

Review

# Comprehensive Review of Innovative Materials for Sustainable Buildings' Energy Performance

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**Abstract:** The building sector, one of the most energy-consuming, is among the most current topics due to the maturing concerns about the anthropogenic factor's impact on CO<sub>2</sub> quantities in the atmosphere and its association with global temperature rise. Using sustainable building materials is a promising alternative in building envelope applications to improve in-use energy efficiency. These materials, having a low environmental impact, the advantage of being renewable, and low embodied energy, contribute to global sustainability. This comprehensive literature review presents a broad overview of these materials' hygrothermal characteristics, thermal performance, and energy use. The main goal is to compile the most important research findings on these materials' capabilities for building construction and their contributions and effects on energy performance and thermal insulation.

**Keywords:** sustainable materials; energy efficiency; thermal conductivity; environmentally friendly; carbon footprint; thermal insulation



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## 1. Introduction

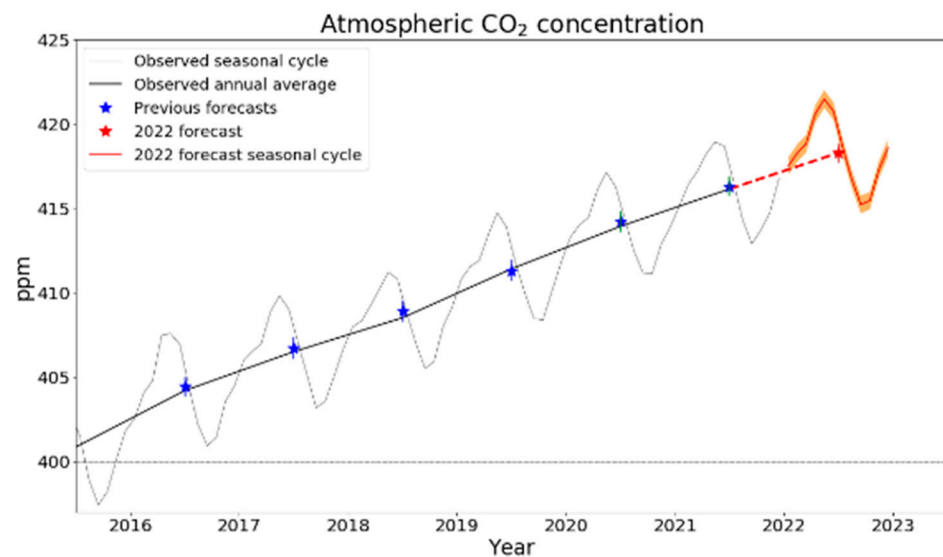
With the passage of time during these generations, a significant increase in the population is being observed in all countries around the globe. This, in return, leads to the rise in urbanization. This later is related to the changes happening to certain cities in terms of their heterogeneity, size, and density; in simpler terms, it is defined as the emergence and growth or reduction in the size of cities. Urbanization is typically accompanied by population movement, segregation, industrialization, and increasing building needs [1]. With this being said, it is crucial to mention that more construction is being witnessed in all countries and cities, leading to more energy consumption and energy source depletion since the nineteenth century until today; the world's population has tremendously increased by six and its gross domestic product (GDP) by sixty. More than 80% of our energy consumption in the energy sector, in which electricity is a subset, depends hugely on fossil fuels, non-renewable and polluting energy sources such as coal, oil, and natural gas. These materials have been reasonably easily accessible, cheap, and abundant [2]. Electrical energy is essential in advancing and developing industrialized nations, especially in the 21st century [3]. In buildings, energy and electricity needed for heating and cooling purposes have notably increased from 118 EJ in 2010 to about 128 EJ in 2019 [4]. If these trends continue to prevail, buildings could be considered the world's largest energy utilizers by 2025, consuming more energy than the combination of both transportation and manufacturing sectors. This industry demands a great amount of raw materials and depletes many resources. Fabricating

these construction materials accounts for more than 80% of the energy consumption, making building energy efficiency a top priority. Integrating energy-efficient policies, practices, and behaviors is mandatory to achieve an environmentally friendly culture. This requires a carbon-centric approach, the main driver of the GHG emissions footprint [5].

With this energy comes climate change that affects many countries' ecological structures, economic systems, and social development [6]. As we advance, individuals in all parts of the world promote sustainability and green goals and abide by the 17 United Nations Sustainable Development Goals (SDGs) that intend to end poverty, protect the planet, and ensure prosperity for all. However, numbers show that at the moment, 1.2 billion people in the lesser developed countries (LDCs) do not have sufficient access to electricity, and 2.9 billion still cook with unclean and inefficient fuels [7]. The constant demand for conventional fuels is increasing exponentially with time, which causes their decline, and the present situation is unsustainable and further aggravated when resource scarcity and demographic growth are considered. Hence, considering sustainable alternatives arises [2,8]. When the availability of fossil fuels, nuclear energy, or renewable sources is insufficient to meet the demand for energy consumption, a situation known as an energy crisis will arise. It can cause numerous problems like price increases, shortages, and disruptions to energy supplies. This huge dependence on such non-renewable materials is associated with all forms of pollution, severely damaging our planet. With the passage of decades, it has been realized that tremendous amounts of CO<sub>2</sub> are being released into the atmosphere due to the combustion of fossil fuels and traditional fuel sources. The exponential increase in its amounts in the atmosphere is seen clearly in Figure 1, which depicts the changes from 2016 to 2022 as per the red line that represents the seasonal forecasted cycle, indicating that the amounts of CO<sub>2</sub> that are foreseen for the coming years also follow the increasing trends. This contributes to the addition of greenhouse gas (GHG) emissions and raises the rate of climate change and global warming, which has harsh consequences on the ecosystem and the human community [9,10]. In order to compensate for the depletion of non-renewable sources, energy production from sustainable, regenerative materials is now a field of interest. To address energy crises, governments and industry leaders must implement energy conservation programs, diversification of energy sources, investment in renewable energy technologies, and improvements in energy efficiency. Renewable plants are one good solution, but they hugely depend on the weather, solar radiation rate, and wind speed. Another solution would be home energy management by integrating local resources and bio-sourced, green, and geo-materials in the building's structure. This solution is more eco-friendly, less pollutant, has been designed to reduce negative environmental impact, and promotes less GHG release.

"Bio" is derived from a Greek word meaning life. Bio-sourced materials are materials made from renewable biological resources such as plants, animals, and microorganisms that can be grown again. It is essential to differentiate between biobased materials and biomaterials. Biomaterials are biocompatible materials employed and adapted to medical applications, which include implantable medical devices, tissue engineering, and drug delivery systems. Biobased materials encompass a wide range, from natural fibers to biopolymers, and are making significant advances in petroleum-based materials industries [11,12]. These materials are often utilized instead of traditional, petroleum-based materials, usually derived from non-renewable fossil fuels. These materials can be considered raw materials for various products: textiles, packaging, plastics, engineering, and construction. On the other hand, geomaterials are renewable and naturally occurring materials constituting the earth's crust, play a fundamental role in shaping its surface, and are used in many engineering and construction applications [13]. Lastly, green materials, also termed sustainable materials or eco-friendly materials, are manufactured, utilized, and disposed of in a sense that reduces harm to the environment and human health. Green materials can be generated from various renewable resources, and their manufacturing processes require lower energy and yield fewer greenhouse gas emissions than traditional materials. The goal is to highlight the most significant research findings on these materials

rather than to be exhaustive. This primary research focused on manufacturing a new sustainable construction material for the building industry. When used for building applications, all these materials are fabricated and designed to have optimum energy-saving performance, thermal insulation [14], reduced impact on natural resources, reduced waste and pollution, and boost a more sustainable and healthier lifestyle [15]. We discussed and presented the availability of sustainable eco-materials and their hygrothermal and energetic performance at the envelope scale. The given review is a dataset detailing all the sustainable materials that can be integrated into a building layer, lower energy consumption, and act as an insulation material; no similar published research is found and expanded as much. My authors dealt with publications similar in the domain are subsets of this comprehensive review as they only deal with one type of sustainable materials, such as bio-sourced, that are being considered to be implemented in the building industry [4,11,12,16,17]. What is interesting about this study is that the majority of these considered resources for building and insulating purposes are available in the Mediterranean and North African regions.



