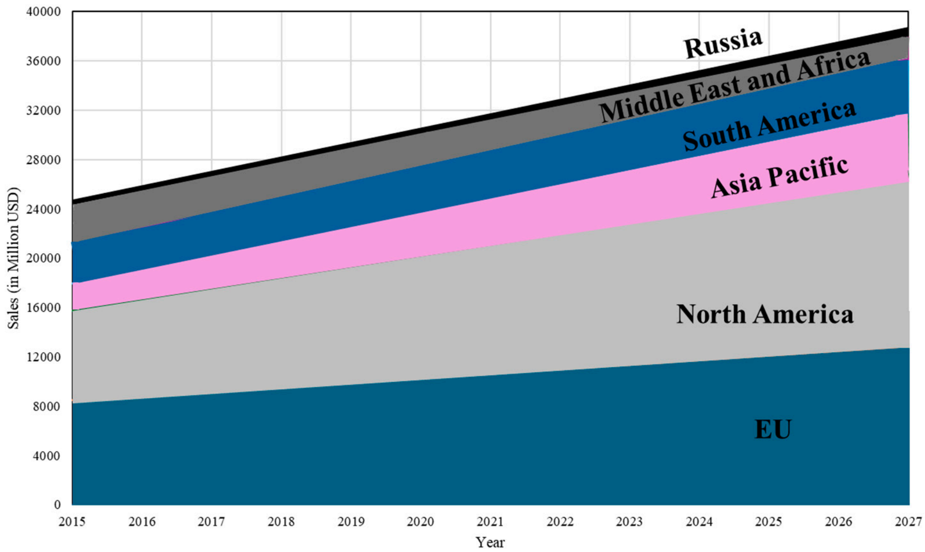


Figure 3. Global thermal insulation market forecast from 2015 to 2027 [19].

Insulation is an energy-efficient method used in residential, commercial, and industrial buildings. Thermal insulation can be made of a material or composite material with a high thermal resistance and can reduce the heat flow rate. Building insulation helps to maintain a comfortable temperature indoors while preventing heat loss to the environment. Due to advancements in research, various materials, such as fiberglass, cellulose, mineral wool, aerogel, polystyrene, and foam, already reached the implementation stage. Properly selecting insulation material depends on various aspects, including the surrounding environment, cost, availability, and insulation goals. For example, a newly developed insulation material such as aerogel has lower thermal conductivity, is lightweight, fire resistant, and has sufficient strength. However, its higher cost may limit its uses for some regions where other suitable and low-cost alternatives can serve the purpose. Similarly, waste products for building insulation play an important role in achieving sustainability in building materials [20]. Waste materials, such as recycled textiles, paper, and glass wool, can be repurposed to create eco-friendly and cost-effective insulation materials with enhanced insulation properties and contribute to waste reduction and resource conservation. These materials demonstrate favorable insulation characteristics and provide thermal comfort, as evidenced by studies such as [21–24]. Moreover, repurposing waste into insulation aligns with circular economy principles, promoting sustainability and reducing environmental impact.

Understanding the importance of thermal insulation and selecting proper insulation material is essential to the building design and overall energy conservation. Therefore, this review paper presents an overview of the traditional and recent advancement in innovative thermal and acoustic insulating materials made from natural, artificial, and recycled materials. This paper discusses the technical parameters and material properties such as density, thermal conductivity, specific heat, sound absorption, fire and vapor resistance, and the sustainability of the various insulation materials. Starting from the traditional insulation strategies, current trends and novel advanced technology materials are highlighted with their applications and availability for commercial applications. Moreover, the feasibility and advantages of using composite insulation over traditional materials are also discussed.

Various problems associated with different insulation strategies and potential solutions to overcome such difficulties are discussed. Finally, a future research direction and important considerations are highlighted to achieve the most suitable insulation for any region. This breadth of coverage is valuable for readers seeking an overview of the field. The emphasis on sustainable materials and the discussion on the use of waste materials for insulation are particularly relevant given the current environmental concerns. Furthermore, the manuscript provides detailed technical parameters and material properties, which can be useful for researchers and practitioners in the field. The inclusion of figures and tables helps in visualizing the data and understanding the trends in the insulation market. Section 2 discusses different types of insulation materials, their production and practical application, important thermal properties, as well as merits and demerits of those materials.

2. Types of Insulation Materials

Insulation materials are essential in modern construction, regulating heat transfer, enhancing energy efficiency, and ensuring occupant comfort. These materials can be broadly classified into organic and inorganic categories, each offering distinct thermal properties. Additionally, advancements in material science led to the emergence of novel materials with exceptional insulating capabilities. Moreover, combining the strengths of various components, composite insulation materials gained prominence for their customized efficiency and versatility in diverse applications. Figure 4 indicates the classification of various insulation materials. According to the literature [25,26], around 60–65% of the insulation materials in the market are inorganic-based (mineral wool), around 21% are organic-based materials, and the remaining account for new and composite materials, as mentioned in Figure 5.

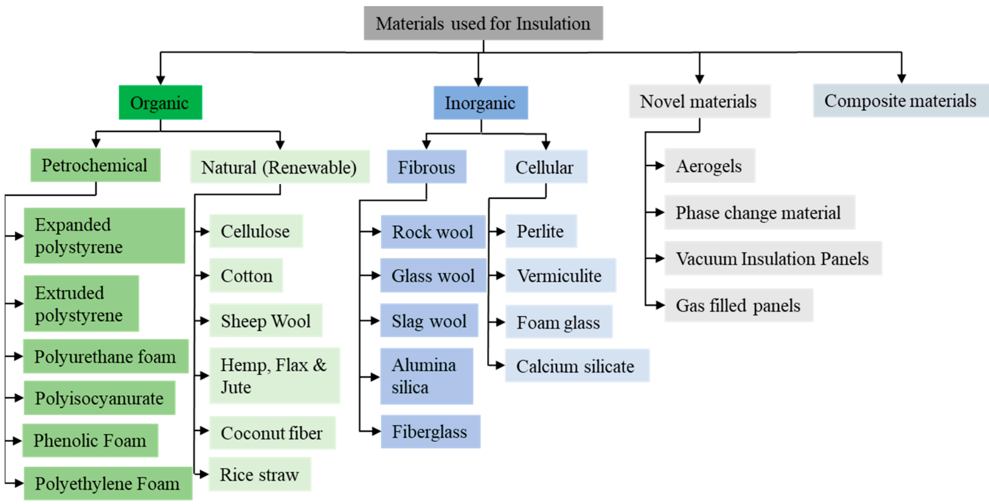


Figure 4. Classification of materials used for insulation.

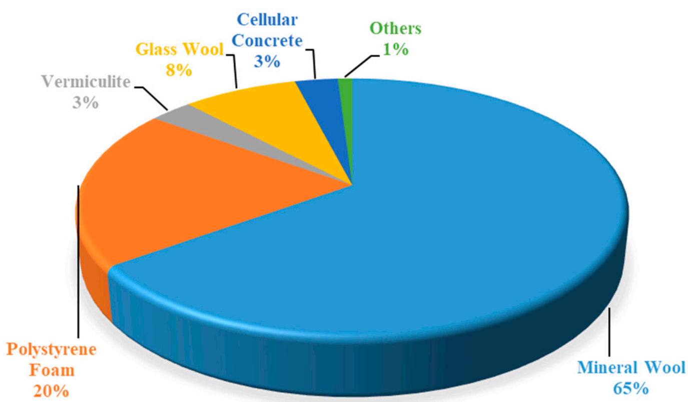


Figure 5. Insulation materials market worldwide [19,26].

2.1. Inorganic-Based Insulation

Inorganic insulation materials are obtained from non-renewable sources categorized into cellular and fibrous materials, accounting for around 60–70% of the insulation material market [26]. In this section, various commonly used inorganic-based materials will be discussed.

Mineral wool is the most used inorganic type of material for buildings. Rock wool, glass wool, and slag wool obtained from different raw materials fall under mineral wool. Rock wool is made from volcanic rock such as basalt [27], glass wool is fabricated utilizing a high content of recycled glass with the addition of limestone, soda ash, and sand [28], and slag wool is obtained from iron ore wastes [29]. Figure 6 illustrates the production process and post-consumption recycling of mineral wool. Mineral wool outperforms other insulation materials, such as fiberglass batts, boasting a notably higher R-value per inch, typically ranging from 22% to 37% greater efficiency. Moreover, it exhibits a stronger environmental profile with 70% recycled content, making it a more sustainable choice than fiberglass, with 20% to 30% recycled material. Mineral wool also maintains its structural integrity better than fiberglass or cellulose, mitigating the risk of settling within wall cavities and the subsequent creation of cold spots along the top plate. Furthermore, its resistance to air infiltration ensures that moisture does not compromise its thermal efficacy, and its composition does not support the growth of microorganisms [30,31].

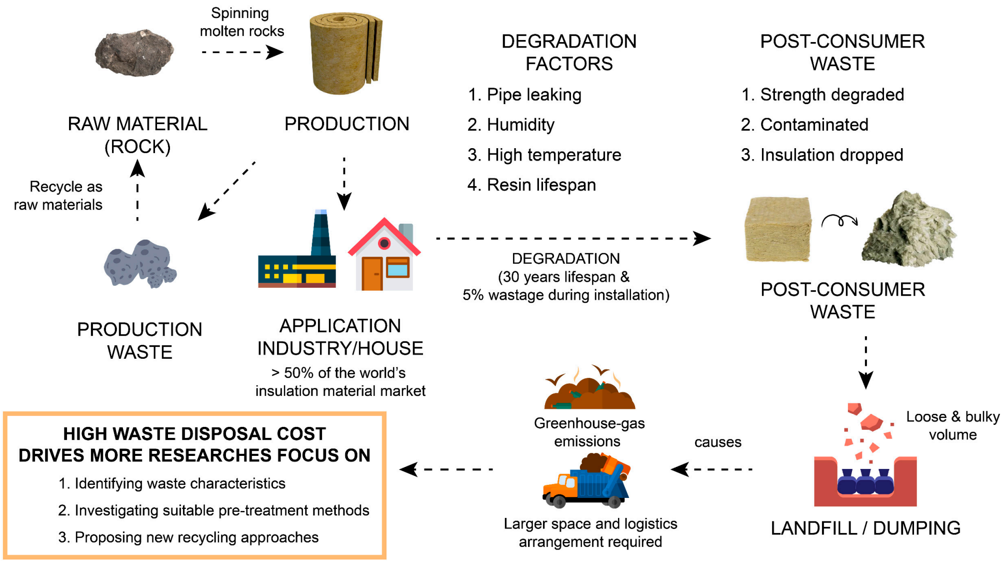
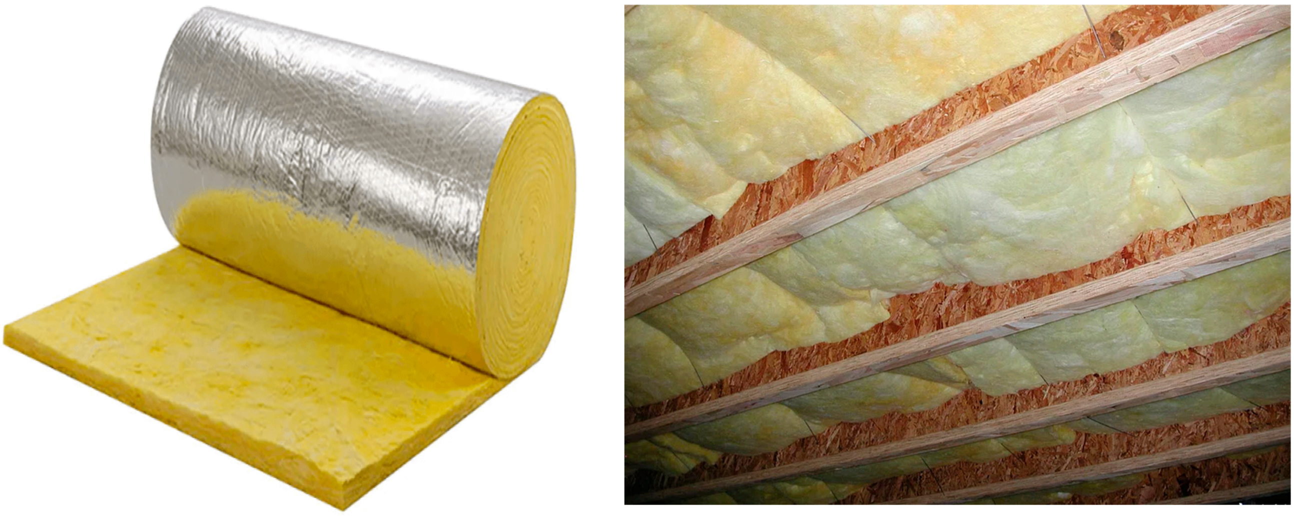


Figure 6. Production process of the mineral wool and its post-consumption recycling [32].

Another most commonly used insulation material is fiberglass. Fiberglass, composed of ultrafine glass fibers with diameters ranging from 0.5 to 3 µm, is a versatile insulation material for both panels and building applications. Its exceptional thermal insulation attributes arise from the minimal diameters of the glass fibers [33]. Cao et al. [34] developed a mathematical model, which was also validated experimentally, to predict the thermal conductivity of the fiberglass accurately. It was reported that the thermal conductivity of other materials with a similar microstructure can also be obtained using the developed model. Cozzarini et al. [35] utilized recycled fiberglass waste to fabricate novel composite insulation material with appealing thermal and acoustic properties. The developed composite material was also found to be beneficial regarding sustainability and circular economy. Fiberglass is still one of the common materials used for thermal insulation due to its thermal and acoustic performance, flexibility in installation, fire resistance, and eco-friendly nature [36]. Figure 7 indicates a typical fiberglass bat used for thermal insulation. Some associated problems with fiberglass are its vulnerability to moisture and air leakage, which can also be avoided by using novel composite materials in combination with fiberglass.



(a) (b)

Figure 7. (a) Glass wool; (b) its application to building panel insulation [37,38].

Unlike mineral wool, cellular inorganic materials such as perlite, vermiculite, calcium silicate, and foam glass are not commonly used for thermal insulation of buildings due to their lack of availability in the market. Despite this, they have a high potential to be excellent thermal insulators and are researched globally. In some cases, expanded perlite is utilized as building insulation material [39–41]. Perlite, an acidic extrusive rock, can be rapidly heated to temperatures ranging from 900 to 1200 °C, producing expanded perlite characterized by low density and thermal conductivity [40]. However, the fabrication process of expanded perlite entails substantial energy consumption [41], and its exploitation or smashing process gives rise to significant environmental pollution and the generation of substantial amounts of perlite tailings [41,42]. Vaou and Panias [43] investigated a novel thermal insulation material derived from perlite tailings, demonstrating exceptional performance characterized by remarkably low thermal conductivity (TC) of 0.03 W/m.K, and high compressive strength (CS) of 0.78 MPa. The development of this innovative thermal insulation material employed a pioneering technique similar to the geopolymer preparation process, involving the activation of perlite tailings through NaOH + H_2O_2. The proposed method holds significant promise, as it not only utilizes perlite tailings as raw material, mitigating environmental concerns associated with expanded perlite production, but also exhibits energy-saving attributes.