**Figure 1.** The steady increase in CO<sub>2</sub> is due to various emissions [18].

## 2. Research Methodology

This review paper's formulation was based on entering search queries on reputable and credible search engines such as Scopus, Google Scholar, Science Direct, and libraries of the University of Balamand (UOB) and University of La Rochelle (ULR) to find relevant articles and extract related research. The keywords were thermal properties, physical properties, insulation, buildings, and energy. This study employs diverse scientific databases, including conferences, dissertations, and journal papers, to reveal the effect on the thermal insulation of buildings and structures upon incorporating the various sustainable materials generated from different renewable sources. The cited and gathered journal papers were found in the largest database of peer-reviewed literature. Upon reading and analyzing the articles, the most relevant ones were kept and cited, and the less relevant ones were eliminated. After compiling them, they were sorted according to the publishing year and grouped to form the sum that was graphed accordingly. Although this paper tends to highlight the present state-of-the-art research for this study, the old, impressive existing literature was also taken into account, as depicted in Figure 2. The highest percentages of referenced research studies were witnessed in the years ranging between 2015 and 2021. As can be seen, to cope with the topic's novelty, the present paper uses much original and newly published research to sustain both innovation and comprehensiveness. Figure 2 illustrates the growth in researchers' interest in current years to identify new generations of materials with low thermal conductivity, thus providing insulation and a

low environmental impact compared to the studies performed and published before 2000. Three subsections are presented in this research paper to accurately determine the effect of various materials with different starting sustainable and renewable raw materials. Section 1 deals with biobased materials, meaning they emerge from living matter or biomass and could be natural or materials fabricated through biomass processes. Section 2 presents the geo-materials influenced by the earth's billion-year-old geological systems. Finally, Section 3 describes the green materials being incorporated and serving many purposes. All three material families fall under the same umbrella, which leads to using a sustainable material that improves structures' thermal insulation and energy efficiency.

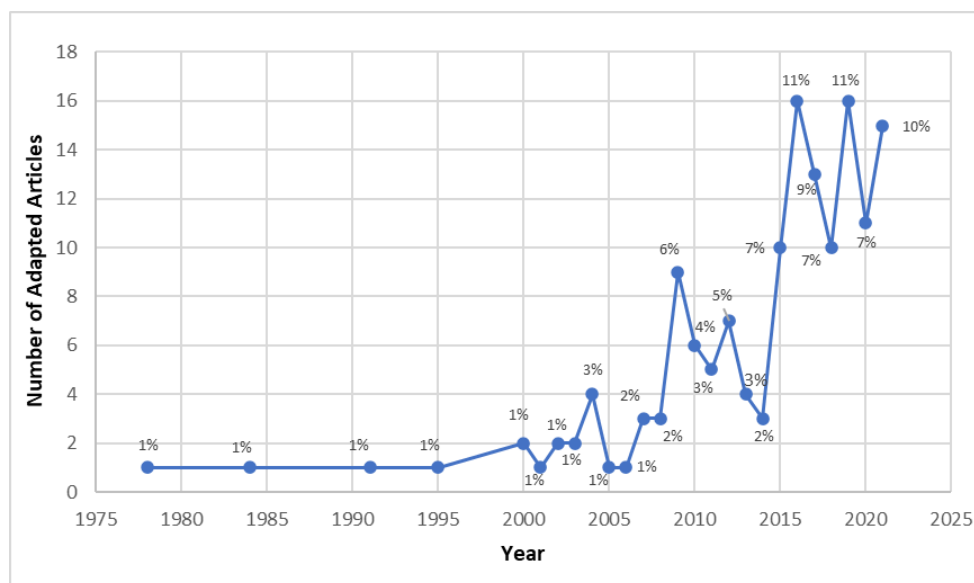


Figure 2. Referenced research articles as a function of the publishing year.

### 3. Application of Sustainable Materials for Insulation and Energy Efficiency in the Building Sector

As mentioned, biomaterials or bio-sourced materials refer to any product synthesized by microorganisms (or part of them) under different/ specific environmental conditions. These materials chiefly accommodate any material derived from existing matter like biomass and arise naturally from products created by biomass developments. In the presence of bio-based materials, conventional materials will be outdated. New biobased materials and their application in novel ways are merely popping out, calling to be explored and applied in research. Several common materials like wood, paper, plants, animal products, and many more are addressed as biobased materials and will be discussed [19]. Also, the reuse of solid waste materials emerging from various sources in buildings via their encapsulation into the matrix of traditional base materials can absorb considerable amounts of waste and possess a wide range of beneficial qualities. During the last decades, waste management and green energy have gained massive popularity as they act on preserving the environment, reducing waste treatment and disposal costs, and generating alternative materials vulnerable to many industrial applications. These materials are sustainable and will positively affect social well-being as they will be replenished by photosynthesis daily. These pragmatic materials are the unsurpassed alternative as they not only target the reduction in daily carbon dioxide emissions but also offer thermal comfort with less energy consumption for the functioning of the buildings [20,21]. With everything happening around us, it is vital to take serious measures when moderating and controlling energy consumption everywhere. The search for new materials with good thermal insulation to integrate into building structures is one of the practical solutions to reduce energy needs and optimize consumption.

### 3.1. Mycelium

To start with some plant-based materials, fungi have a substance in their roots called the micilia. Mycelium composites are cheap and environmentally sustainable materials gaining great interest and commercialization in the USA and EU regions, especially in construction applications. These materials take advantage of their natural fungal growth as a low-energy bio-fabrication technique to upcycle plentiful agricultural wastes and by-products into more environmentally friendly substitutes for the traditional synthetic construction materials that require much energy. Based on their composition, these materials are easily customizable. They can replace traditional ingredients such as foams, timber, and plastics in applications such as insulation, door cores, paneling, flooring, cabinetry, and other furnishings. They are characterized by their durability, strength, low thermal conductivity ( $0.03\text{--}0.06\text{ W}^{-1}\cdot\text{m}\cdot\text{K}^{-1}$ ), high specific heat capacity ( $10.2\text{ kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$ ), fire resistance, and acoustic absorption. However, mycelium composites have certain limitations that stem from their foam-like mechanical properties and high-water absorption ability. This calls for using mycelium composites as non- or semi-structural supplements to traditional construction materials. Having convenient material properties, a low cost, a simple manufacturing process, and, most notably, environmental sustainability will be significant in future green construction. This mycelium will be compressed into bricks and thus used in the construction industry as insulation and a non-toxic building material. Three great examples of well-known buildings that utilize load-bearing mycelium components and encourage using such plant-based bio-sourced material as they possess a firm structure and support facilities are the Hy-Fi presented in Figure 3, The Organic Mushroom-Brick Tower in New York, the growing pavilion in the Netherlands, and the MycoTree Project in South Korea, which is a spatial branching structure. All of these show mycelium's firm structure and support to buildings [16,22]. Mycelium based on primitive species, such as *T. versicolor* or *multicolor*, recorded a higher tensile and flexural strength of 0.04 Mpa and 0.22 MPa, respectively, compared to monomitic species, such as *P. ostreatus* fungi, that exhibit a tensile strength of 0.01 MPa, and a flexural strength of 0.06 MPa when grown on rapeseed straw [23]. Mycelium can be merged with many materials to form composites with improved mechanical and thermal properties.



**Figure 3.** Hy-Fi Mushroom-Brick Tower in New York [16].

The density of the mycelium composite materials ranged from  $0.10$  to  $0.39\text{ g/cm}^3$ . It is safe to say that mycelium-based materials are lighter compared to other wood composites, like medium-density fiberboard, having a density ranging between  $0.50\text{--}1.00\text{ g/cm}^3$ , and oriented strand board (OSB) wood composite, with a calculated density of  $0.55\text{--}0.70\text{ g/cm}^3$  [24]. The hybridization of mycelium composites is usually performed to improve mechanical performance upon adding small quantities of synthetic rubbers, such as styrene-butadiene rubber, or natural reinforcements, such as cellulose nanofibrils. According to Juan et al. [25], the



*P. ostreatus* fungi had a compressive strength of 177 kPa, which could be doubled by adding only 5 vol% styrene-butadiene rubber to reach a value of 343 kPa. This is due to the decrease in the void volume and increase in the density associated with including the latex from 181 kg/m<sup>3</sup> to 225 kg/m<sup>3</sup> [25]. Moving on to thermal insulation, high-performance natural insulators such as straw and hemp fibers could be added to the mycelium and its composites, a practical, low-cost, and environmentally sustainable substitute for conventional commercial building insulation materials.