Gao et al. [44] propose a new, environmentally friendly method to create lightweight, foamy thermal insulation materials from perlite tailings with low thermal conductivity and high mechanical strength. The resulting materials outperform other reported inorganic thermal insulation materials, offering a promising, non-flammable insulation solution while addressing the issue of solid tailings utilization. In addition to thermal resistance, the insulation material should have sufficient fire resistance capacity and needs to pass certain fire standards. The most commonly adopted ones are the Euro standard [45] and the British standard [46]. The fire classification mentioned in Table 1 is according to the Euro Code for fire classification of construction products [45], which is replicated in the current study while comparing the fire performance of various insulation products. Detailed properties of inorganic-based insulation materials are mentioned in Table 2. Similarly, Table 3 indicates the advantages and disadvantages of using inorganic-based thermal insulation materials.

Table 1. Fire Classification Table as per Euro Code [45].

Class	Description
A1	No contribution to fire
A2	Very limited contribution to fire
B	Limited contribution to fire
C	Minor contribution to fire
D	Medium contribution to fire
E	High contribution to fire
F	Easily flammable

Table 2. Important properties of various inorganic-based insulation materials.

Material Category	Material Type	Thermal Conductivity W/m.K	Thermal Resistance R/inch $ft^2 \cdot {}^\circ F \cdot h/BTU$	Density kg/m^3	Specific Heat kJ/kg.K	Fire Class	u-Value	Refs.
Fibrous	Rock Wool	0.029–0.042	3.0–3.3	40–200	0.8–1.0	A1–A2	1.0–1.3	[47,48]
	Glass Wool	0.031–0.037	2.2–2.7	13–100	0.9–1.0	A1	1.0–1.1	[49]
	Slag Wool	0.04	4.0–4.2	50	0.7	A1	0.5	[48,50]
	Fiberglass	0.030–0.050	2.2–5.0	10–100	0.8–1.0	A1	1.0–1.3	[51,52]
Cellular	Perlite	0.04–0.06	2.7	32–176	0.2	A1	3.5	[48]
	Vermiculite	0.04–0.064	2.1–2.3	64–130	0.84–1.08	A1	3–5	[53,54]
	Foam Glass	0.038–0.045	3.1–4.2	100–120	0.21	A1	–	[55,56]
	Calcium Silicate	0.045–0.065	2.63	115–300	1.3	A1	6–20	[51]

Table 3. Advantages and disadvantages of in-organic based insulation materials.

Advantages	Disadvantages
1. Abundant in supply 2. High durability 3. Moisture resistance 4. Resistance to decay 5. Good thermal resistance 6. Excellent thermal stability 7. Easy to install 8. Most are environmentally friendly and do not release harmful gases	1. Comparatively heavier 2. Brittle in nature 3. Requires additional structural support 4. Higher production energy 5. Some inorganic materials can release harmful airborne particles irritating to skin (e.g., fiberglass) 6. Upon exposure to moisture, their thermal properties can vary

2.2. Organic-Based Insulation

The organic materials used for thermal insulation are mainly obtained from natural and renewable resources, and therefore, thermal insulation with such materials is also an appealing option. Such materials include polystyrene, polyurethane, phenolic, cellulose, wood wool, and sheep's wool. A more detailed list of such materials and important thermal properties are listed in Table 4. These organic insulating products have several appealing qualities, including renewability, recyclability, non-toxicity, environmental friendliness, and minimal resource production needs. Additionally, compared to traditional insulation materials, the energy used to manufacture organic insulation materials is often lower. Cotton, straw, reed grass, linen, hay, lichens, hemp, flax, and organic fibers are more examples of organic materials used for insulation. In addition to helping with vapor-permeable construction layers and efforts to reduce heating load demand in buildings, these materials have been used for thermal isolation since ancient times. Various organic-based insulation materials are illustrated in Figure 4. Organic materials used for insulation are classified into three groups: petrochemical materials (derived from oil or coal), renewable materials (derived from plants and animals), and expanded foamed-based materials. This section discusses various examples of each group with its application and limitations.

Table 4. Important properties of organic-based insulation materials.

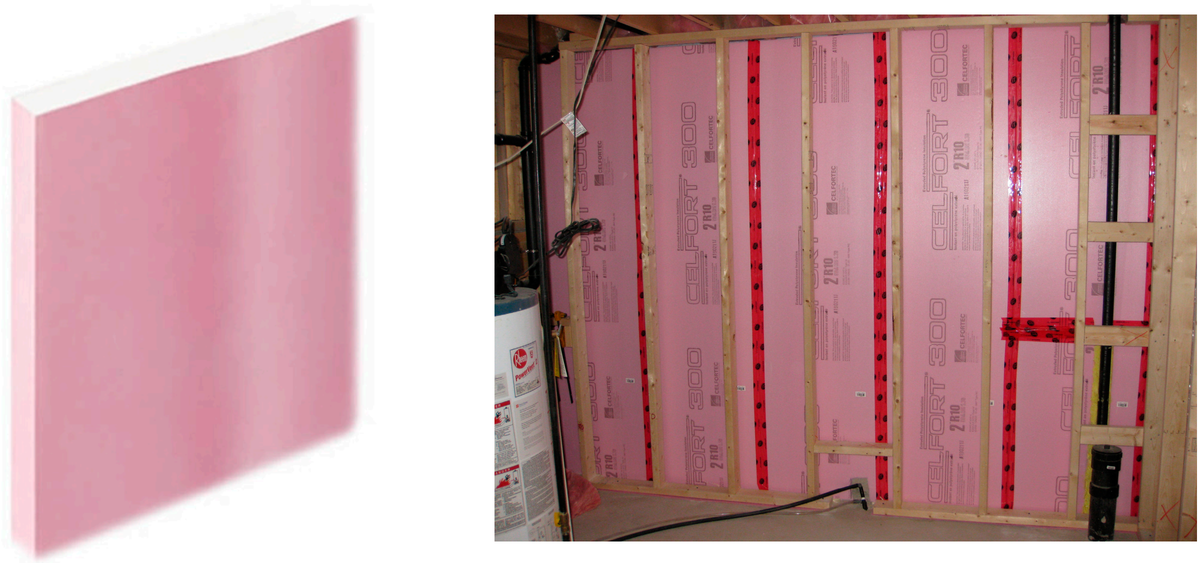
Material Category	Material Type	Thermal Conductivity W/m.K	Thermal Resistance R/inch ft2·°F·h/BTU	Density kg/m^3	Specific Heat kJ/kg.K	Fire Class	u-Value	Refs.
Petro-chemical	EPS	0.029–0.041	3.8–4.4	18–50	1.25	E	20–70	[57–59]
	XPS	0.030–0.040	5.0	25–45	1.45–1.70	E	80–150	[51,60,61]
	PUR	0.022–0.046	3.6–6.8	30–100	1.30–1.45	D–F	50–100	[47,62,63]
	PIR	0.018–0.028	4.8–8.3	30–45	1.40–1.50	B	55–150	[59,64,65]
	Phenolic Foam	0.018–0.024	6.7–7.5	40–160	1.30–1.40	B–C	35	[51,66,67]
Renewable	Cotton	0.058–0.082	3.8	150–450	0.13	E	-	[48]
	Sheep Wool	0.038–0.054	3.5–3.8	10–20	1.3–1.7	E	4–5	[47]
	Hemp	0.038–0.123	3.5	25–100	1.7–1.8	E	1–10	[48]
	Flax	0.030–0.045	3.5	20–80	1.6	C	1–5.28	[51]
	Jute	0.038–0.055	3.91	35–100	2.4	-	0.2–0.56	[25]
	Rice Straw	0.039	1.3–1.6	80–100	0.6	E	3.2–5.47	[68,69]
	Coconut Fiber	0.042–0.086	-	174–664	2.6	E	1–10	[48]
	Paper waste	0.04–0.093	3.2–3.8	200–348	0.37–1.4	-	2.3–3.9	[70,71]
	Cork	0.036–0.065	3.6–4.2	65–240	1.5–1.7	E	5–54.61	[72,73]

Polystyrene products are usually made of cellular organic plastic. Expanded polystyrene (EPS) and extruded polystyrene (XPS) are the two commercial types of polystyrene that are used for insulation. Expanded polystyrene (EPS) is a well-established insulation material widely used for various applications due to its lightweight and rigid foam structure, excellent thermal insulation properties, and high impact resistance. The thermal conductivity of EPS typically varies between 0.029 and 0.041 W/m.K depending on moisture content and density [57,58]. EPS foam is commonly incorporated into concrete floors as a resilient material to reduce noise transmission and preserve heat, resulting in energy savings. It is a closed-cell, rigid foam material produced from solid beads of polystyrene, and it offers benefits such as cost-effectiveness, energy efficiency, cushioning for shock-sensitive goods, and resistance to water absorption and vapor permeance [74]. EPS foam is also utilized in geotechnical applications as geofoam due to its lightweight nature. Overall, EPS foam is a versatile and effective insulation material with many applications in the construction and packaging industries [58].

On the other hand, extruded polystyrene (XPS) is a thermoplastic polymer derived from melted polystyrene sourced from crude oil. To create XPS, an expansion gas such as hydrofluorocarbons (HFC), carbon dioxide (CO_2), or hexane (C_6H_6) is added, causing the polystyrene mass to expand when extruded through a nozzle with pressure release. The resulting insulation material is produced in continuous lengths and then cut after cooling [60]. XPS possesses a closed-cell structure, rendering it stronger and with higher mechanical performance than expanded polystyrene (EPS) [61]. However, it is typically more expensive than EPS. Moreover, XPS has a density range of approximately 25–45 kg/m^3, and its thermal conductivity values lie between 0.030 and 0.040 W/m.K. The thermal conductivity of XPS can be influenced by factors such as temperature, moisture content, and density. Notably, XPS products can be easily installed and adjusted in various shapes at the construction site without affecting their thermal resistance [75]. Figures 8 and 9 indicate typical EPS and XPS foam and their corresponding application, respectively.

(**a**) (**b**)

Figure 8. (**a**) Fabrication process of EPS; (**b**) application of EPS for structural panel insulation [57,76].



(**a**) (**b**)

Figure 9. (**a**) Fabrication process of XPS foam for panel insulation; (**b**) application of XPS for structures [77,78].

Polyurethane foam (PUR) is another widely used organic material for thermal insulation purposes. When a di- or polyisocyanate and a polyol combine, a closed-cell thermoset polymer called polyurethane foam (PUR) is created [79]. It is offered in closed-cell and open-cell formulations, acting as insulation for various uses, including pipes, industrial systems, floors, roofs, and cavity walls [80]. PUR has a lower heat conductivity than mineral wool, polystyrene, and cellulose-based goods, ranging from 0.025 to 0.046 W/m.K [62]. Notably, temperature, moisture content, and mass density all affect PUR's thermal conductivity, with a jump from 0.025 to 0.046 W/m.K shown when moisture content increases from 0% to 10%. A smaller cell size also results in a lower heat conductivity for PUR [63]. Figure 10 indicates a typical PUR panel and its structural insulation application.

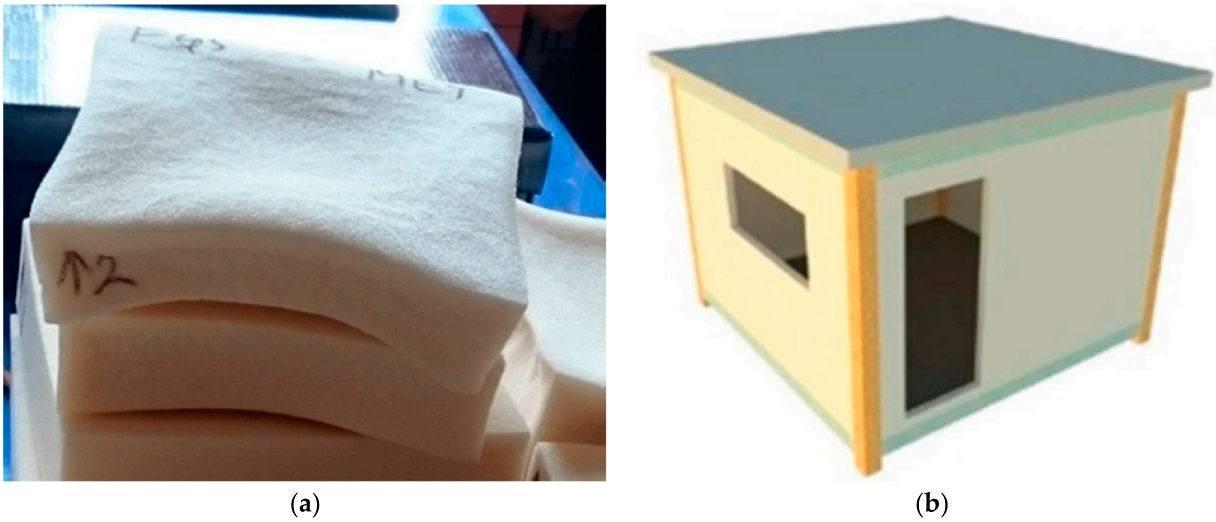


Figure 10. (**a**) PUR foam for panel insulation; (**b**) application of PUR for panels [81,82].

Polyisocyanurate (PIR), shown in Figure 11a, is also a foam-based organic material renowned for its superior R-value, leading to enhanced energy efficiency compared to other foam-based insulation materials. PIR achieves thermal resistance from blowing agents, typically a pentane gas mixture trapped in the foam cells [64]. Pentane isomers, commonly used in Europe, contribute to the manufacturing of rigid insulating polyurethane foams, enabling thermal conductivity as low as 0.018 W/m.K. However, PIR's thermal conductivity can vary due to gas exchange with environmental gases during operation and in low-temperature environments with blowing gas condensation [64,65]. Despite its advantages, the building industry perceives PIR as impermeable or semi-permeable, limiting its application as exterior insulation. Over time, environmental factors lead to aging in closed-cell PIR foam as air diffuses into the foam cells, and the blowing agent gas diffuses out, altering the cell gas composition and thermal conductivity. These aging factors are influenced by environmental air, radiation temperature, humidity, chemical agents, and microorganisms [83].