### 3.2. Coffee Grounds

Waste generation is a phenomenon that one cannot avoid. Among the most prevalent waste is coffee grounds (CGs). Coffee grounds are known to be solid organic residues since coffee can be considered one of the most consumed beverages worldwide and is available in large quantities. Having said this, many attempts to use these coffee grounds have been made. Due to its high organic matter content, low dry densities ranging between 308 and 399 kg/m<sup>3</sup>, and high optimum moisture content, it was introduced as a fuel in industrial boilers due to its high calorific power for producing biodiesel and fuel pellets and as non-structural materials in road embankments. Not only that, coffee stood out as a cheap and abundantly available adsorbent for removing cationic dyes in wastewater [26]. Moreover, it was also recommended as an antioxidant material source. As the building sector is deeply concerned, CG's utilization in this industry may be a significant challenge. Coffee grounds were tested to produce new geopolymer building materials. Based on the calculations of Oliveros et al., a porosity of 9.8% and 34.2% for green and roasted beans was found [27]. To ensure high standards and regulatory requirements related to thermal insulation and without jeopardizing the bricks' compressive strength, many tests have been conducted to calculate the optimum percentage of spent coffee grounds and to assess the practicality of mixing high amounts of the coffee ground as a solid waste material with raw clay. From the literature, it can be seen that only counted works deal with the potential utilization of spent coffee grounds (SCGs) to improve the thermal insulation capacity of base materials as they possess a thermal conductivity falling between 0.038 and 0.054 W·m<sup>-1</sup>·K<sup>-1</sup> in addition to their high specific heat capacity of 1400 J·kg<sup>-1</sup>·K<sup>-1</sup> [16,26].

### 3.3. Hemp

The cement industry is amongst the most significant contributors to global warming as it accounts for significant carbon dioxide emissions. Conversely, hempcrete is not associated with burning fuels, and its production is not associated with the traditional chemical processes that usually unleash and are responsible for significant greenhouse emissions. Many of the fastest-growing biomasses conjointly exist on planet Earth. In construction, hempcrete was one of the first materials to develop non-weight-bearing infill walls, especially in France. The hempcrete material is a mixture of hemp with water and lime. It is most known for its lightweight properties that can reduce the personified energy of a building by avoiding the unwanted emissions related to moving significant materials. The nature of the hemp, with its woody and thick pulp, offers various uses and can even be developed in an extensive selection of soils and climates. Hemp concrete is classified as a highly porous material with an open and interconnected porosity of 71.51%. Depending on its application, its density falls between 200 and 800 kg/m<sup>3</sup>. Accordingly, its low thermal conductivity is measured to be between 0.06 and 0.18 W/m K. Other studies have shown that hempcrete is a strongly hygroscopic material with high moisture transfer and storage capacities. Its water vapor permeability is about  $3.2 \times 10^{-11}$  kg·m<sup>-1</sup> s<sup>-1</sup> Pa<sup>-1</sup>, and its moisture buffer value (MBV) is around 2 g/(m<sup>2</sup> %RH) which, according to the Nordtest Project, classifies it as a good to excellent hygric regulator [28–33]. In his studies, Bennai et al. [33] found out that the tested hemp presented a very porous structure. Due to that, water accessibility is 72.38%, and the maximum water content is 148.52%. Based on these parameters, the hemp material was classified as having excellent hygrothermal properties. Moreover, the sorption curves presented a high hysteresis loop between the adsorption

and desorption, which confirms that hemp concrete moderates ambient relative humidity variations. Benmahiddine et al. characterized the hemp concrete with and without aging. They found out that the reference hempcrete had a heat capacity of  $872.34 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$  and a water vapor permeability of  $2.85 \times 10^{-11} \text{ kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$ , a porosity of 71.51% with a standard deviation of  $2.18 \times 10^{-4}$ , a thermal conductivity of  $100.7 \text{ mW} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$  with a standard deviation of  $2.3 \text{ mW} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ ) [34,35]. All these data were found to be coherent with the ones found previously in the literature in the works of Bennai [29,33] and Sawadogo [30]. Typical compressive strengths for a 2:1 binder ratio to hemp mixes range from 0.12 to 0.2 MPa based on density, binder type, and age. Its flexural strength is low; research shows it falls between 0.06 and 1.2 MPa. This low strength is mainly due to the hemp particles' ductile nature and disordered arrangement [36–38]. Since it has a rapid growth rate, hemp and hempcrete structural blocks and panels get to substitute numerous old-fashioned timber framing and cement blocks. This will positively impact forests and reduce deforestation rates, and hence, will have a significant influence in reducing pollution and combating heating. The hemp core, or “Shiv”, has a high silica content, allowing it to bind well with the added lime. This lime will seize the  $\text{CO}_2$  from the atmosphere to permit the hydrated oxide to toughen into rock [39]. The shiv's high porosity causes the lower mechanical strength of the concrete in reference to other lightweight concretes. This distinguished property is unique to the hemp plant among all-natural fibers. It is essential to point out that each part of the industrial hemp plant is beneficial in a particular application. The hemp stalk has long and sturdy fibers; the inner core admits moisture absorption and insulation properties, and the seed is a source of oil and protein. The three main characteristics that make hemp valuable in the construction industry are its insulation capacity, the fiber's mechanical resistance, and low density ( $110 \text{ kg/m}^3$ ). The shives can absorb much water, reaching 3.5–5 times their weight. The hemp will target the removal of  $\text{CO}_2$  from the atmosphere less than 12 months before the material is embodied within the structure of a building. Since the interest is focused on construction and, more specifically, integrating bio-sources in building, hemp is a primary ingredient for ecological building materials. These crops offer many possibilities as the stalks and the fires are processed into construction materials. Moreover, housing insulation fabricated from hemp is becoming a popular eco-friendly alternative to traditional insulation materials. Not only is hemp a more sustainable raw material, but the obtained final product is carbon-negative, meaning it can absorb more greenhouse gases over its lifetime than emitted during its production process [40]. This material is beneficial on many levels. It is domestically prepared as a renewable agricultural source and does not require the use of extensive agrochemical merchandise. It may be a vital crop in activating and supporting rural economies. It is an excellent insulator and, as mentioned before, is very light weighted, which supports hempcrete in handling a considerable degree of movement, mold, fire, and pest resistance, and it is a non-toxic green material that reduces the carbon footprint associated with the building sector if appropriately used. It was and is now used to make construction blocks, as an alternative to wood-based panels such as plywood, introduced as infills for interior walls, production of countertops and cabinets, serves well in plastering, and, most importantly, has been introduced to be used as mortar and also found its way into concrete mixes. This material is an outstanding insulation substitute for subfloors, attics, and walls as long as it is not exposed to extreme humidity or water. The lime-hemp mix is applied by spraying, depositing in a sliding casing, or building with prefab-pressed bricks. It also is advantageous for sealing and rain protection. Even though its compressive strength is not as high as concrete, its low density makes it an attractive alternative for earthquake-prone areas [16,40,41].

### 3.4. Straw

A widely available and abundant resource is straw, which is considered a reasonable artifact. Ancient buildings that integrate straw in their roofs are scattered along the globe [16]. Straw is generated and grown from cereal crops like barley, oats, wheat, rice,

and rye, comprising nodes and internodes. The internodes are hollow connecting tubes, and the nodes are where the plants' leaves grow. Most of the cereal crop reaching 90% is cellulose, hemicellulose, and lignin; the rest is water-soluble elements, ash, and silica. The more silica content in the straw plant, the better its durability. Being widely available and considered an affordable building material, straw has been integrated into construction since the dawn of agricultural societies. Traditional, historical uses are roofings, bales in load-bearing wall substrates for plasters, bio-aggregates to clay and lime plasters, and loose floor covering. In contemporary construction, straw is still employed as a bio-aggregate to clay and lime materials and as raw material for compressed straw products. The principal building benefit of straw bales is their beneficial insulating qualities. Regarding the bale wall-building applications, three main ones exist load-bearing walls, non-load-bearing in situ walls, and prefabricated panel construction, as shown in Figure 4 [40,42,43]. It is interesting because it shows that plant-based bio-sources are being incorporated in all parts of the world; in this case, it integrated specially designed straw or hemp bales. These materials enable house builders (both big and small) to meet their carbon targets, stay profitable, and provide people with the quality, style, and comfort they want.



**Figure 4.** BaleHaus, University of Bath: Straw load-bearing walls [43].

Going into more detail, low-rise load-bearing walls highlighted the initial use of the straw bales by using them to support vertical loads and resist lateral forces resource-efficiently. This is important as it will avert the need for a separate structural frame. Here, the bales are stacked into a low-density bio-masonry wall. In general, load-bearing straw-bale walls are plastered, and based on the research of Vardy et al. [44], it has been confirmed that the assembly of the plaster coats, restrained by the straw bales, provides the primary load resistance. Moving on, non-load-bearing straw-bale construction uses the straw's thermal insulation properties; however, it requires an additional structural system for support. It is a less risky approach as the structure is no longer entirely dependent on the straw. Finally, prefabricated straw-bale construction has become a subject of interest. As the name implies, the use of panels is usually witnessed, and the use of timber frames fabricated off-site to minimize risks like fire and wet-weather damage is the approach. Due to the prefabricated panel construction, the straw industry is now exposed to a more mainstream market, and related products are currently certified and warranted. Even though straw does not possess a thermal resistance as high as other insulation materials, straw-bale walls provide excellent thermal insulation due to their relative thickness (450–500 mm). The density of square-shaped straw bales is from 100 to 160 kg/m<sup>3</sup>, which suits the building requirements of many countries. Like any other bio-based building material, straw also responds to changes in relative humidity. The behavior of straw could be counted as hygroscopic in general, meaning that its weight at 90% RH is higher than when it is at 30% RH [40] and that it passes through five stages during water absorption, starting with



single layers of adsorption and ending by the supersaturation state. Its moisture buffer value (MBV) was calculated to be  $1.853 \text{ g}/(\text{m}^2 \cdot \% \text{RH})$ , making it a good regulator for the surrounding humidity. In their article, Tlaji et al. found that for a density of  $100 \text{ kg}/\text{m}^3$ , the straw boards have a porosity of 93% and specific heat of  $2426 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$ . Since the straw bale density, humidity, and orientation of fibers and the temperature all affect its thermal properties, a unique value for its thermal conductivity and capacity cannot be set and they fall within the ranges of  $0.033$  to  $0.19 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$  and  $1338$  to  $2000 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$ , respectively. Moving on to the thermal transmittance (U-Value) of the straw bales, it was recorded to be  $0.16 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$  [45–47].

### 3.5. Flax

In the times when oil and energy prices are rising and environmental standards towards traditional materials are changing, there is a bright future for these bio-sourced materials, of which flax is one. The demand for flax fibers and composites is increasing due to its innovation on all levels. Flax (*Linum*) is an annual green plant from the *Linaceae* family. In modern and current years, the production of oily flax has been increasing and being observed in many countries. This is because of the high value of linseed as a concentrate and oil feed and its beneficial effects on human and animal health. One of the semi-products produced from flax straws is shives [48], which are small pieces of the stalk without fibers, making up 70% to 85% of the total weight of flax straw. Benmahiddine et al. [49] manufactured the flax in various sizes in order to check its effect (Figure 5). Therefore, searching for new implementations of this raw material is wise. Flax adapts excellent properties and offers countless benefits, making it suitable for many applications. One of the leading applications is particle and flax boards. Flax boards can have smooth, sanded surfaces, making them appear similar to particle boards by increasing the panel density at the faces. Natural and fire-resistant properties characterize these panels. Generally, Flaxboard has a pale straw color. It is usually integrated into dry environments with fire-check doors, door partitions, and cores. Flaxboard is a designed sheet secured along with artificial resin adhesives. Since it is a lightweight board with natural features that aid hearth resistance, it will definitely show outstanding surface properties [16,50].



**Figure 5.** Flax shives: (a) bulk, (b) medium, and (c) large [49].

Moreover, flax fibers are additives in cementitious, mineral-based composites and insulation products aiming to improve cement or plaster insulation properties. In return, this creates new innovative market opportunities as these fiber composites make their way into construction products, ensuring the company achieves sustainable, cost-effective, and environmentally friendly building practices. New techniques to blend flax fibers with concrete are emerging and are in place [50,51]. These composites' beneficial properties are their low bulk density, ranging between  $400$  and  $600 \text{ kg}/\text{m}^3$ , and low water vapor resistance coefficient that limits the risk of condensation in the walls comprising this material [52–54]. Concerning the porosity of the flax concrete, it is, on average, between

72% and 76% in relation to the amount of flax shives used. In addition, flax has a low thermal conductivity of  $0.082\text{--}0.111\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  that depends on the orientation and arrangement of the vegetative particles and their relative percentage to one another, and a low density of about  $110\text{ kg}/\text{m}^3$  [49,53]. Since shives make up these composites, and due to the cellular construction and natural porosity of these plant materials, high thermal insulation of composites results accordingly [55]. In their study, Benmahiddine et al. noted through microscopic observations that the average thickness of the flax is close to  $300\text{ }\mu\text{m}$ , and its cross-section exhibited a porous and very complex structure containing pores of various sizes and orientations [49]. Recent articles have been tackling research on flax concrete, which has begun to develop more and more because of its energy and environmental performance. Flax concrete is produced from flax shives, a binder, typically lime, and water. It has a high water absorption capacity of roughly two to three times its weight within 48 h. This is due to its pores organization taking the form of parallel capillaries and its high cellulose content. As mentioned above, since flax is known for its high insulation and low thermal conductivity properties, this mixture is utilized in insulation blocks placed in wall cavities in structures and buildings with studs, drywall systems, and infilled masonry frames [49,55,56]. According to the literature, the moisture buffer value (MBV) of the flax concretes used surpassed 2, meaning that flax concrete is an excellent moisture regulator, according to the Nordtest project [49,54]. Based on the studies, flax as a construction material has a low thermal conductivity, which is a possible asset to the rising energy crisis. In fact, the contents of the flax shives and the thermal conductivity were found to be inversely proportional. The arrangement and distribution of the flax shives in the material highly affect the thermal conductivity. Therefore, a homogeneous particle size causes a slightly better distribution; hence, the particle's microstructure will be less complex. Consequently, this will promote heat transfer kinetics and reduce the material's insulating properties [16,50].

### 3.6. Reed and Grass

#### 3.6.1. Reed Plant

The reed plant is one of the most famous old-style materials used in roof construction in many parts of the world. When integrated into a structure correctly, it will serve for long periods, typically over fifty years, without entailing major care. However, in the case of poor raw material quality, inadequate fitting detailing, and moisture, premature decay in reed-based roofs and structures will be seen, and the maintenance-free period will significantly reduce. Previous studies explain that the reed properties are highly related to its origin, harvesting methods, and periods [16,17,30,57]. Any changes in the quality of the roofing material are seen to have effects on the moisture and the durability of the material. As mentioned, moisture on roofs is one of the main parameters that will cause early deterioration. The morphological capillary structure, also identified as the diameter, wall thickness, and length of the stems, mainly determines the reed plant's stem water absorption. The lignin ingredient could prevent water absorption in the vascular bundles, and the hemicellulose ingredient targets microbiological activities if the stem is wet [40]. In their article, Tsapko et al. fabricated reed mats having the dimensions  $180 \times 155\text{ mm}$  and a density of  $137.6\text{ kg}/\text{m}^3$ , and experiments showed that they possess a thermal conductivity  $\lambda = 0.056\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  and a heat capacity of  $508\text{ J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$ , which passes off the reed as a good insulation material. Two new factors were calculated: the thermal activity and temperature conductivity equal  $200.1\text{ W}\cdot\text{s}^{1/2}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$  and  $0.08 \times 10^{-6}\text{ m}^2/\text{s}$ , respectively [58].