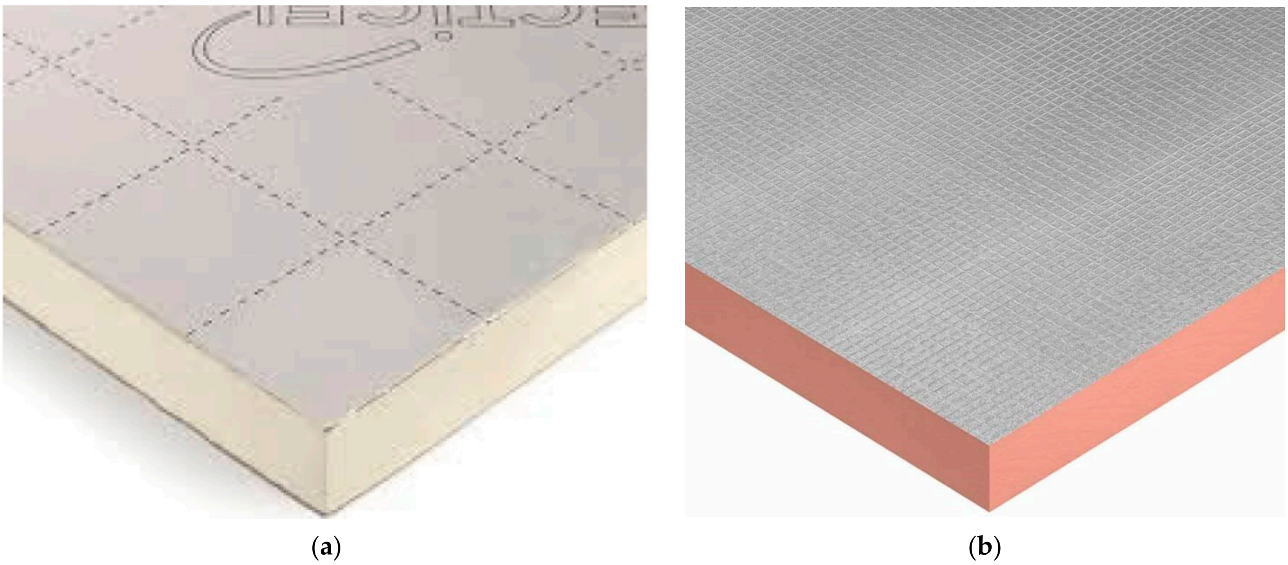


Figure 11. (**a**) PIR foam panel for thermal insulation; (**b**) phenolic foam panels for thermal insulation [38].

Phenolic foam mentioned in Figure 11b, a significant organic polymer class with diverse applications, is produced using components such as resin, surfactant, blowing agent, and curing agent. Notable for its low thermal conductivity, density, smoke emission, and high fire retardancy, it is also chlorofluorocarbons (CFCs) and hydrofluorocarbons (HFCs)-free, water-resistant, and chemically inert [51]. Consequently, phenolic foam finds wide application in the construction, transportation, and aerospace sectors for insulation. Tseng and Kuo [84] investigated the thermal radiative properties of phenolic foams, with or without activated carbon. However, despite their superior insulative qualities, these foams often derive from non-renewable sources, contributing to heightened environmental pollution during production. Recently, researchers also studied to resolve this issue. Sarita et al. [67] presented an overview of progress in bio-based phenolic foam, its properties, current challenges, and possible applications.

Polyethylene foam, known for its elasticity and high porosity, exhibits exceptional thermal insulation capacity. It possesses notable tensile strength, water resistance, and low vapor permeability. The foam can be hot air welded, but its combustibility limits its applications. To broaden the scope of polyethylene foam products, researchers such as Zakaryan et al. [85] explored modified compositions to assess flammability and evaluate their properties at low temperatures. Their work includes developing insulation systems for buildings in Arctic and Antarctic regions with permafrost soils. Similarly, Zhukov et al. [86] studied modified polyethylene foam to assess combustibility. Polyethylene foam finds is used in facades and roofs for heat-soundproofing and waterproofing purposes, as well as in hangar insulation systems, with various companies, such as Foam Factory (Canada), UFP Technologies (USA), and The Rubber Company (UK), contributing to its development. The potential applications in construction can be further expanded if the issue of its flammability is addressed.

Melamine foam (MF) exhibits exceptional insulating properties by obstructing air convection and limiting heat transfer. With a thermal conductivity of 0.035 W/m.K, it finds applications in duct lining for heating, ventilation, and air conditioning systems. Unlike fiberglass, its robust cell structure ensures durability over time, maintaining effective insulation. The foam is lightweight and resistant to heat, low flame, and smoke, making it an ideal choice without undue additional weight. Wang et al. [87] investigated MF foam's thermal stability and the impact of various emulsifiers on morphology, apparent density, fire retardancy, and mechanical properties. Li et al. [88] highlighted MF rigid foams' low water absorption, superior thermal insulation, and flame retardancy, which are suitable for exterior wall thermal insulation. Yang and Bo [89] pioneered multifunctional composite foams by infusing phase change paraffin into melamine foam's interconnective pores and coating it with a thermal insulation layer containing S_iO_2 nanoparticles. The resulting composite insulation demonstrated outstanding thermal regulation.

Despite several advantages, the organic base insulation materials also have some drawbacks, which sometimes limit their commercial use. Table 5 indicates the advantages and disadvantages of using organic-based insulation materials.

Table 5. Advantages and disadvantages of using organic-based insulation materials.

Advantages	Disadvantages
1. Low-density and lightweight 2. High thermal resistance 3. Sustainable and renewable 4. No health problems 5. Moisture resistance 6. Environmentally friendly 7. Easy to install in batts	1. Higher upfront cost 2. Vulnerable to fire 3. Larger space requirement for installation 4. Higher production energy and need chemical treatments 5. Can emit toxic gases upon catching fire

2.3. Sustainable Natural and Recycled Materials

As the idea of "sustainability" spread throughout the construction industry, various researchers recently prioritized insulation solutions made of natural and recycled materials [90]. In terms of such sustainable insulation, some of these products are currently on the market, while others are still in the research and development stages. Wood fiber, Jute, hemp, flax, linen, straw bale, etc., are some other naturally available insulation materials. However, due to a lack of research on these materials, their ability to enhance the thermal performance of the building is rarely known, which is why these materials are not commonly used for insulation globally. Various available natural insulation materials are listed in Figure 12. The utilization of such natural and sustainable materials could be particularly significant and helpful in developing regions that lack clear recycling rules and experience disposal problems due to the abundance of agricultural and industrial byproducts. Utilizing such insulation materials will not only lower the environmental effects of the building industry, but also focus on improving the energy efficiency of buildings [91]. Magwood et al. [92] studied the material carbon emission (MCE) of 20 different insulation materials for a specific area and thermal resistance value. It was observed that the natural insulation material had minimum carbon emission compared to other insulation materials, as mentioned in Figure 13. It is also worth mentioning that inorganic-based insulation materials such as XPS, EPS, aerogels, and spray foam have the highest carbon emissions. Moreover, a study by Huang et al. [93] showed that the emission of greenhouse gases considerably reduces with the increase in the thickness of insulation material. The combustion of fossil fuel, which is used for achieving indoor thermal comfort can emit toxic gases such as CO_2 and SO_2. Therefore, an efficient insulation reduces the energy demand and therefore also reduces the consumption of fuels. The authors studied five different insulation materials considering three fuel types. A considerable reduction was observed in the CO_2 and SO_2 emissions when the thickness of the insulation layer increases from 0 mm to 10 mm; afterward, it tends towards achieving stability, as shown in Figure 14. It is worth mentioning that the aerogel blankets were found to have minimum greenhouse gas emissions among the others.

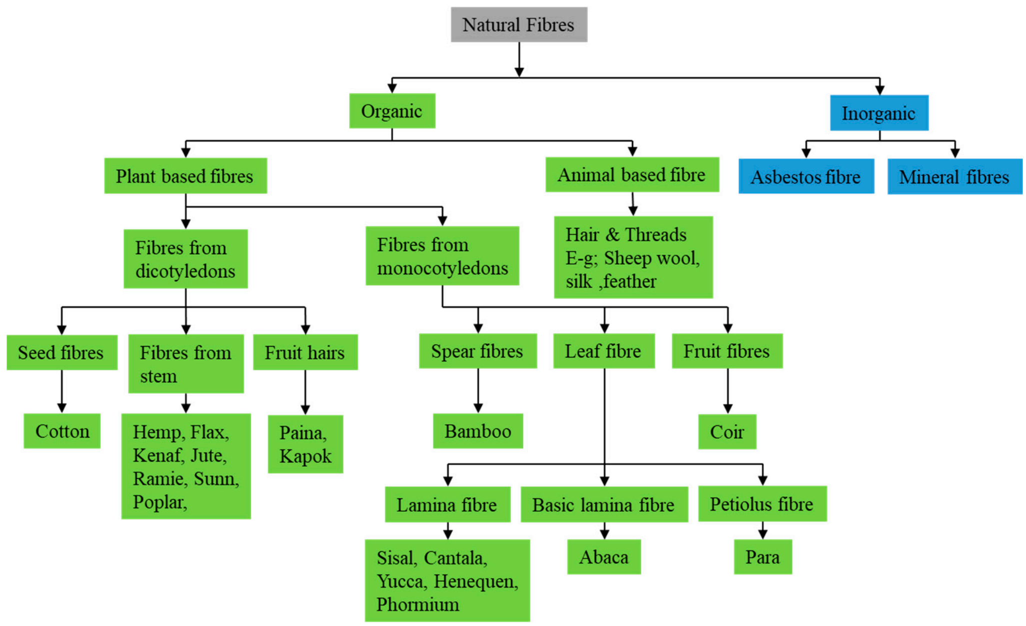


Figure 12. Classification of some commonly used naturally available insulation materials.

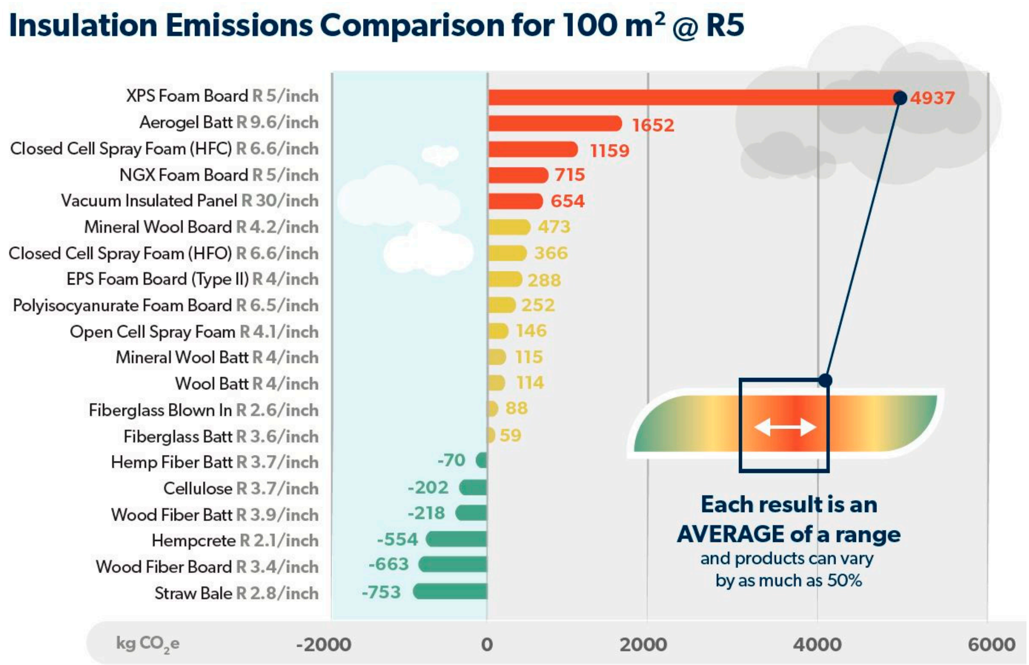


Figure 13. Material carbon emission for various commonly used insulation materials [92].

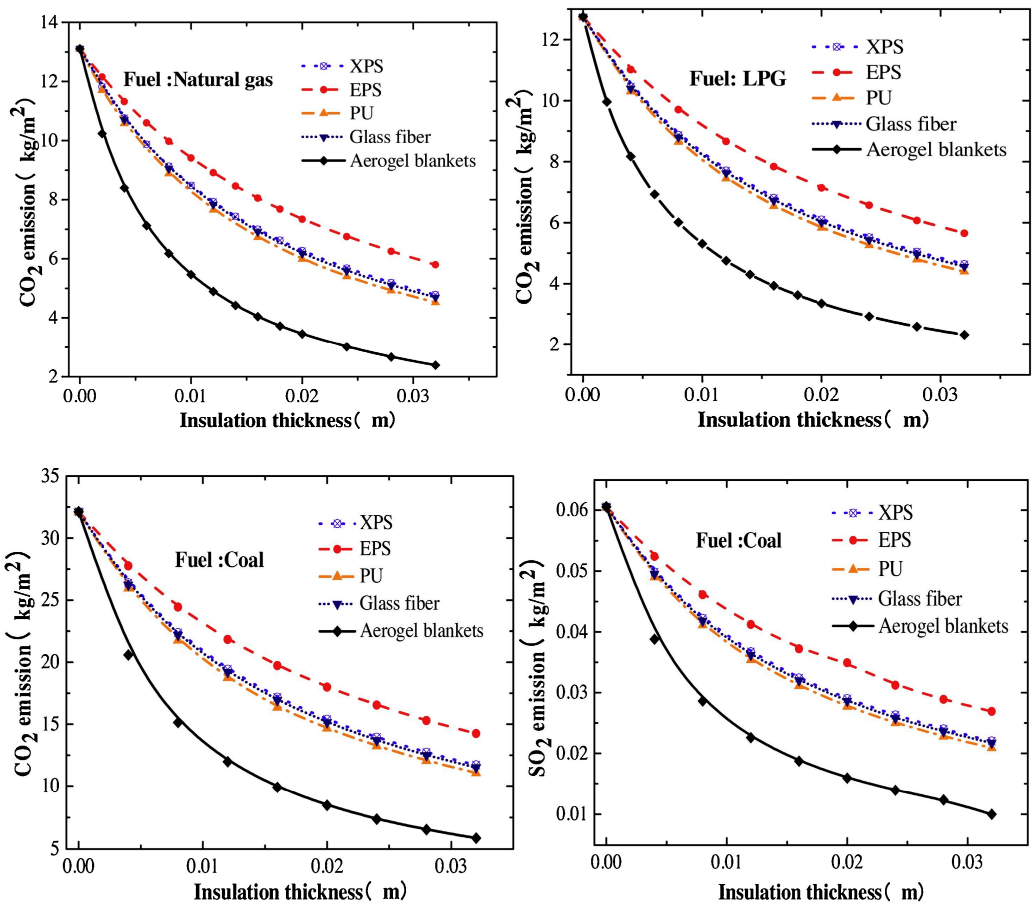


Figure 14. CO_2 and SO_2 emissions for various thicknesses of the insulation material [93].