#### 3.6.2. Grass

Simple green grass is one of the most widespread, versatile, and available renewable materials used for many purposes. One of the more recent uses of grass has been in construction. While taking advantage of grass in a building may seem bizarre, this practice has many benefits. Hay, the derivative of meadow plants, is often stored in attics, serves as

a feedstock for domestic animals, and provides thermal insulation in rural buildings. To begin with, the most important factor that encourages the use of grass is its sustainability aspect. Grass is a renewable resource that proliferates and does not require much water, fertilizer, and care. This means it can be grown and harvested without being affiliated with any environmental damage. Additionally, using grass in the construction industry can help reduce the waste produced by other industries. Secondly, as the energy crisis is expanding, and many solutions are needed to save electricity and energy, grass is a material that can be useful. Yaghoobian et al. [59] presented different ground materials' thermal and radiative properties in their article. Grass has a thermal conductivity of  $1.1 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  and a heat capacity of  $2.8 \times 10^6 \text{ J}\cdot\text{m}^{-3}\cdot\text{K}^{-1}$ , implying that it has natural insulating properties, making it a very beneficial additive to construction. It can help regulate buildings and structures' temperature and humidity levels, reducing energy costs. It also targets noise insulation, reducing noise levels and making it an attractive option for buildings in crowded areas. Moving on to its aesthetic advantage, it is being linked to green roofs, which are becoming increasingly popular in urban areas. Even though grass fulfills essential benefits, its durability and maintenance impose significant drawbacks. Of course, grass is classified as strong and durable; nevertheless, it is not on the same level as other building materials such as concrete or steel. This implies that buildings made predominantly from grass require replacement more frequently than those constructed from traditional materials. It is high maintenance could be costly and time-consuming. It needs to be regularly watered and trimmed to prevent it from becoming overgrown. Grass attracts pests like insects and rodents, which could be problematic for buildings located in urban areas. Finally, the grass is highly flammable and can ignite quickly, especially in dry conditions and regions. This indicates that buildings may be at a higher risk of fire damage than those made from conventional materials [16,40]. Table 1 presents the bio-sourced materials with some of their relevant thermal and hydric properties.

**Table 1.** Summary of the bio-sourced materials' respective properties and applications.

Bio-Source	Common Feedstock	Density (kg/m <sup>3</sup> )	Thermal Conductivity Value (W·m <sup>-1</sup> ·K <sup>-1</sup> )	Specific Heat Capacity (J·kg <sup>-1</sup> ·K <sup>-1</sup> )	Porosity (%)	Moisture Buffer Value g/(m <sup>2</sup> %RH)	Compressive Strength (Pa)	References
Mycelium	Mycelia in Fungi Roots	100–309	0.03–0.06	10,200	NOT APPLICABLE	NOT APPLICABLE	<i>P. ostreatus</i> family of Fungii: 0.177	[16,22–25,60]
Coffee	Coffee Grounds	308–399	0.038–0.054	1400	Green beans: 9.8 Roasted beans: 34.2	NOT APPLICABLE	NOT APPLICABLE	[16,26]
Hemp	Hemp Core, or “Shiv”	200–800	0.1007	872.34	71.51	NOT APPLICABLE	0.2 to 0.12	[28–41]
Straw	Cereal Crop Containing Cellulose, Hemicellulose, Lignin, Ash, and Silica	100 to 160	0.033 and 0.19	1338 and 2000	46.39–84.24	1.853	NOT APPLICABLE	[16,40–42,44–47]
Flax	Flax Shives	110	0.082–0.111	1500 to 2700	72–76	~2	NOT APPLICABLE	[16,48,49,51–56,61]
Reed (reed mats)	Reed Plant	137.6	0.056	508	NOT APPLICABLE	NOT APPLICABLE	NOT APPLICABLE	[16,17,36,40,58]
Grass	Grass	NOT APPLICABLE	1.10	$2.8 \times 10^6$	NOT APPLICABLE	NOT APPLICABLE	NOT APPLICABLE	[16,40,59]

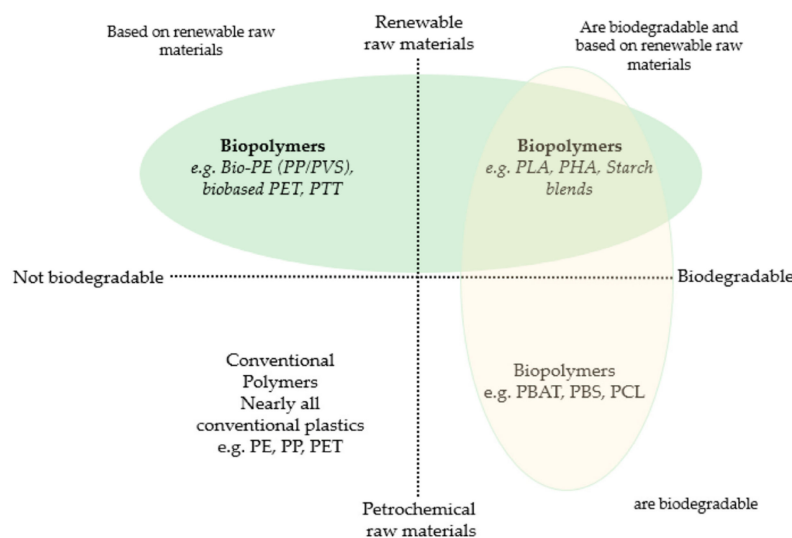
### 3.7. Bioplastics

Plastic is a material that encompasses a vast category of polymer composites that use polymers as a building block. These polymeric materials could be classified as either thermoplastic or thermosetting. Thermoplastic materials are the ones that soften when heated and stiffen when cooled, and thermosetting polymers are those that stay intact and do not soften when they have been molded. These materials are petroleum-

based and non-renewable, limiting the polymer industry [61]. This is the main reason behind the misconception that plastic waste is portrayed as a plastic composition issue rather than a global overproduction problem. Fortunately, plastics can be modified into something more sustainable via technological advancements and consumer preferences, making them more achievable than ever. When the term biomaterials is mentioned, it includes chemical products that are totally or partially synthesized by microorganisms under different environmental conditions and that have found broad biotechnological applications. Many living organisms and species can intake them as they are biodegradable and biocompatible, meaning they do not cause toxic effects in the host [20]. A critical family that falls under biomaterials is bioplastics. Bioplastics are the type of plastic classified as bio-based, biodegradable, or even both, depending on the generation source. In a more general sense, bioplastic could also refer to petroleum-based plastics that are biodegradable. Being a bioplastic is having the ability to be bio-based, whether partially, completely, or non-bio-based, biodegradable, or compostable, ensuring that it is not non-bio-based and non-biodegradable [62,63]. They are extensively linked to sustainable development as they exploit renewable content and recycling materials, lower manufacturing energy, and return material to nature at the end of its life. Hence, the primary motivation behind these bioplastics is sustainability. Its principle is the satisfaction of people's needs for survival and well-being, directly and indirectly, from our natural environment. Sustainable action ensures conditions under which nature and humans co-exist harmoniously and where the present and future generations' environmental, social, and economic requirements are met. Bioplastics are extensively scattered polyesters formed by various microbes, cultured under diverse nutrient and environmental conditions, and stored intracellularly in microorganisms as storage granules, with physicochemical properties similar to petrochemical plastics. The demand for bioplastics has tremendously increased in the industrial and research sectors. This is mainly because individuals worldwide are worried about pollution in the environment; stricter laws to protect the environment are being imposed by local and international groups [64]. The expansion in demand drives the growth in bioplastics, and a shift from compostable (biodegradable) to durable bioplastics, away from single-use applications, toward more valuable, high-performance goods is witnessed. This trend is coupled with the high performance of these biopolymer and bioplastic products. Whether microorganisms, anaerobic digestion, house or industrial composting as an end-of-life option for decomposing bioplastics, all these encourage a more sustainable circular economy. With bioplastics having less dependency on carbon dioxide ( $\text{CO}_2$ ), the quantities of greenhouse gases associated with its production are diminished by 30 to 70% [51] since  $\text{CO}_2$  absorbed during photosynthesis makes up for the  $\text{CO}_2$  generated during biodegradation, making it carbon-neutral or even carbon negative [20,65–67]. In buildings, these materials are currently being integrated into walls or other parts of the building structure, and in insulating, heating/cooling systems grace to their insulation and hygrothermal properties. As insulation materials, they are processed into rigid foam or board-like structures to enhance energy efficiency and regulate heat losses and gains. The building's heating and cooling systems play a significant role in energy consumption and dissipation, which is why bioplastics are integrated into them, particularly in radiant heating and cooling systems. Radiant systems are the ones that benefit from the thermal energy to heat or cool building surfaces that will act accordingly to ensure the thermal comfort of the occupants. For instance, once installed, bioplastic pipes or panels facilitate the circulation of hot or cold water, positively impacting thermal energy transfer. A key point regarding these materials is monitoring and understanding the mode of action and behavior upon their interaction with moisture, humidity, and heat, especially when introducing them into building applications. Bioplastic's hygrothermal behavior can impact the building's performance, durability, and overall effectiveness. Based on the chemical composition and the bioplastic structure, each possesses a varying degree of water absorption. Starch-based polymers can instantly absorb water; however, biodegradable polyesters are more moisture-resistant. This water absorption property can lead to either the swelling or softening of the material,