Cotton, derived from textile waste, is an eco-friendly insulation material for panels and building insulation. Consisting of 85% recycled cotton and 15% plastic fibers, cotton insulation offers an R-value of about 3 to 4 per inch, making it an effective thermal insulator when dry. However, its susceptibility to moisture and fire is a notable disadvantage that should be considered when selecting insulation materials for specific applications. Researchers also studied the effect of various factors on the insulation properties of cotton boards. Zhou et al. [21] studied the effect of moisture content, materials density, and pressing time to fabricate the cotton boards on the thermal conductivity of the binderless cotton stalk fiberboard. Such fiberboard was found to be efficient for walls and ceilings. Moreover, Binici and Aksogan [94] used waste cotton with fly ash to fabricate composite blocks, which was superior to concrete blocks in thermal and acoustic insulation. An application of recycled cotton in the thermal insulation of a house is illustrated in Figure 15.

Figure 15. Recycled cotton for building panel insulation [20].

Sheep wool, categorized as a bioproduct derived from sustainable biological resources, emerges as a promising alternative insulating material for buildings due to its ability to trap air within its fibers [95]. Sheep wool is usually used as a batt for thermal insulation, as shown in Figure 16. With a notable focus on sustainability, sheep's wool gained attention for its potential as an eco-friendly insulation option. Using sheep wool as an insulation material for panels and building insulation offers numerous advantages, including excellent thermal performance, sustainability, ease of installation, eco-friendliness, cost-effectiveness, and breathability, indicating its ability to naturally absorb and release moisture [96]. Researchers also used sheep wool as a composite material. For example, Denes et al. [97] used acrylic-polyurethane resin and natural rubber latex to improve the thermal performance of sheep wool.

Figure 16. Sheep wool panels for thermal insulation [38].

Cellulose, an eco-friendly insulation material made from recycled paper fibers, is a viable option for panel and building insulation [98]. Cellulose fiberboard is the most common form used in building insulation. It has good thermal properties, controls indoor humidity, and has considerably lower environmental effects and low embodied energy, making it a sustainable choice [99]. However, its limited use compared to traditional insulation materials can be attributed to a lack of expertise in its application and properties. Further research and promotion of cellulose insulation could help increase its adoption in the construction industry [100]. Wood fiber insulation panel is also an environmentally friendly option for insulation applications as it is derived from the recycling of waste wood produced by sawmills [101,102].

Cork is a lightweight, reusable, and biodegradable material obtained from the bark of the cork oak tree, harvested every 9–12 years. It possesses a homogeneous cell structure with thin and regularly arranged cell walls, lacking intercellular spaces. Countries such as Portugal, Spain, Italy, and North Africa are primary sources of cork oak. Cork-based materials exhibit favorable acoustic properties, making them suitable for impact insulation, airborne insulation, and sound absorption [103]. For building thermal applications, cork is used in the form of insulation cork boards (ICB), as mentioned in Figure 17. Since cork is obtained from a renewable resource, it also contributes to agricultural waste recycling. Researchers obtained that the thermal conductivity of ICB ranges from 0.036 to 0.065 W/m.K, with densities varying between 65 and 240 kg/m^3, and specific heat falling within 1.5 to 1.7 kJ/kg.K [73,104]. With a water vapor diffusion resistance factor of 5–54.61, cork materials demonstrate commendable hydric properties for moisture insulation [105,106].

(**a**) (**b**)

Figure 17. (**a**) Cork particles in natural form; and (**b**) application of cork panels for structure insulation [107].

Reed panels, a classical insulation material, are applicable as interior and exterior walls and roof insulation covered with plaster. It was found that the reed panel has density and thermal conductivity in the range of 130–190 kg/m^3 and 0.045–0.056 W/m.K, respectively. Although it is abundant, its usage is minimal [108]. Manohar [109] studied the utilization of Bagasse in fabricating thermal insulation boards. Bagasse is a byproduct of sugar production and is mainly treated as waste. It was found that such boards have a thermal conductivity of 0.046 W/m.K with density in the range of 70 to 120 kg/m^3. Luamkanchanaphan et al. [110] used cattail plant fibers to fabricate thermal insulation panels that showed thermal conductivity and density in the range of 0.0438 to 0.0606 W/m.K and 200 to 400 kg/m^3, respectively. Cotton stalks, another byproduct obtained during cotton production, are used as insulation material by Zhou et al. [21]. It was observed that the thermal conductivity, which was found to be in the range of 0.0585 to 0.0815 W/m.K, increases with the increase in density. Similarly, some other naturally available materials such as date palm wastes [111], durian peel [112], oil palm fiber [113], pineapple leaves [114], rice hulls [115], polyester reinforced Sansevieria fiber [116], sunflower composites [22], and wheat straw bale [117] were also studied for their thermal insulation application. A binder is usually added to the material to make it suitable for insulation. Figure 18 indicates various bio-based sustainable materials that could be used for thermal insulation.

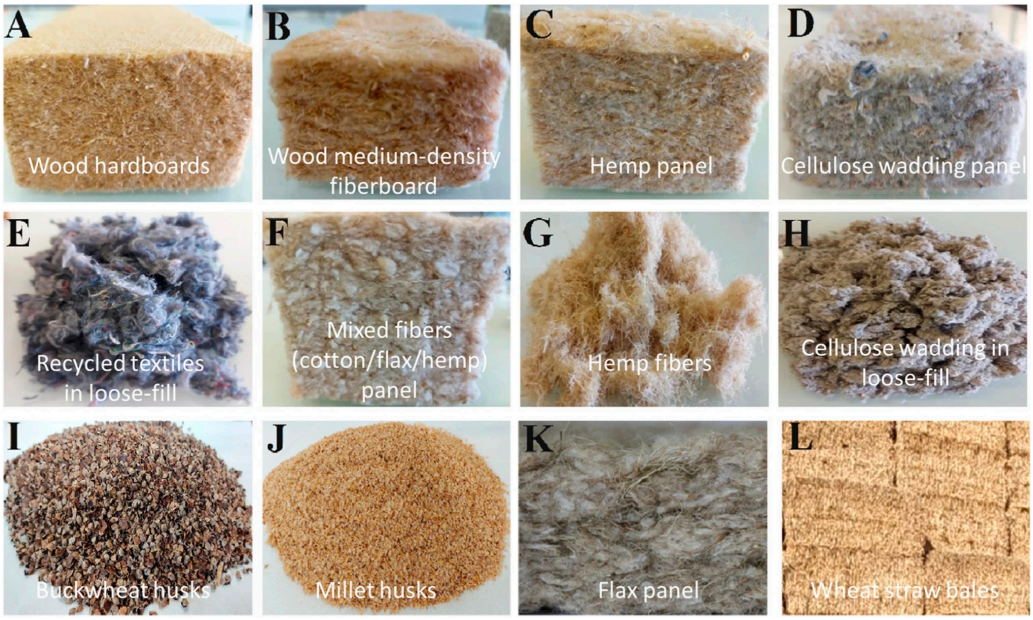


Figure 18. Various bio-mass-based sustainable materials for thermal insulation; (**A**) wood hardboards; (**B**) medium density wooden fiberboard; (**C**) Hemp panel; (**D**) Cellulose panels in compacted form; (**E**) recycled textile fibers; (**F**) mixture of cotton, flax and hemp fibers; (**G**) hemp fibers; (**H**) cellulose fiber in loose fill; (**I**) wheat husk; (**J**) millet husk; (**K**) flax panel; and (**L**)wheat straw bales [118].

Using recycled materials or industrial by-products for insulation purposes presents a viable and sustainable approach to mitigate the consumption of virgin resources and minimize landfill waste. Table 6 indicates the advantages and disadvantages of using natural materials for thermal insulation. Moreover, researchers conducted numerous investigations to explore novel, sustainable, and environmentally friendly applications of these materials within the construction industry, particularly in insulation solutions. To study its thermal and acoustic performance, a porous granular form was fabricated from waste glass. It was found that an insulating material with excellent thermal (0.031 W/m.K) and acoustic (R = 15 dB) capabilities can be created by grinding raw materials to particle sizes less than 0.1 mm. The material was also discovered to have a particle density of 0.5 g/cm^3, a strength of 17.50 MPa, and a 95% water adsorption rate, with a temperature range of 850 °C [119]. Similarly, Intini and Kühtz [120] utilized polyethylene terephthalate (PET) bottles after the consumer used them for thermal insulation, which is also used by other researchers [121] to fabricate polyester fiber panels for thermal insulation. The recycled PET was not only found as an environmentally sustainable solution, but also had an excellent thermal insulation performance. Textile fibers are another material that can be recycled and used as a thermal insulator. Valverde et al. [122] utilized polyester and polyurethane as waste materials in the textile industry to fabricate heat insulation panels. The panels were experimentally tested for their thermal performance. Depending upon the density, thermal conductivity was found to be in the range of 0.053 and 0.041 W/m.K), indicating the panels' higher thermal resistance.

Table 6. Advantages and disadvantages of using natural materials for thermal insulation.

Advantages	Disadvantages
1. Low to zero toxin, significant health benefits 2. Low-carbon footprint 3. Sustainable and renewable 4. Biodegradable 5. Locally available 6. Good hygroscopic behavior and moisture-regulating ability 7. Easy to install in batts 8. Higher thermal and acoustic performance	1. Higher upfront cost 2. Lower mechanical strength 3. Vulnerable to fire 4. Larger space requirement for installation 5. Non-biodegradable binders added in some cases 6. Can emit harmful gases in some cases 7. Low market worldwide

2.4. Novel Insulation Materials

Various thermal insulation materials were developed recently, considering the idea of global sustainability, higher energy efficiency, and lower environmental damage. Such advanced insulation materials were found to be efficient based on their suitability for thermal insulation, as they possess a low thermal conductivity value, are lightweight, are fire-resistant, and are cost-effective. Table 7 indicates the essential properties of the novel thermal insulation materials. These materials are also termed super insulation materials.

Table 7. Properties of various novel and super insulation materials.

Material	Thermal Conductivity W/m.K	Thermal Resistance R/inch ft2·°F·h/BTU	Density kg/m^3	Specific Heat kJ/kg.K	Fire Category	u-Value	Refs.
Aerogel	0.01–0.02	10.3	70–150	1.05	A1–A2	5.0–5.5	[123]
PCM	0.1–0.54	-	530–830	1.9–2.22	A, B, E	3.26–4.29	[124–127]
VIP	0.002–0.008	25	150–300	0.8	A1	2.66–7.03	[128]
GFP	0.010–0.035	5.5–11	32–38	-	A	-	[129–131]

2.4.1. Aerogel

Aerogels, the lightest known solid element of earth, characterized by their exceptionally high porosity and low density, were first discovered by Kistler in the early 1930s [132]. Silica aerogels are synthesized through a two-step process, initially involving traditional low-temperature sol-gel chemistry. Unlike xerogels, where wet gels are typically dried via evaporation, aerogels are primarily dried through a process known as supercritical drying. This method enables the preservation of the intricate three-dimensional pore structure, contributing to the unique material. Depending upon the fabrication method and purity, the pores of the aerogel account for 85 to 99.8% of the total volume of aerogel [123]. In the case of silica aerogels, the pore size ranges from 5 nm to 70 nm, which is 10 nm to 100 nm in the case of pure aerogel. Such higher porosity is the primary reason for its low density, making it the world's lightest known solid element. Figure 19a indicates a typical silica aerogel, indicating its high fire-resisting capabilities, and Figure 19b illustrates a range of aerogel applications in industry.

(**a**) (**b**)

Figure 19. (**a**) Silica-based aerogel and (**b**) application range of aerogel in the building sector [123,133].

Solid aerogels are nano-porous materials characterized by their low density and nano-structured cells fabricated through the supercritical drying of various gels, predominantly silica gel. It is widely recognized as a remarkable super-insulation material, exhibiting a thermal conductivity lower than that of air under normal conditions, typically 0.015 W/(m.K), and also possessing promising mechanical properties [134,135]. There are various aerogel-based composites available today. However, fiber-reinforced is the most commonly used type of building insulation. It is also noteworthy that the thermal insulation performance of aerogel can be significantly affected by moisture and humid environments, as highlighted in several studies reported in the literature [136,137]. Furthermore, some investigations demonstrated that thermal annealing induces structural and chemical alterations in the aerogel matrix [138–140]. Thermal annealing is the heating and cooling process of the material, which can be considered an artificial aging process to simulate the passage of time [138]. Guinoa et al. [141] presented that the novel aerogel composite takes advantage of nanotechnology, which results in reduced insulation thickness and higher durability, as it has a higher lifetime. It was also reported that due to the low thermal conductivity of the aerogel, only 10 mm thickness of the insulation can achieve the same thermal insulation level as the 25 mm thickness of the standard expanded polystyrene panel.

The high cost, complex preparation process, and safety risk create various limitations on the commercial utilization of most aerogels. During the preparation of most aerogels, a higher temperature and pressure must exceed the critical temperature and pressure. To this end, researchers recently focused on new types of low-cost aerogels that can be prepared easily. One such effort was fabricating clay-based aerogel composite, which is fabricated using the lyophilization process, where the product is dehydrated, then frozen and vacuumed, which allows the ice stage to change directly to the gaseous state without going through the liquid state. Using this process can create aerogels that are similar in nature to silica aerogels. Due to their layered structure, smectite clays are usually used for such aerogels [142].

An associated problem with such unreinforced clay-based aerogels is that their compressive strength is too weak to be measured unless the content of the clay is increased, which again increases the aerogel's density. It was also suggested previously that a higher compressive strength can be achieved by incorporating natural and synthetic polymers with a minimum increase in the density of the aerogel composite. Using glass fibers as a reinforcer was proposed as the most reliable method that can enhance the compressive strength of the clay-based aerogel composites. Figure 20 indicates the fabrication process of such aerogel composites, where various layers of aerogel and glass fibers can be added [142].

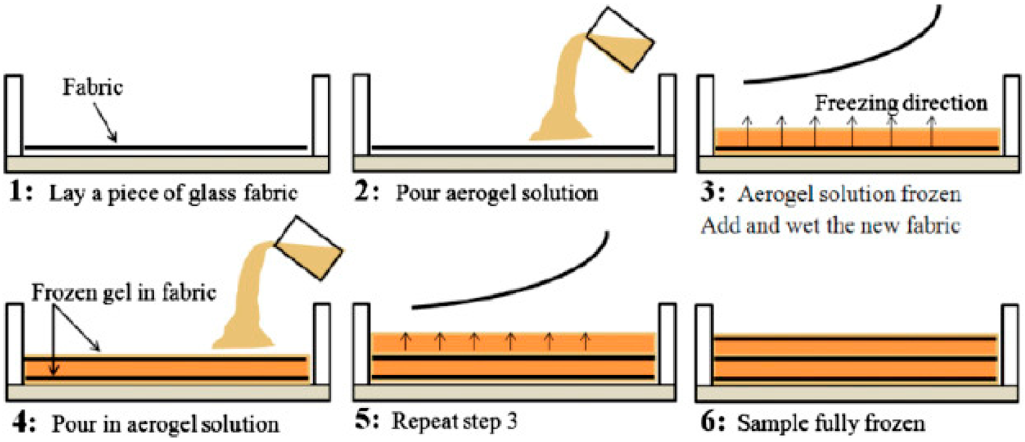
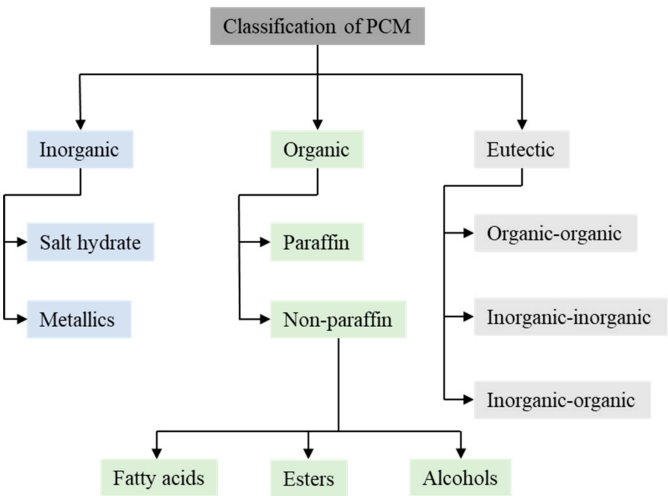


Figure 20. Fabrication process of glass fiber reinforced aerogel composites [142].

Fedyukhin et al. [143] experimentally investigated aerogel and basalt fiber as two different insulation strategies. It was observed that the aerogel has superior thermal performance and surpasses the basalt fiber insulation in all key thermo-physical aspects. However, the higher cost of aerogel is the only limitation in its vast industrial applications, which needs to be addressed.

2.4.2. Phase Change Material

Phase change materials (PCMs) can store and release a large amount of energy based on a phase change, such as melting or freezing. They are widely developed for various applications, including building insulation, which can help reduce energy demand and control internal temperature, thus enhancing thermal comfort [144–147]. Figure 21a indicates the classification of PCM, where three broad categories include organic, inorganic, and eutectic, which is a combination of organic and inorganic materials [148], and Figure 21b indicates the application of PCM for buildings [144]. While they are often associated with heat absorption and release for hot weather insulation, their unique properties make them equally suitable for cold climates.



(**a**)

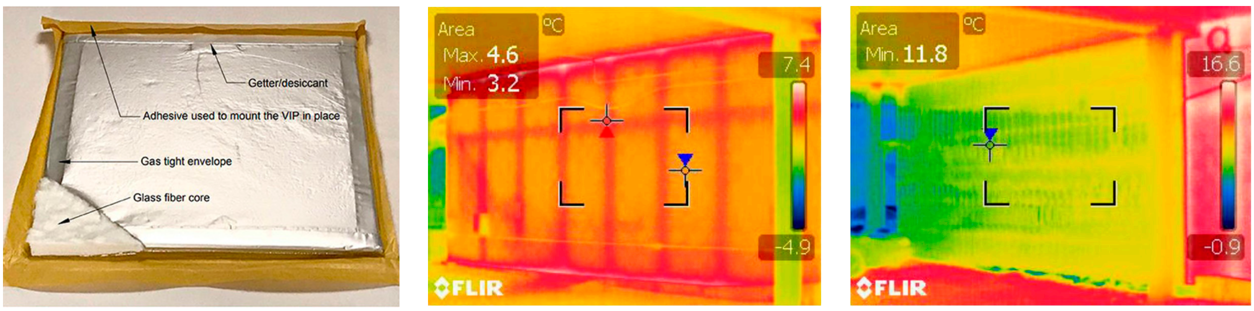
(**b**)

Figure 21. (**a**) Classification of PCM; (**b**) application of PCM in buildings [149].

In cold weather, PCMs can operate in reverse by absorbing heat from the surroundings as they freeze and releasing it when they melt. This property helps maintain a more stable indoor temperature and reduces the need for active heating systems. In extremely cold environments where temperatures can drop below freezing, PCMs can assist in preventing heat loss through walls and roofs, thereby enhancing building energy efficiency and reducing heating costs. Various researchers studied the effectiveness of PCM as a building insulation material during the summer season. Staszczuk and Kuczyński [150] compared the PCM and traditional building materials, such as reinforced concrete, to study the influence of PCM during the summer season. Memon [151] reviewed the studies incorporating PCM into structural elements and materials used for construction, such as cement, plaster, concrete, and timber. Although PCM is considered an excellent choice for hotter regions, some researchers claim that it may not be suitable for extremely cold climates, and the primary reason for that is that there is very limited research in cold climate regions [152]. In extreme cold regions such as Northern Ontario, utilizing a phase change material (PCM) with an excessively low transition temperature (−52 °C) results in the inability to store heat, as the PCM cannot undergo a phase transition from solid to liquid. Therefore, in a cooling-dominated climate, extremely low temperatures hinder its effectiveness in thermal regulation [153,154].

2.4.3. Vacuum Insulation Panels (VIP's)

Vacuum insulation panels (VIPs) fall within the category of super insulation materials, denoting materials with a thermal conductivity below 0.023 W/(m.K) [155]. A vacuum insulation panel constitutes a porous core material encased within a metallic foil, as illustrated in Figure 22a. The VIPs are fabricated with nearly all the air sealed or evacuated to a pressure of as low as ten bar, which eliminates both convection and conduction pathways through the panel's core [156]. This exceptional low-pressure state and structural configuration synergistically confer a remarkable thermal resistance per unit thickness, thus rendering VIPs conducive to curbing building space conditioning energy demand. VIPs yield an elevated RSI value per unit thickness, potentially surpassing fiberglass batt insulation by a factor of 10 [157].



(**a**) (**b**) (**c**)

Figure 22. (**a**) Glass fiber core vacuum insulation panel; (**b**) thermal infrared imageries of the model before retrofitting with insulation; and (**c**) after retrofitting with insulation [157].

Chan et al. [157] used glass fiber core vacuum insulation panels (VIPs) for a commercial building in an extremely cold region of northern Canada Yukon, where the minimum temperature of −63 °C was observed in winter during 1947 [158–160]. The installed insulation was observed from 2011 to 2018, and it was observed that less than 0.9% variations were observed in the thermal performance of the insulation over the eight years. Figure 22b,c indicate the infrared thermal images that show significant improvement after the retrofit. Mukhopadhyaya et al. [161] investigated XPS-sandwiched VIP foam used for insulating a house in a subarctic Canadian location (Yukon). They monitored the insulation performance over three years. It was observed that the proposed insulation system performed well, and no significant changes were observed under such extreme weather. Table 8 indicates various advantages and disadvantages of using superinsulation material.

Table 8. Advantages and disadvantages of using super insulation materials.

Advantages	Disadvantages
1. Higher thermal performance	1. Extremely higher cost
2. Requires less thickness	2. Difficult to manufacture
3. Lightweight in nature	3. Difficult installation
4. Usually hydrophobic in nature	4. Requires higher production energy
5. High fire resistance capacity	5. Not commonly used for housing insulation
6. Moisture and pest resistance	6. Usually, the material is not environmentally friendly, and a sustainable option

2.4.4. Composite Insulation

Composite insulation is nowadays emerging due to its various interesting and appealing characteristics. There are various higher-performing insulation materials, such as aerogels; however, they are limited in use due to their high cost. With composite insulation, using such high-performing insulation materials can be more practical. For example, a thick layer of aerogel may be required to achieve a specific thermal resistance value for any particular region, which results in high costs. Reducing aerogel's required thickness and achieving the desired thermal resistance can be possible by mixing another low-cost material or even with another layer of insulation material. This other layer could be a waste product such as wastepaper pulp from the paper industry, polyester, and polyurethane obtained as waste material from the textile industry, or any sustainable material discussed above.

About 55% of the fly ash in the USA is dumped into landfills each year, which is obtained from coal-burning plants [162]. Van de Lindt et al. [162] utilized such recycled fly ash and mixed it with scrap tire fiber, which is also used in various other applications [163,164], in specific portions to fabricate a composite insulation material. Various specimens were tested, and the thermal conductivity found was 0.035 W/m.K. Annie Paul et al. [165] developed a novel composite insulation material using polypropylene fiber mixed with treated banana fiber. It was observed that 10% NaOH-treated banana fibers had a good thermal performance. Sezgin et al. [166] used waste cotton fibers and polypropylene/polyethylene fibers obtained from waste bottles and containers. The PP/PE fibers were used as reinforcement material. The insulation board was fabricated by pressing layers of each material with a heated plate, as mentioned in Figure 23. A detailed experimental study was conducted on the fabricated composite material to identify its thermal and acoustic performance. It was concluded that the proposed composite insulation material possesses promising thermal and acoustic behavior and is also environmentally friendly as it was fabricated from 100% recycled products. However, the fire resistance performance was not identified by the researchers.

The core material used for the vacuum insulation panel, which plays a vital role in the overall performance of the panel, was also explored by various researchers. Nemanic and Zumer [167] utilized melamine-formaldehyde fiber as a core material and concluded that the performance of MF as a core material was relatively comparable to that of commonly used glass fibers as a core material. However, MF is a petrochemical product and not renewable, which is a drawback. Similarly, Zhao et al. [168] developed composite vacuum insulation panels utilizing glass fiber and wood pulp as core material, as shown in Figure 24. The proposed composite VIP was experimentally tested for its thermal performance and under accelerated aging conditions to evaluate its durability. The authors suggested that the proposed composite core material's service life and aging performance need to be improved.

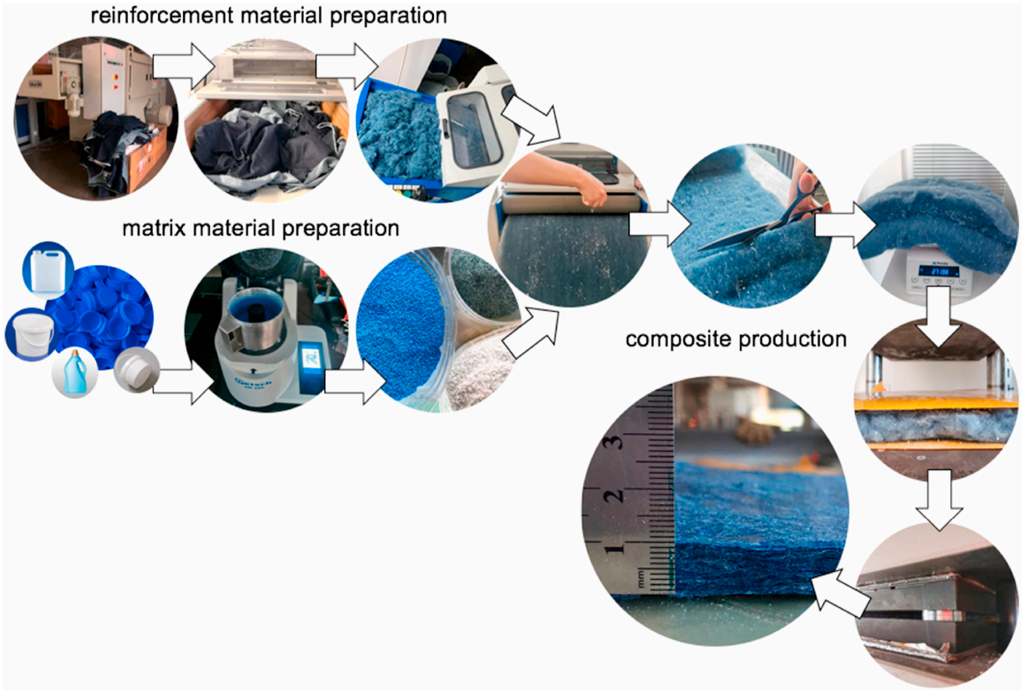


Figure 23. Fabrication of a composite insulation material using waste cotton and PP/PE fibers [166].

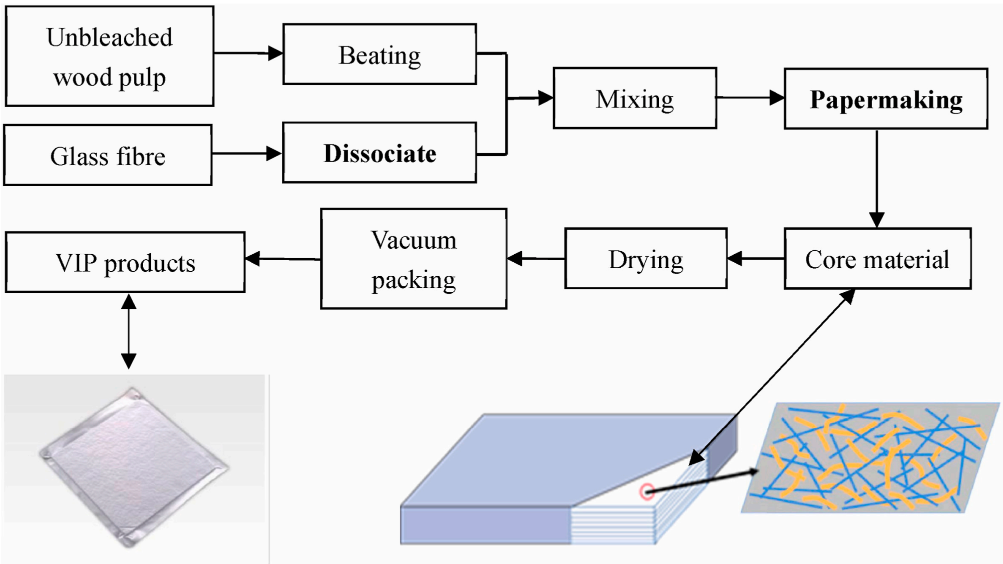


Figure 24. Composite vacuum insulation panels with wood pulp and glass fiber as a core material [168].

Hsu et al. [169] used an aerogel to improve the thermal performance of mineral wool. The thermal performance of the aerogel-based mineral wool composite was experimentally studied, and it was reported that utilizing the aerogel can enhance the thermal insulation properties of mineral wool and reduce its required thickness to achieve the desired thermal resistance. Similarly, researchers utilized natural materials to develop sustainable composite insulation for building applications. Hussain et al. [170] developed a hemp-shiv-based composite for building applications. The proposed composite insulation material was found to have low thermal conductivity, be lightweight, and have higher water moisture resistance capacity. Marques et al. [171] utilized expanded cork and rice husk ash to develop a polymer-based composite for thermal insulation. A detailed thermal and mechanical analysis was conducted on the composite materials, and various construction solutions were proposed. It was concluded that the proposed composite insulation could be used as a sustainable and efficient insulation material with lower environmental effects.