reducing its mechanical properties. Moving on to moisture diffusion, another critical aspect of bioplastics that shapes their hygrothermal behavior. Some bioplastics have a low permeability to water vapor, which is favorable to preventing and limiting the moisture flow into the building, such as its walls, insulation materials, or other components. Understanding moisture diffusion has a role in maintaining the stoutness of the building envelopes and avoiding mold growth and structural degradation [65,66].

Figure 6 is a scheme that lists the different types of bioplastics, and their classifications are detailed below. As formerly indicated, if a material is bio-based, that does not mean that it is inherently biodegradable; that is, it encloses carbon derived from renewable or fossil fuel substances [63]. For instance, bio-polyethylene terephthalate (bio-PET), Polyethylene furan-2,5-dicarboxylate (PEF), and bio-polyethylene (bio-PE) are chemical duplicates of the fossil fuels-based PET and polyethylene (PE). Another type of non-biodegradable plastic is polyamides (PA). Biodegradable but non-biologically derived polymers include poly(butylene adipate-co-terephthalate) (PBAT), polycaprolactone (PCL), polyvinyl alcohol (PVA), and polybutylene succinate (PBS). PLA (polylactide), Polybutylene adipate terephthalate (PBAT), and Polyhydroxyalkanoates (PHA) are all also gaining interest nowadays [68].



**Figure 6.** Scheme depicting the manufacturing of different types of bioplastics. Information collected from European Bioplastics ([www.european-bioplastics.org](http://www.european-bioplastics.org), accessed on 4 October 2023) [69,70].

Apart from all their benefits in achieving sustainability and reducing pollution, bioplastics face several challenges when coping with the construction market needs due to their demand for materials with specific properties and performance characteristics. First and foremost, bioplastics are derived from plant-based materials, meaning that they may not have the compulsory mechanical properties to replace traditional construction materials like concrete, brick, steel, or PVC in applications that require high durability, strength, and resistance; they are not the best candidates, which can limit their use to specific industries [65]. As known, construction materials must be resistant to water, humidity, and moisture to prevent structural damage and decay and maintain their properties with time. In contrast, bioplastics absorb water and can be damaged over time, making them less suitable. Moreover, bioplastics are liable to contribute to pollution and toxicity [71]. Their production from plant-based sources demands considerable energy, which can increase greenhouse gas levels and negate some of their environmental benefits. In terms of their stability and heat resistance also, they have shown certain limitations under extreme temperature fluctuations [72]. Finally, their high production cost makes them less economically viable and discourages widespread adoption in the cost-sensitive construction industry [73]. Although bioplastics are not a direct alternative to conventional building materials in all



applications, continuous research is being done to enhance their performance characteristics and extend their potential usage in the construction sector. It is critical to strike a balance between sustainability goals and the practical demands of the construction industry to guarantee that bioplastics can significantly lower the environmental effect of building materials in the future. Overall, even though bioplastics can potentially reduce the environmental impact of plastics, they are associated with their own environmental and economic barriers.

### 3.7.1. Bio Polyethylene (PE) and Bio Propylene (PP)

Bio Polyethylene (Bio-PE) is a derivative of biomass feedstocks, sugar beet, sugar cane, corn, or wheat grain; thus, its manufacturing results in the capturing and fixation of carbon dioxide from the atmosphere throughout bioethanol production that leads to the reduction of its carbon footprint and its heavy dependence on non-renewable resources. The production process of Bio-PE is based on three main steps [63].

- Step one: The alcohol is extracted from the plant biomass;
- Step two: Ethylene monomer is obtained from the dehydrogenation of alcohol;
- Step three: Polymerization of this Ethylene monomer into Bio-PE.

After completing these steps, the obtained polyethylene can be bio-based or bio-polyethylene. They are broken down into three types, which are: low-density PE (LDPE) with a density between 910 and 940 kg/m<sup>3</sup>, linear low-density PE (LLDPE) with a density ranging from 910 and 920 kg/m<sup>3</sup>, and high-density PE (HDPE) varying between 941 and 967 kg/m<sup>3</sup>. Biobased polyethylene was first marketed by a Brazilian company, “Braskem”, in the year 2010 by operating local sugarcane-derived ethanol/ethylene as their feedstock. The manufactured material’s composition and performance were similar and comparable to petroleum-based PE [74]. Similarly, propylene is accessible and can be mass-produced using propylene monomer from natural materials such as corn, vegetable oil, sugarcane, and other biomass. Bio-based polypropylene (Bio-PP) adapts characteristics similar to synthetic polypropylene (PP), which is not biodegradable/compostable and has a density alternating between 900 and 910 kg/m<sup>3</sup>. The process of its formation from methane is via ethylene dimerization followed by metathesis. The Brazilian company, “Braskem”, aims to build a 30,000–50,000 ton/year biobased PP production plant. Lately, in 2019, Borealis, one of the leading companies in producing polyethylene and polypropylene, has begun manufacturing renewable propane in its manufacturing facilities in Kallo and Beringen in Belgium, starting with a Neste-produced renewable feedstock. The NEXBT<sup>TM</sup> technology is being utilized to generate renewable propane, which Neste then supplies to the Borealis propane dehydrogenation plant in Kallo. In this plant, the renewable propane is transformed into propylene, which is also renewable, and then is biobased PP [75]. Moving on to their importance in the construction sector, bio-PE and bio-PP stand out in many applications, such as packaging, pipes, insulation, roofing materials, and plastic packaging for building materials, such as screws, nails, and other hardware. They are also used in construction as an insulating means as they possess high thermal resistance and thermal conductivities of 0.4 W·m<sup>−1</sup>·K<sup>−1</sup> for PE and 0.11 W·m<sup>−1</sup>·K<sup>−1</sup> for PP. Bio-PE’s tensile strength ranges from 7 to 15 MPa for LDPE and from 31 to 42 MPa for the HDPE, and its flexural ranges between 6 and 26 MPa for LDPE and 10–50 MPa for the HDPE, respectively. As for the Bio-PP’s tensile and flexural strength, it is given by 28–40 MPa and 10–20 MPa, respectively. It could be integrated into buildings’ roofs, walls, and floors to improve energy efficiency and reduce heating and cooling costs. Poly- Propylene tends to absorb moisture more than PE, having a rate of 1–10 g/m<sup>2</sup>/day compared to the latter, with a rate of 0.5–5 g/m<sup>2</sup>/day. They also resist UV radiation and weathering and are characterized by their low weight, durability, and easy installation [63,65]. The automotive industry is the most prominent market for biobased PP, as around 50% of car plastic is PP [74].

### 3.7.2. Polylactic Acid (PLA)

Being derived from biomass, PLA is a conventional bioplastic formulated in three simple steps: fermentation, separation, and polymerization. Polylactic Acid (PLA) or Polylactate is produced from a lactic acid monomer manufactured from the microorganism-induced fermentation of sugar or starch. Typical raw materials for this reaction are inexhaustible resources such as cornstarch, sugarcane, potato, and tapioca (a starch extracted from cassava root). Now, this lactic acid is produced; it undergoes polycondensation and/or ring opening polymerization of lactide. They are classified as aliphatic polyesters and are considered examples of bio-based and biodegradable plastics. Chemically speaking, PLA is not a polyacid (polyelectrolyte) but rather a polyester. In short, PLA is a thermoplastic biodegradable polyester [63,74,76]. This bioplastic is gaining interest due to its eco-friendly and compostable nature, which makes it a sustainable alternative to traditionally used petroleum-based plastics. It is characterized by its different characteristics, such as [77]

- Biodegradability: PLA tends to be broken down into natural materials such as water ( $H_2O$ ) and carbon dioxide through the action of microorganisms;
- Low toxicity: when degraded, this plastic is non-toxic and does not generate harmful chemicals in the environment during its degradation and breakdown;
- Renewable: PLA is constituted of renewable resources, making it a more sustainable option than other traditional plastics;
- Energy-efficient: Its production from raw materials demands less energy than conventional plastics, thus diminishing the emission of greenhouse gases. Also, it has a thermal conductivity of  $0.183 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$  that positively improves upon adding nanofillers.

PLA can be integrated into many fields and applications. It introduces several benefits due to their flexibility, weight (density of  $1240 \text{ kg/m}^3$ ), ease of processing and implementation, cheapness, disposability, and biocompatibility [76]. Its primary applications are food packaging, especially yogurt cups, disposable cutlery, medical and bio-medical industries, and textiles. It is also used for fused deposition modeling (FDM) in 3D printing due to its ease of use and ability to produce high-quality prints [65,78,79]. With FDM and 3D printing, PLA is used to manufacture elemental insulating structures for buildings and can also be reinforced with natural fibers (flax, wood, silk, etc.) to improve its hygrothermal properties [80–82]. PLA's degradation is only induced by its exposure to prolonged exposures to high temperatures, usually around  $60^\circ\text{C}$ . This implies that its degradation is expected to occur in an industrial compost facility; however, it will not biodegrade in nature like PLA films or in a landfill. Mirroring its advantages, PLA possesses specific issues such as low strength: tensile strength of 50 MPa and flexural strength of 80 MPa, imparts an off taste to water when used for water bottles, melts when used in hot beverages, and is also expensive compared to PE and PP. Due to these material properties, its heat resistance, impact resistance, and low glass transition temperature, polylactic acid is often blended with conventional petro-plastics [72].

### 3.7.3. Polybutylene Adipate Terephthalate (PBAT)

Amongst all the co-existing aliphatic and aromatic co-polyesters, Polybutylene Adipate Terephthalate (PBAT) can be considered the most promising and popular since it adapts potential development prospects. PBAT can be generated as a product of the polycondensation reaction that occurs when 1,4-butanediol reacts with both adipic and terephthalic acids (or butylene adipate) [63,72,74]. Based on the literature, it has been shown that this combination is the most effective, and it yields excellent properties and good biodegradability [83]. The polycondensation reaction may be enhanced by adding rare earth compounds or zinc catalysts; however, industrial facilities did not favor such a choice even though these catalysts called for the preparation of PBAT on a laboratory scale [84]. Slow kinetics, synthesis, and preparation necessitate long reaction times, high vacuum conditions, and high temperatures, usually exceeding  $190^\circ\text{C}$ . As mentioned, one

of PBAT's outstanding properties is its complete biodegradability. On the other hand, this type of plastic is flexible, with Young's modulus of 20–35 MPa, a tensile strength of 32–36 MPa, flexural strength of 7.5 MPa, and higher elongation than most biodegradable polyesters, such as poly (lactic acid) and polybutylene succinate [85].

In order to enhance its properties, the integration of various materials into the PBAT matrix to form nanocomposites based on different fillers was tested. Cellulose nanocrystals (CNC) [86,87] natural fibers [88], red mud, Montmorillonites (MMT), coffee grounds [65,89,90], nano fibrillated cellulose (CNF) [91], and finally distillers dried grains with solubles (DDGS) were seen in various research articles. In his article, Mukherjee et al. [91] showed that the addition of nano-fibrillated cellulose exhibited improvements in both storage modulus ( $G'$ ) and dynamic viscosity ( $g^*$ ). Another study by Chen et al. [92] tested the thermal and mechanical properties of a PBAT and clay composite containing unmodified and organically modified MMT, which improved mechanical properties and thermal stability. In the PBAT matrix, Fukushima et al. [93] fused unmodified and modified clay nanoparticles, sepiolite, MMTs, and fluorohectorites. This incorporation was accompanied by an increase in the thermal stability of the PBAT matrix as a consequence of the barrier effect of the nano-clays. In contrast, the reinforcement effect of nanomaterials caused a higher elastic modulus and hardness. In addition, the sepiolite particles promoted polymer PBAT crystallization, thus improving polymer crystallinity. Mostafa et al. [65,89,90] reported that PBAT-based composites manufactured by adding coffee grounds displayed improvements in thermo-mechanical properties and hydrophobicity. PBAT and its manufactured composites are currently used in different areas and exhibit various applications such as biomedical [94,95] food packaging, medical devices, and agricultural, environmental, and industrial applications. The main goal is energy conservation and thermal insulation in construction and buildings; as could be inferred from above, PBAT ( $1260 \text{ kg/m}^3$ ) is not commonly used in construction. One of the main reasons is that it possesses a relatively low mechanical strength compared to other plastics commonly operated in construction, meaning it may not withstand the high stresses and loads of construction applications, particularly for load-bearing structures. Moreover, its biodegradability is a helpful feature in specific contexts, and it may not be ideal in construction as longevity and durability are essential and crucial for structures that must last for many years. Depending on its thickness and composition, PBAT may be characterized by some insulating properties. It may be able to provide thermal resistance, although it is as ineffective as other insulation materials [80].

#### 3.7.4. Polyhydroxyalkanoates (PHA)

Another well-known type of bioplastics is polyhydroxyalkanoates (PHAs). They are polyesters accumulated in bacterial biomass as storage compounds [81,96]. They get built up in the form of granules inside the cells of many bacterial species. After their accumulation, a cell can use these substances as intracellular carbon and energy sources. The most important PHA polymers are poly-3-hydroxybutyrate (PHB) with monomer formula  $(-\text{OCH}(\text{CH}_3)-\text{CH}_2-\text{C}(\text{O})-)$  and polyhydroxy valerate (PHV) with monomer formula  $(-\text{OCH}(\text{CH}_2\text{CH}_3)-\text{CH}_2-\text{C}(\text{O})-)$  [97]. These polyesters need the interference of numerous microorganisms that carry out this bacterial fermentation. As a result, they get produced by the action of bacteria from sugar or lipids through polyhydroxy fatty acids from anaerobic digestion. On average, 250 different bacteria were found to generate PHAs with a  $1260 \text{ kg/m}^3$  density. The bioplastic is harvested and produced via the destruction of the bacteria and its separation from the microbial cell matter through centrifugation and/or filtration and biomass drying.

PHA extraction, which occurs by the use of solvents such as chloroform, is followed by PHA drying and packaging [63,74,98]. PHA's have a melting temperature ranging from 160 to 180 °C, a tensile strength of 24–40 MPa, an elongation of 3–142%, and Young's modulus of 3.5 GPa. These properties are similar and comparable to the properties of petroleum-based thermoplastics. It has been shown that to reduce the cost of this bioplastic, it must be manufactured from low-priced raw materials using batch or continuous

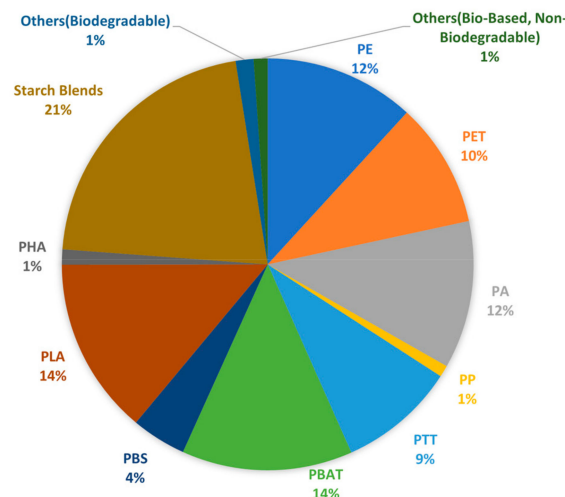
cultivation of mixed bacterial culture, and it could even be without extraction of the bioplastic from the bacterial biomass. The adapted raw materials can be the organic fraction of municipal wastewater treatment plants' solid or liquid wastes, corn cobs, stalks and leaves, coffee husks and hulls, agricultural wastes, and sugar cane bagasse. Therefore, it is safe to say that various starting materials such as carbohydrates and organic acids and methods like the multistage transformation of the carbon and energy sources could be used for PHA production, and its accumulation could be based on either hydrogen or non-carbohydrates. PHAs could either be thermoplastic or elastomers in nature. They have decent barrier properties and are known to be biodegradable and hence are classified as attractive for biomedical uses, for medical applications such as skin substitutes, heart valves, vascular grafts, scaffolds, bone graft substitutes, and drug delivery microspheres due to their biocompatibility and biodegradability [63,97].