Composite insulation could be used to overcome several disadvantages of any insulation materials. For example, using wastepaper pulp as an additional material with aerogel could significantly reduce the higher cost of aerogel while still achieving the required thermal performance. Combining aerogel's thermal efficiency and wastepaper pulp's cost-effectiveness, an energy-efficient and sustainable solution for the building industry could be achieved. Utilizing wastepaper pulp not only helps reduce the required thickness of the aerogel, which is expensive, but also promotes resource conservation and circular economy principles. Section 3 discusses various factors that affect the performance of insulation materials.

3. Factors Affecting Insulation Performance

3.1. Thickness

The optimization of insulation thickness in buildings plays a vital role in minimizing heating and cooling demands within a given zone. While increasing the insulation thickness decreases energy consumption and related costs, it simultaneously raises the initial cost of the construction. Hence, it is crucial to determine the optimal insulation thickness that balances total insulation costs and energy consumption throughout the building's lifespan, facilitating thorough economic analysis. Figure 25 compares the cost and thickness of various commonly used insulation materials. It is also worth mentioning that the cost of the insulation and the energy are related to the thickness of the insulation layer. With the increase in the insulation thickness, the initial cost grows higher; on the other hand, the energy cost is significantly reduced. Additionally, it can be observed from Figure 25b that up to a certain thickness, the total cost reduces; however, after that, the increase in the thickness of the insulation only increases the upfront cost. Similarly, a relation between the insulation layer thickness of various materials and annual heating load demand and corresponding energy saving is mentioned in Figure 26. It can be observed that with the increase in isolation layer thickness, the annual heating load decreases, which enhances energy conservation. Among the studied materials, the phenolic foam was found to have lower heating load demand and higher energy saving.

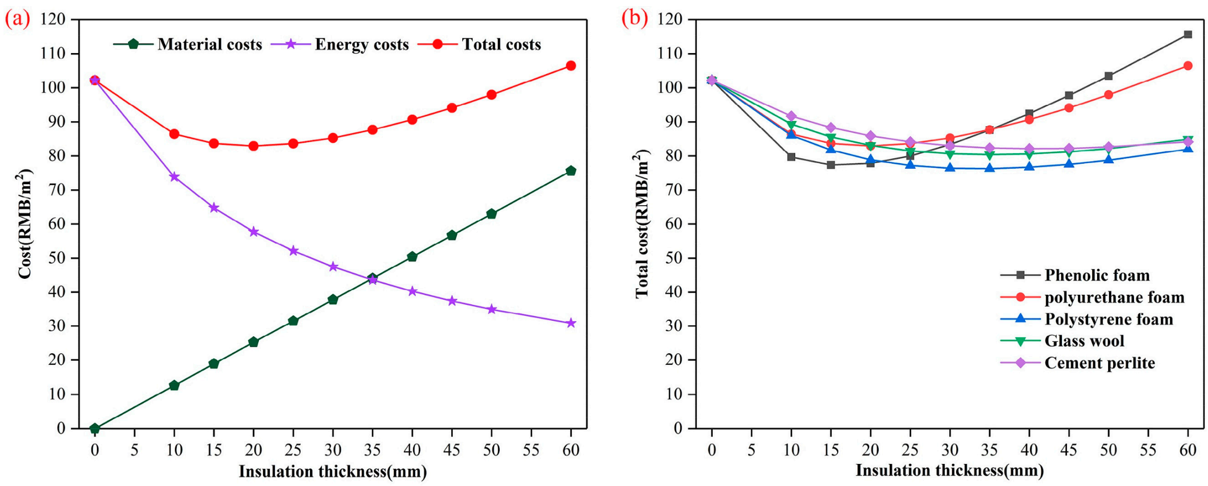


Figure 25. Comparison of insulation layer thickness and cost of various insulation materials; (**a**) comparison of insulation material cost with energy cost with varying insulation thickness; and (**b**) variations in total cost for various material with varying insulation thickness [172].

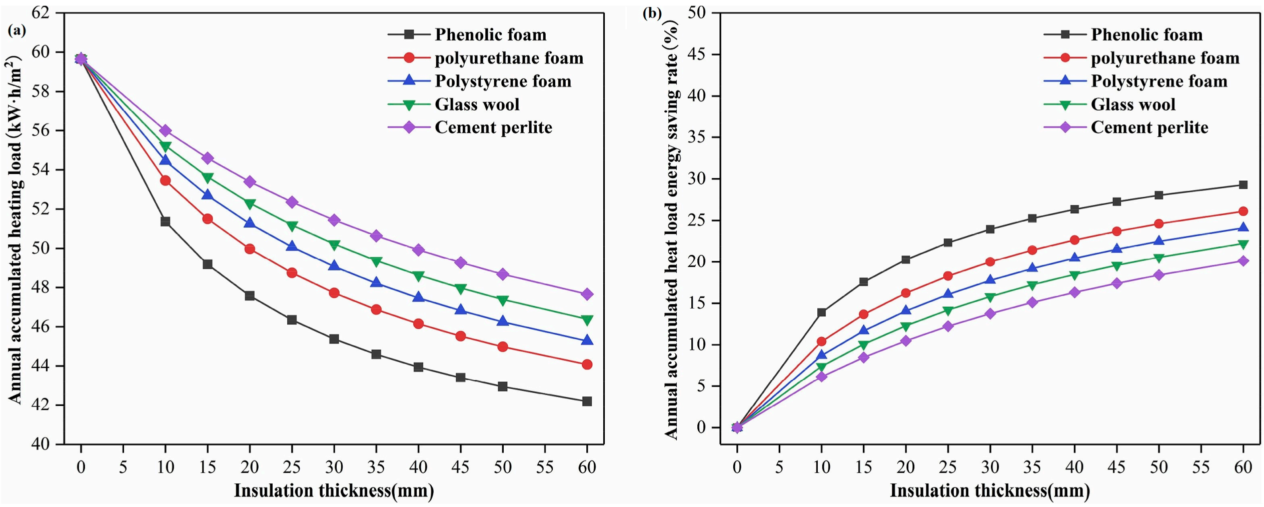


Figure 26. Effect of insulation thickness on heating load demand and annual energy saving; (**a**) reduction in heating load demand; and (**b**) increase in energy saving [172].

Many researchers reported that the optimum thickness of the insulation layer depends on accurately identifying heating and cooling loads, assuming steady-state heat transfer. However, these methods may lead to inaccuracies, as they do not consider solar radiation and thermal mass. Previous researchers ascertained the optimal insulation thickness by analyzing the annual transmission loads under transient conditions, employing either analytical approaches [173] or numerical methods [174]. Daouas [173] investigated the impact of wall orientation on the optimal insulation thickness of external walls. The study calculated the optimal insulation thickness, energy savings, and payback period for a representative wall structure, considering yearly cooling and heating loads. The analytical method employed in this analysis was based on the complex finite Fourier transform (CFFT). It was observed that wall orientation minimally influenced the optimal insulation thickness while exhibiting a more pronounced effect on energy savings. Ozel [175] conducted an extensive economic analysis to establish the correlation between the optimal thickness of insulation materials and different wall orientations, utilizing extruded polystyrene and polyurethane as insulation materials. The study revealed that the optimal insulation thickness can vary by up to 1.6 cm and 0.5 cm when altering the wall orientation.

Yu et al. [176] use five different insulation materials: expanded polystyrene, foamed polyurethane, extruded polystyrene, perlite, and foamed polyvinyl chloride in five different cities of China, considering various climate zones. A typical residential wall is used to identify the optimum insulation considering insulation thickness, varying orientation, surface color, and material type. It was identified that the expanded polystyrene performs the best among others, with the optimum thickness ranging from 53 mm to 236 mm and the payback period ranging from 1.9 to 4.7 years over a 20-year life cycle. The expanded polystyrene was found to have a minimum payback period with higher life cycle savings. The additional insulation cost can be recovered over time by saving in the form of fuel usage. This time to recover the initial insulation cost is called a payback period. In other words, the payback period is the time it takes for the insulation system to recover the initial additional cost of the insulation system in terms of minimum fuel usage for heating and cooling.

Through numerical analysis, Zhang et al. [177] investigated the influence of external wall insulation thickness and position on the heating and cooling loads of a commercial building in five cities from different climatic zones in China. The study employs the life cycle cost analysis (LCCA) method to determine the optimal insulation thickness of the building in each city. In addition, the time lag and decrement factor of different insulation layer positions embedded in the wall are examined. The findings reveal that the increase in insulation thickness significantly affects the building heating load. However, it has a relatively small impact on the cooling load. Moreover, the research highlights that building energy savings vary across different climatic zones.

The successful combination of external wall thermal insulation and fuel source exploitation presents a substantial opportunity for enhancing energy conservation in buildings. Yuan et al. [139] endeavor to ascertain the most favorable combination of four unique insulation materials and four diverse fuel sources for residential buildings that rely on electricity for heating and cooling across the six climatic zones of Japan. An evaluation of the optimal thermal resistance (OTR) of insulation materials, the energy cost savings per unit area of external walls, and the return-on-investment periods correlated with the implementation of OTR across the six climatic zones are executed through a cost analysis and the degree-day (DD) method, which other researchers also use to obtain the optimum insulation thickness [178]. The results reveal that the quintessential combination for all climatic zones comprises the employment of rock wool as the insulation material and liquefied natural gas (LNG) as the fuel source. The degree day is the measurement unit for a region's coldness and hotness. The difference between the daily mean temperature and the standard temperature is usually taken at 65 °F. Mathematically, it can be expressed by Equation (1).

$$\frac{T_h + T_l}{2} - 65 \tag{1}$$

where T_h and T_l Indicate the highest and lowest temperatures in a day, respectively. If the difference of the above equation is greater than 0, it is called a cooling-degree day, and vice versa for the heating-degree day.

Kurekci [179] calculated the optimum thickness for five different zones of Turkey, considering the net saving and payback period. This study considered three cases (i.e., both heated and cooled, cooled but not heated, and heated but not cooled). Five materials were used for insulation (polyurethane, glass wool, rock wool, expanded polystyrene, and extruded polystyrene). Four fuels were used, i.e., coal, natural gas, liquid petroleum gas, and fuel oil. It was observed that the optimum thickness changes with the change in insulation material and fuel type.

Although researchers focused on the importance of using the optimum thickness of the insulation materials, some researchers also observed that under certain circumstances, the thickness of the insulation materials does not affect their thermal conductivity [20]. Lakatos et al. [180] studied the effect of varying thickness of EPS form on the thermal conductivity and observed that the thermal conductivity of EPS is independent of its thickness.

3.2. Location of Insulation in Wall and Building

The positioning or configuration of insulation within a wall gained significant attention due to its impact on cooling and heating loads, time lag, and decrement factor, among other factors. Bojic and Loveday [181] investigated the distribution of insulation within a three-layer construction, revealing potential energy savings ranging from 32% to 72% for different structures. Asan [59] examined four distinct insulation locations and observed a profound influence of insulation thickness and position on time lag and decrement factor. Asan [182] further explored six different wall configurations, identifying the optimal arrangement with the minimum decrement factor and maximum time lag.

Six different wall configurations at six different climate zones were used, and the energy analysis of a single-story residential building was conducted using DOE—2.1E by Kossecka and Kosny [140]. It was concluded that the insulation configuration can significantly affect the annual heating and cooling load. Al Sanea and Zedan [183] studied the effect of insulation layer location installed in a building panel under transient conditions. Two cases were studied for January and July, where the insulation layer was installed at the inside and outside locations. It was observed that the average heat transmission was around three times lower for the inside insulation compared to the outside. The R-value considering four different faces of the building (north, south, east, and west) was also significantly higher. Zhang et al. [184] studied the effect of insulation location for four different cases and it was observed that the internal thermal insulation reduces the heat flow, which ultimately enhances the thermal resistance. Ozel [185] numerically studied the influence of insulation layer location and thickness of the layer on the heat transfer and overall performance of the isolation system considering various configurations, as shown in Figure 27a. It was observed that the location of the insulation has a significant effect on the decrement factor and time lag, which is mentioned in Figure 27c.

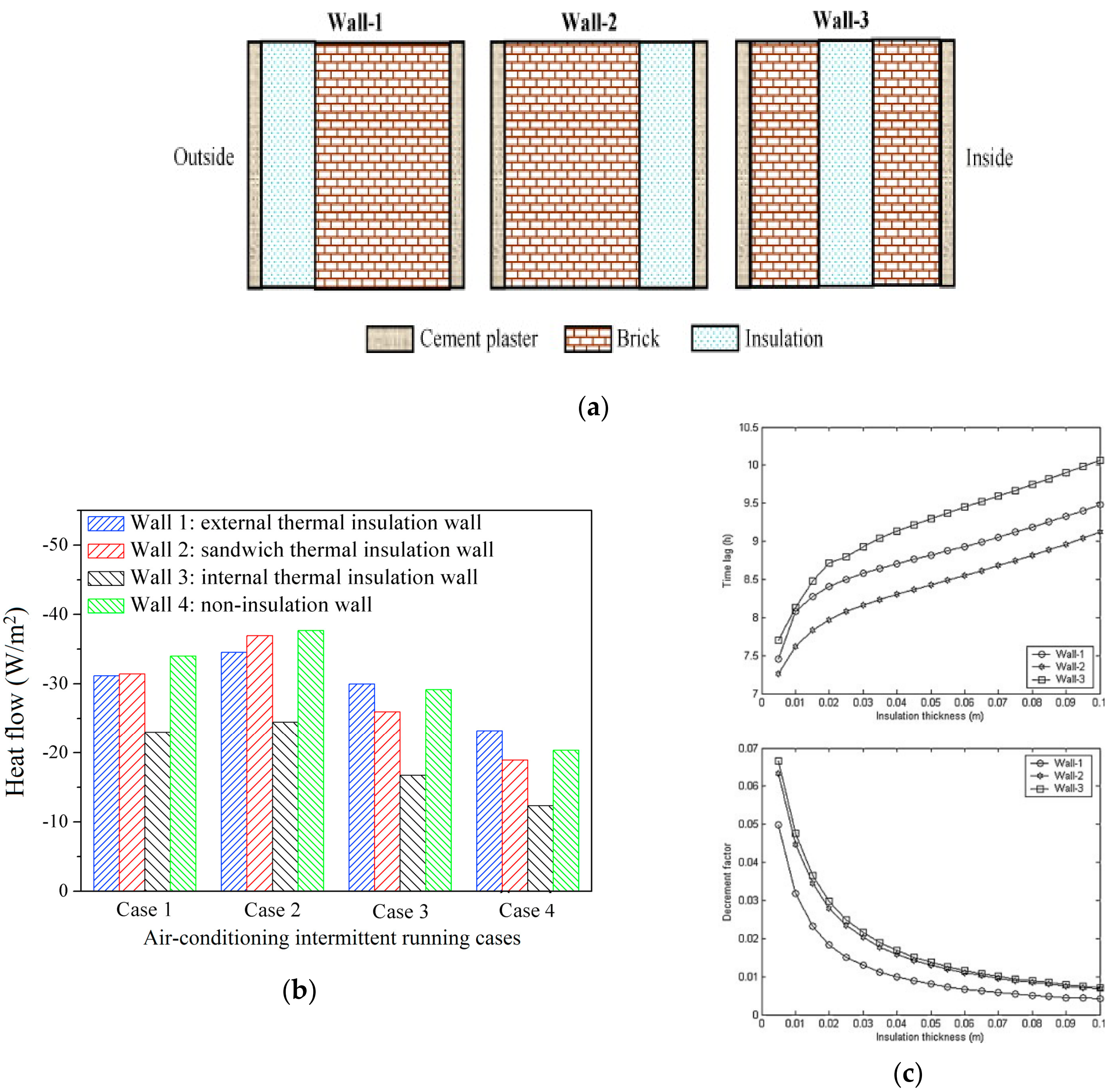


Figure 27. (**a**) Various insulation layer configurations; (**b**) variation in R-value corresponding to adopting insulation on the inside and outside of the panel; and (**c**) effect of insulation on time lag and decrement factor [184,185].

3.3. Temperature

Various authors report that the thermal conductivity of the insulation material is greatly affected by temperature. Figure 28 indicates the impact of temperature on the thermal conductivity of various insulation materials, with temperatures ranging from −20 °C to 60 °C, where one can observe a constant thermal conductivity increase with the temperature increase [25,186]. Moreover, the thermal conductivity of some materials is significantly affected compared to other materials. One can observe in Figure 28 that the variations in the case of aerogel and VIP are relatively lower compared to fiberglass and wood wool. The material's insulation characteristics are usually reported at a mean temperature of 23.8 °C. Steady-state testing methods, such as ASTM C518 [187], specify that R-value evaluations must follow specific temperature guidelines, requiring testing to be carried out at an average temperature of 75 °F (23.8 °C) [188]. During these measurements, the temperature difference between the hot and cold plate shall not be less than 10 K. Therefore, while conducting a thermal conductivity test, the warmer side is set to 100 °F (about 37.8 °C), and the colder side is set at 50 °F (about 10 °C). However, this standard accepts fluctuations in the cold-side temperature, allowing a range of 50 °F (about 10 °C). As a result, the cold-side temperature may range from 45 to 55 °F, while the hot-side temperature should be in the 95 to 105 °F range [189].

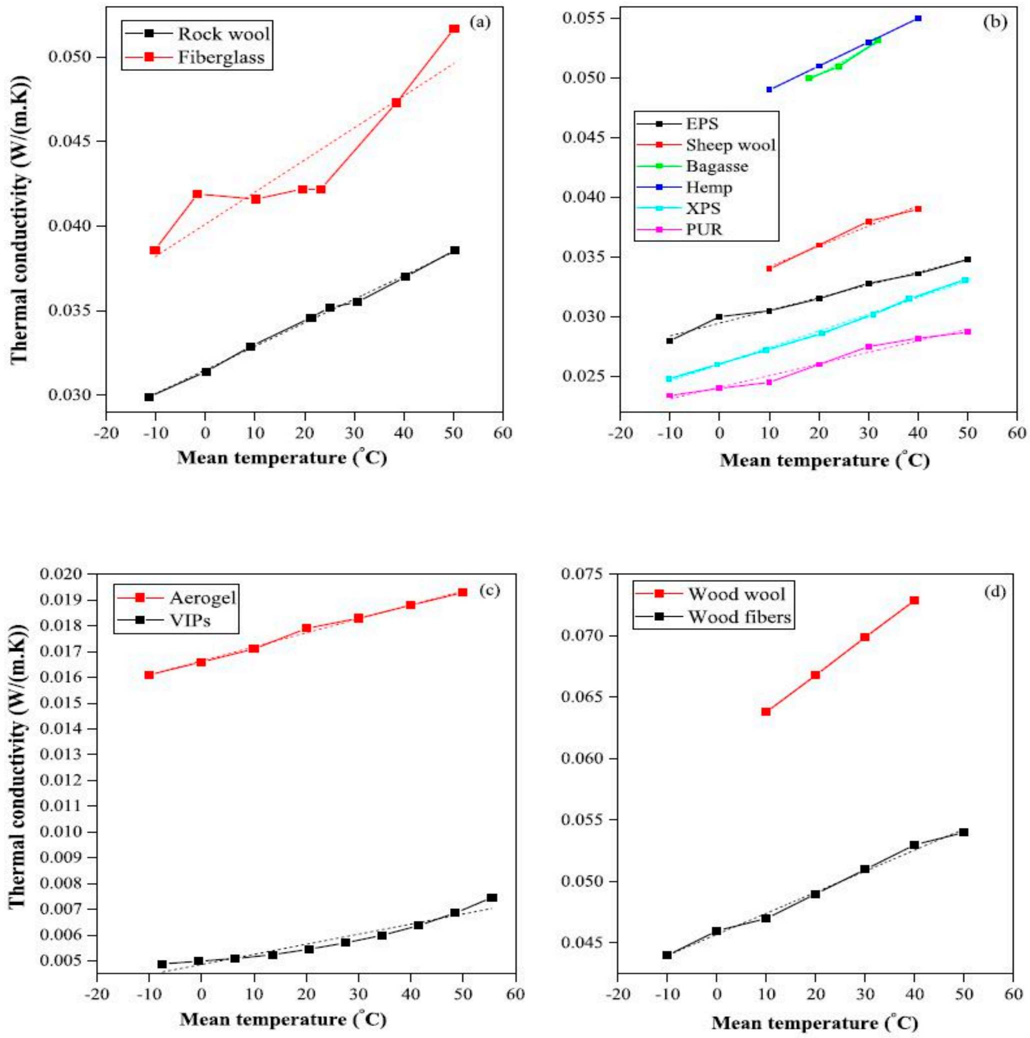


Figure 28. Effect of temperature variation on the thermal conductivity of various commonly used insulation materials: (**a**) inorganic materials; (**b**) organic materials; (**c**) advanced materials; and (**d**) combined materials [25].

Lakatos [138] conducted an experimental study to evaluate the thermal properties of aerogel-based insulation blankets. The samples were thermally annealed at temperatures ranging from 70 °C to 210 °C for 1 h, and thermal conductivity measurements, specific heat capacity, and density were performed. Thermal diffusivity, effusivity, and thermal inertia were calculated based on the measurement results, and effective heat capacities were also determined. The study demonstrated the importance of using heat flow meters and differentiated scanning measurements to assess the thermal performance of insulation materials accurately. It was observed that the insulation remained stable up to 150 °C; however, annealing the samples at higher temperatures resulted in significant changes in thermal behavior. Specifically, the diffusivity decreased while the effusivity and effective heat capacity increased. These findings suggest that exposure to elevated temperatures beyond 150 °C may compromise the insulation capability of the material. The study emphasized steady-state methods for measuring thermal conductivity and transient methods for determining diffusivity. Investigating the thermal performance of materials is crucial for understanding their transient thermal behavior, particularly in the context of building materials.

It was reported previously that the thermal conductivity of the insulation system varies over time. However, it was also stated that the temperature effect is almost negligible under −15 °C to 25 °C. On the other hand, significant change in the insulation properties can be expected under higher temperatures such as 25 °C < T < 200 °C. Such higher temperatures can be considered as thermal annealing, which can significantly provoke changes in the physical, chemical, and thermal properties of the Aerogel-based insulation.

3.4. Density

Several studies reported that higher-density insulation materials tend to have lower thermal conductivity due to increased resistance to heat transfer [190]. However, some exceptions were reported where unusual behavior was observed [25]. The above statement applies to most organic and inorganic insulation materials (such as mineral wool, EPS, XPS, PU, etc.). However, it may not be accurate for new and advanced materials such as aerogel, as the increase in aerogel content in aerogel-based composites reduces the density and the thermal conductivity. Gnip et al. [191] reported that the thermal conductivity of EPS reduces from 0.050 to 0.032 W/(m.K) with the increase in density from 14 to 38 kg/m^3. This phenomenon may be attributed to variations in air bubble sizes within porous materials, particularly when comparing materials of low density to those with higher-density foam compositions. Materials with lower density tend to exhibit larger air bubbles, facilitating more pronounced heat transfer properties within the material. Conversely, as material density increases, the size of the air bubbles diminishes, and the structural framework becomes more intricate. Within these smaller bubbles, heat transfer rates decrease. Additionally, the increasingly intricate solid matrix system contributes to higher thermal resistance. Elevated material density leads to a greater proportion of solid components within the system, thereby enhancing the dominance of thermal conductivity in the solid portions. These three interrelated phenomena, i.e., variations in bubble size, structural complexity, and solid content, contribute collectively to an effective thermal conductivity that may reach a minimum threshold. Khoukhi and Tahat [192] experimentally studied the effect of variations in densities on the thermal performance of polystyrene under different temperatures. The authors reported a reduction in thermal conductivity with the increase in density. Figure 29 indicates the variations in thermal conductivity of various commonly used insulation materials with the variations in density. A general trend is that the thermal conductivity increases with the increase in the density of the material. However, for porous materials, the thermal conductivity initially reduces with the increase in the density up to a certain point, and after that, when the density is further increased, the thermal conductivity increases.

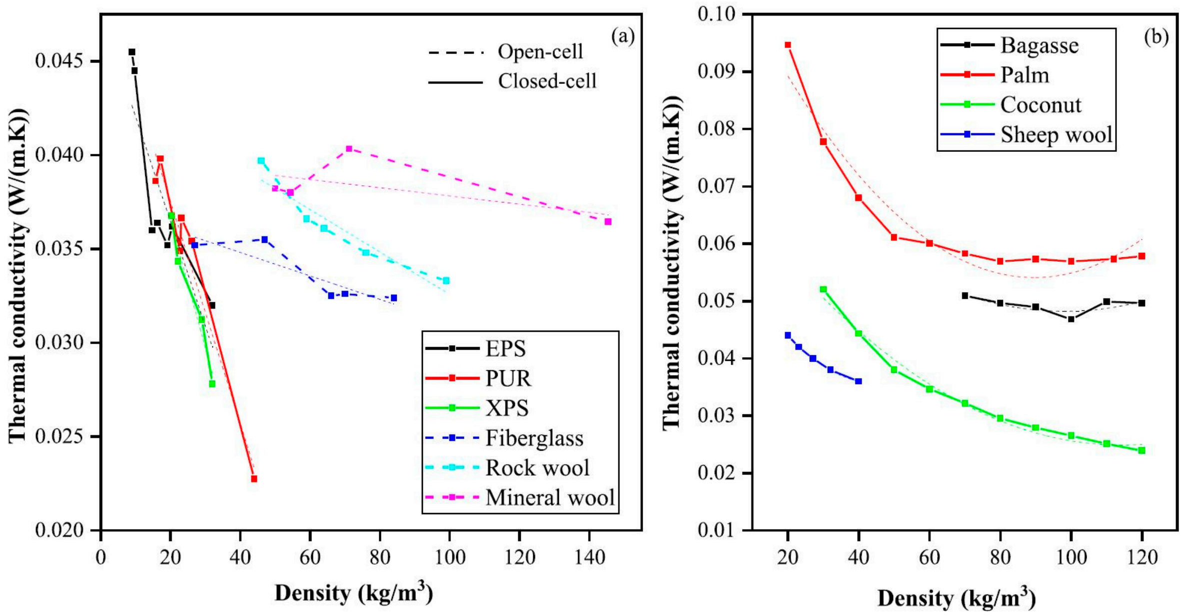


Figure 29. Variation in thermal conductivity with varying density for various insulation materials; (**a**) conventional materials used for insulation; and (**b**) natural fibrous materials [25].

3.5. Moisture Content

Moisture present in insulation materials can increase their thermal conductivity as highlighted in Figure 30 and reduce their thermal resistance and durability [193,194]. Although a general trend is that with the increase in the moisture content of insulation material the thermal conductivity also increases; however, it is also affected by the density of the material. As mentioned in Figure 30, the materials with higher density tend to resist moisture and therefore the thermal conductivity is not significantly affected. A common example is a higher porous material such as aerogel, where the thermal conductivity significantly goes higher for low-density aerogel; however, the effect is not very prominent in the case of higher-density aerogels, as mentioned in Figure 30d. Considering that the insulation material might encounter prolonged exposure to water immersion conditions and elevated humidity levels throughout its operational lifespan, it must exhibit robust, water-resistant characteristics. This encompasses factors such as resistance to water absorption, moisture transfer, and capillary action. Additionally, the material should demonstrate resilience against freeze–thaw cycles to preserve its insulation efficacy. Consequently, in North America, the prevailing standard designates rigid polystyrene insulation boards, specifically those that adhere to CAN/ULC-S701.1, Type 4 specifications with the temperature range of −54 °C to 75 °C, as the singular insulation type deemed suitable for such demanding environmental conditions [195,196]. Wang et al. [197] experimentally studied the impact of relative humidity and temperature on the thermal performance of various insulation materials (glass wool, rock wool, EPS, XPS, and phenolic foam). The thermal conductivity was observed to vary from 14.8% to 186.7% by changing humidity from 0% to 100%. On the other hand, the variation of 8.8% to 21.4% was observed by varying the temperature from 20 °C to 60 °C. Pei et al. [198] proposed a model that can predict the thermal conductivity of insulation materials with varying moisture content and porosity in cold regions. It was reported that the thermal conductivity of the insulation material can increase up to 50% with water adsorption.

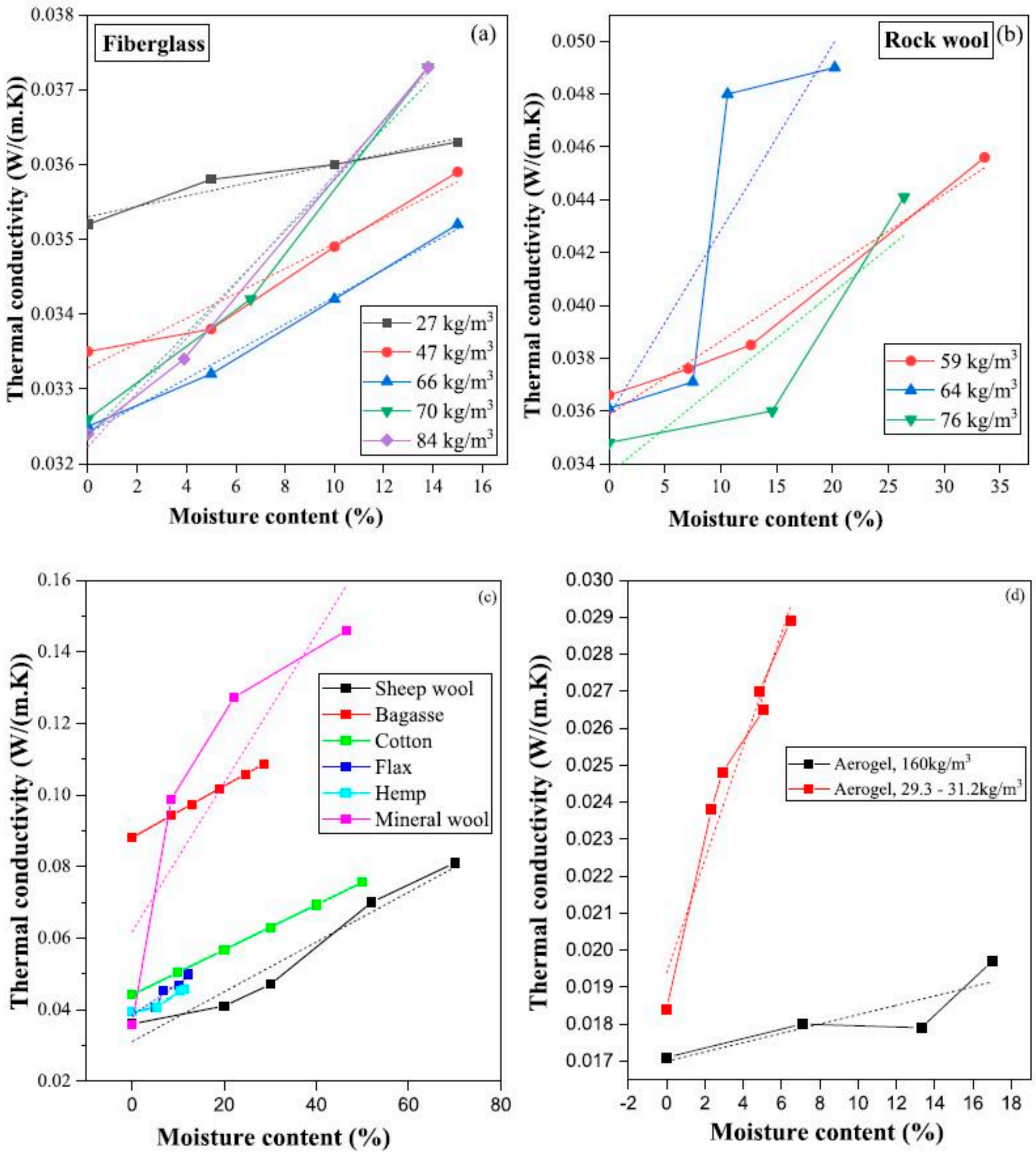


Figure 30. Effect of moisture content on the thermal conductivity of various insulation materials and varying densities; (**a**) fiberglass; (**b**) rockwool; (**c**) natural materials; and (**d**) aerogels [25].

3.6. Thermal Conductivity, Transmittance, and Resistance

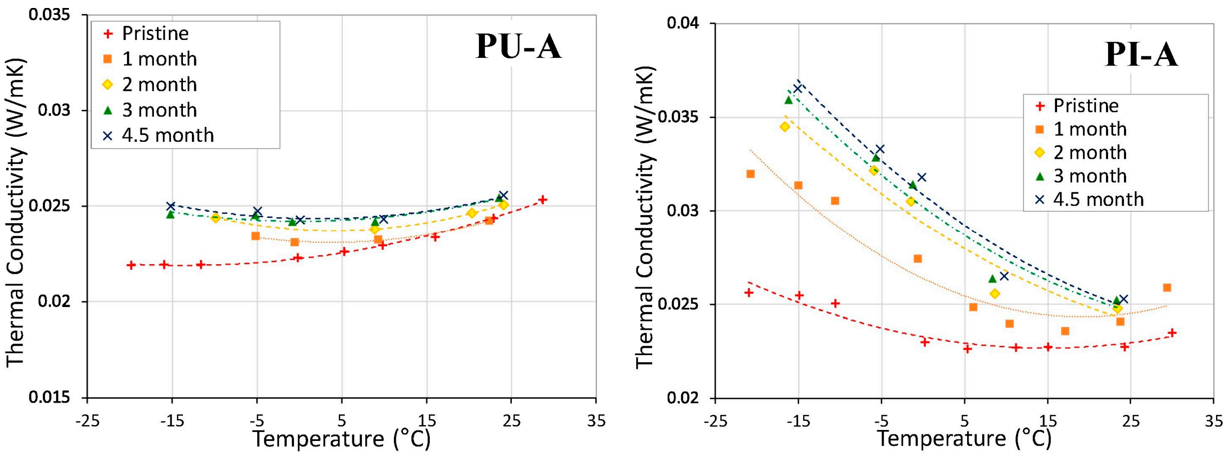
Thermal conductivity and transmittance are the primary properties of the insulation system and need to be analyzed first to decide whether a typical material can be used as an insulator. To qualify as a thermal insulator, a material's thermal conductivity (λ) should be below 0.1 W/m.K [199]. Some traditional materials used for insulation, such as glass wool, mineral wool, expanded polystyrene, and foam glass, exhibit λ values within the range of 0.034 to 0.045 W/m.K. Moreover, high-performing materials such as polyurethane and phenolic-resin-based polymeric foams have λ values between 0.020 and 0.029 W/m.K. Finally, materials with λ values below 0.020 W/m.K are classified as super insulators. Examples of such extraordinary insulating materials include silica and organic aerogels (0.011 to 0.034 W/m.K), vacuum insulation panels (0.003 to 0.011 W/m.K), and vacuum glazing (0.0001 to 0.0005 W/m.K) [134].

The steady-state heat flow across a unit surface area caused by a 1 K temperature differential is known as thermal transmittance, also known as U-value, and it includes convective and radiative heat exchanges. It is assessed using the hot box technique and is given in $W/m^2.K$ [200]. Researchers proposed various measurement methods for the U-value of the building envelope and also studied the effect of variation in U-value on the heating and cooling demand of a reference building [201,202]. Ficco et al. [203] and Scarpa et al. [204] used the heat flux meter method to measure the in situ U-value of a building. It was observed that the operative conditions can bring some uncertainties in the in situ measurement of the U-value. In a steady state, thermal conductivity and transmittance are employed to characterize insulating properties; in an unstable system, the most used parameter is thermal diffusivity D, which compares the thermal energy transport and storage capabilities of various materials. The product of density, specific heat, and thermal conductivity ratio determines it. It is measured per ISO 22007-2 and expressed in m^2/s [205]. The amount of energy needed to change a 1 kg material's temperature by 1 K is termed the specific heat of that material, which is measured in J/kg.K. Even with low density, a substance with a high specific heat value can nonetheless provide low diffusivity values.

Similarly, insulation materials with higher thermal resistance values (R-value) typically have lower thermal conductivity. R-value, which is expressed in $m^2.°C/W$ or $ft^2.°F/Btu$, is commonly used to measure the thermal performance of insulating materials. In other words, it measures the material's resistance to the flow of heat and is primarily a function of the material's thermal conductivity, density, and thickness. The Federal Trade Commission (FTC) established the R-value Rule in 1979, which requires manufacturers to declare a specific value based on standardized testing at a mean temperature of 24 °C with a temperature differential of ±5 °C. This standardization made it easier for customers to compare products and communicate with businesses. Despite being initially designed for residential insulation, R-values found use in commercial, institutional, and industrial insulation solutions. The guarded hot plate (GHP), referred to as ASTM C177 [206], and the heat flow meter (HFM), referred to as ASTM C518 [187], are frequently used test procedures for calculating the thermal conductivity, which can be utilized to obtain R-values. In contrast to the HFM method, the GHP method utilizes a guard plate to reduce lateral heat transfer, making it more accurate. Similarly, various other international standards such as EN 12664 [207], which is used for low thermal resistance, EN 12667 [208], usually used for high thermal resistance, and EN 12939 [209], preferable for thick materials, are commonly used for identifying the thermal conductivity of the materials used for insulation. Moreover, researchers developed various experimental methods for measuring the thermal performance of building materials. Bruno et al. [210] developed a climate chamber to measure the thermal properties of the building materials. Nardi et al. [211] and Basak et al. [212] evaluated the U-value of an opaque wall and insulation material using various calculation methods in a guarded hot box. Manufacturer-specified R-values were adopted as design values to meet building energy code requirements relating to minimum R-values (or maximum U-values) for building envelope elements, even though they were first created for product comparisons. However, they rely on the R-value supplied by the manufacturer, as design values can result in errors in energy calculations. It is worth mentioning that manufacturer-specified R-values, established under precise testing circumstances (24 °C mean temperature with ±5 °C variation), offer a useful way of swiftly comparing the thermal performance of insulating materials. However, a key drawback of this metric is that it does not consider in-service conditions, which can deviate greatly from typical testing conditions, particularly in terms of temperature and moisture content. For instance, due to exposure to intense solar radiation and nighttime cooling, roof surfaces may undergo significant temperature changes, ranging from −46 °C to 110 °C. Consequently, while being important elements in real-world applications, temperature and moisture impacts are not taken into account when calculating R-values.

3.7. Aging and Deterioration of Insulation Materials

Over time, insulation materials may deteriorate or settle, potentially affecting their thermal conductivity and overall performance. Extreme temperatures, sun radiation, higher temperature fluctuations, moisture, and higher pollution can cause the aging and deterioration of the insulation materials [213,214]. Therefore, it is important to consider the expected temperature range, moisture, and other factors when selecting insulation. Berardi [213] studied various polyurethane and polyisocyanurate foams subjected to elevated temperatures, higher relative humidity, and freeze–thaw cycles. Unlike polyurethane, the thermal performance of polyisocyanurate was significantly influenced by aging under higher temperatures and moisture content. As mentioned in Figure 31, thermal conductivity increases at higher temperatures. On the other hand, the lower temperature does not significantly affect thermal conductivity. Moreover, with aging, the thermal conductivity increased for polyisocyanurate, but the effect on polyurethane was negligible as mentioned in Figure 31, where a higher thermal conductivity was observed for 4.5 months of specimens compared to others.



(**a**) (**b**)

Figure 31. Effect of aging on thermal conductivity under various temperatures; (**a**) effect on polyurethane; and (**b**) effect on polyisocyanurate [213].

Heat treatment is an efficient way to modify aerogels' crosslinking structure and chemistry, which can significantly affect the morphology, microstructure, and pore structure. Lakatos et al. [215] investigated the impact of different aging and temperature conditions on the structure and thermal conductivity of glass fiber-reinforced silica aerogel. The authors analyzed sorption isotherms, and the structural and thermal properties were modified through scanning electron microscopy (SEM), differential scanning calorimetry (DSC), and X-ray diffractometer (XRD) tests.

Aging and temperature conditions significantly impact the volume shrinkage of silica aerogels, especially those composed of small particles [216]. Similarly, the effect of time, solvent, and temperature was studied by Omranpour and Motahari [217]. Four different solvents were used for aging, namely methanol, tetraethyl orthosilicate (TEOS), n-hexane, and deionized water. It was observed that the compression properties of the aerogels were enhanced with increasing time and aging temperature. Moreover, it was also stated that those samples aged underwater indicated higher compressive properties than others.

Aging can also significantly affect the physicochemical properties of silica aerogel, particularly ambient dried materials. Iswar et al. [218] studied the aerogel's bulk density and specific surface area, which decrease with aging. It was also stated that ambient pressure drying could successfully produce low-density silica aerogels. Section 4 highlights important considerations that one needs to keep in mind while choosing any particular insulation system for any specific case.

4. Considerations for Choosing an Insulation System

Various factors affecting the performance of an insulation system are discussed in detail in the previous section. In this section, some important properties and considerations to take into account before choosing any particular insulation for any region are highlighted in Table 9.

Table 9. Important considerations for using thermal insulation in buildings.

Thermal conductivity	Thermal conductivity and transmittance are the primary properties of the insulation system and need to be analyzed first to decide whether a typical material can be used as an insulator. To qualify as a thermal insulator, a material's thermal conductivity (λ) should be below 0.1 $W.m^{-1}.K^{-1}$.
Cost	The upfront cost and long-term savings associated with the insulation material are essential, as the insulation needs to be affordable. The life cycle cost analysis (LCCA) could be a suitable approach to monitor the efficiency and cost of the insulation material.
R-Value	The measure of thermal resistance provided by the insulation material is termed as R-value. A higher R-value signifies better insulation effectiveness. The materials available in the market are provided with the specific R-value.
Moisture Resistance	The insulation material needs to resist moisture absorption or prevent water vapor transmission. Insulation should maintain its thermal performance even in humid or higher-moisture environments. Therefore, some hydrophobic materials, such as aerogel, could be suitable options in humid regions.
Fire Resistance	Fire-resistant insulation material is crucial for safety in buildings. Building codes indicate some specific fire resistance category for the material to be used as insulation.
Environmental Impact	The insulation material's sustainability, recyclability, and ecological footprint are significant. Choosing environmentally friendly options is essential for long-term sustainability. As such, cellulose is environmentally friendly compared to polystyrene foams.
Durability and Longevity	The insulation material's expected lifespan and ability to retain its performance over time must be considered. Durable insulation ensures long-term energy efficiency.
Compatibility and Application	Insulation materials should be suitable for the specific application and building requirements and accessible in installation. Insulation materials need to have sufficient rigidity to install them easily.
Health and Safety	Consider the material's potential for off-gassing, emissions, or adverse health effects. Insulation should meet health and safety standards, as there are materials such as fiberglass which have health concerns.
Quality Control	Quality control during the construction stage is another important aspect that can vary the performance of the insulation material.

5. Conclusions and Recommendations

This study presented an overview of traditional natural and artificial insulation materials along with recent trends in thermal insulation materials. They are discussed along with their essential properties, applications, advantages, and disadvantages; from state-of-the-art organic and inorganic materials to novel Aerogel, VIP, PCM, and composite materials. Various factors affecting the performance of insulation materials are elaborated on, and important considerations before selecting any particular insulation material for a specific region are highlighted. It was observed that the inorganic-based materials have high thermal resistance; however, they are associated with higher embodied energy and carbon footprint. On the other hand, organic-based insulation materials, particularly renewable materials, have slightly lower thermal resistance, and their low cost and sustainability make them a suitable alternative. This study concluded that the naturally available materials (although a sustainable option) are not used abundantly due to their higher space requirements, lower thermal performance, moisture resistance, and lower fire resistance. Moreover, the lack of research on utilizing natural materials for thermal insulation is also a factor due to which they are not widely used for thermal insulation, as there are very few studies on utilizing natural materials for insulation. Similarly, the commonly used mineral wool is heavier, which may also cause serious health issues, and petrochemical products (EPS, XPS, PU), the second most commonly used materials, require higher production energy, are brittle in nature, and are prone to fire hazards. Therefore, composite material could be a suitable alternative to overcome these problems, where additional fibers, usually waste products, are utilized to overcome the associated deficiencies of homogenous material. For future studies, the authors intend to utilize wastepaper pulp and aerogel particles to obtain a composite insulation material suitable for extreme environments in the northern Canadian Indigenous communities. Combining aerogel's thermal efficiency and wastepaper pulp's cost-effectiveness, the proposed insulation material aims to provide an energy-efficient and sustainable solution for the building industry.

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