Additionally, the applications of PHAs bioplastic extend to being produced and used as biodegradable construction materials, diminishing the land area required for their landfilling since they quickly degrade in the soil or landfills. It could be used as foam for wall insulation, sealants, and insulants, thus substituting conventional petrochemical plastics. They are being integrated into silt and dust. Since the bioplastic foam requires no incineration after demolition, it could be a big market as a biodegradable construction material. Integrating PHA as an insulating material in buildings requires various steps to ensure efficiency. Firstly, PHA needs to be produced in mass amounts to meet the demand for insulation, and this could be achieved by using microorganisms that can produce PHAs from renewable feedstocks. Upon its production, it could be molded into foam insulation boards or sprayed into cavities found in walls, floors, or ceilings. As additional protection, this insulation layer could then be covered with a vapor barrier to avoid moisture and prevent it from penetrating the insulation and causing damage to the building. PHA insulation possesses properties that differ from traditional insulation materials. For instance, foam insulation based on PHA may have a lower thermal conductivity, requiring a thicker layer to reach the same insulation value. Furthermore, compared to traditional insulation materials, PHA insulation may have different fire resistance properties [99,100]. Figure 7 breaks down the production of biopolymers in the year 2019. It is clear that starch-based blends, followed by PLA and PBAT, are the most produced biopolymers, whereas PE, polyamide (PA), PET, and poly (trimethylene terephthalate) (PTT) are the more frequently manufactured bio-based, non-biodegradable polymers. In total, 44.5% of the biopolymers that are annually produced encompass bio-based, non-biodegradable PE, PET, and PA. In contrast, biodegradable polymers comprise 55.5% of the universal production of biopolymers. The promotion of bio-based polypropylene (PP) started in 2019, and its production capacity is predicted to increase by 2024, owing to its application in various sectors [101]. Table 2 serves as a summary that compiles the essential characteristics and properties of the biopolymers mentioned above.

**Table 2.** Summary of the main characteristics of bio-plastics and their applications.

Bioplastic	Acronym	Common Feedstock	Production Technique	Melting Temperatures (°C)	Density (kg/m <sup>3</sup> )	Tensile Strength (MPa)	Flexural Strength (MPa)	Thermal Conductivity (W·m <sup>−1</sup> ·K <sup>−1</sup> )	References
Bio Polyethylene	PE	Biomass Sugar Beet, Sugar Cane, Corn, or Wheat Grain	Bioethanol Dehydration	118	LDPE: 910–940	LDPE: 7–15	LDPE: 6–26	0.4	[63,74]
					LLDPE: 910–920	LLDPE: -	LLDPE: -		
					HDPE: 941–967	HDPE: 31–42	HDPE: 10–50		
Bio Propylene	PP	Corn, sugar cane, vegetable oil, and biomass	Ethylene Dimerization, then Metathesis	165	900–910	28–40	10–20 MPa	0.11	[60,62,71,72]
Poly- Lactic acid	PLAY	Corn, Corn Stover, Sugarcane Bagasse, Sugar Beet, Rice Hulls	Ring Opening Lactic Acid Technique, Polycondensation	150 to 160	1240	50	80	0.183	[62,64,66,71,74,76–79]
Polybutylene Adipate Terephthalate	PBAT	Purified terephthalic acid (PTA), butanediol, and adipic acid	Polycondensation/ Polymerization Reaction	120	1260	32–36	7.5	3	[63,65,72,74,80,83–95]
Polyhydroxyalkanoate	PHA	Sugars and Emerging Trials with Waste Biomass	Microbial Fermentation	65–180	1260	24–40	Not Applicable	Not Applicable	[63,74,81,96–101]





**Figure 7.** Annual production of biopolymers in 2019. Information collected from the European Biopolymers Organization ([www.european-biopolymers.org](http://www.european-biopolymers.org), accessed on 4 October 2023) [70,101].

### 3.8. Phase Change Materials (PCMs)

For many years now, and as mentioned before, the rapid increase in global energy consumption rates, environmental problems, and the expenditure of fossil fuel reserves have dramatically highlighted the importance of adequate energy utilization. Due to that, it is imperative to shed light on the development of a new method of energy conservation that can be achieved through thermal energy storage (TES) systems. These systems are meant to store thermal energy in a medium like phase change materials (PCM) or sensible heat storage materials such as rock or water and then release it when needed. TES systems are gaining popularity in numerous industries as they are being continuously utilized to improve energy efficiency and increase the use of renewable energy sources, thus minimizing energy consumption. The heat storage in the TES systems can be of three main types: sensible, latent, and thermochemical storage [102]. To begin with, sensible heat storage is associated with the energy used to induce a temperature change. The most common materials are water, rocks, and concrete. On the other hand, latent heat storage is the energy absorbed or released during a phase change, for instance, melting or freezing. As their name implies, phase change materials (PCMs) store large amounts of thermal energy in a small volume. Finally, thermochemical heat storage holds up thermal energy by using reversible chemical reactions with a large enthalpy. Thermochemical storage materials are usually metal hydrides, which absorb and release hydrogen gas as heat [103,104]. To zoom into PCMs more, they are materials that can store and release considerable amounts of thermal energy upon changing their state or phase. This is mainly because of the latent heat of fusion or vaporization accompanying the phase change. The phase change could be solid-solid, solid-liquid, solid-gas, and liquid-gas, the most common being the solid-liquid transformation. Its principle is quite simple: as the temperature increases, the material will change its phase from a solid to a liquid. With the reaction being endothermic, the PCM will eventually absorb heat. Likewise, the material transforms from liquid to solid when the temperature decreases. This reaction is exothermic, meaning the PCM will release the heat.

The usual thermal comfort in summer falls in the range of 22 to 27 °C and decreases to 18 to 25 °C in winter [104]. Three basic types of PCM exist: organic, inorganic, and eutectic. Organic PCM encompasses materials such as paraffin and non-paraffin compounds like fatty acids, alcohol, polyethylene glycol, and esters. At the same time, inorganic PCMs include materials such as salt hydrates, metals, and alloys [105]. Since biobased products are our main aim, non-paraffin compounds are the way to go. One of the essential features of the PCM is the sustainability part [102]; therefore, its production from biological, renewable sources is the most preferred path. Many types of pure fatty acids exist, such as capric

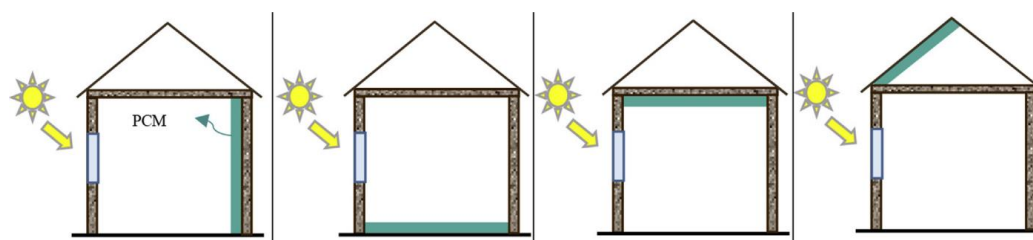
acid, lauric acid, myristic acid, palmitic acid, and stearic acid, and their benefits can be expanded through their incorporation into construction materials, such as concrete. By this, the purpose of thermal insulation and energy savings could be achieved [30].

Table 3 presents some of the basic properties of the fatty acid PCMs that influence their choosing, highlighting that only a few possess a temperature of fusion in the appropriate temperature range (15–45 °C) to get integrated into the construction sector. It is possible to mix and match these PCMs, forming eutectic mixtures with the temperature range that suits the application [30,106,107].

**Table 3.** General properties of most common fatty acid-based PCMs.

PCM	Acronym	Formula	Melting/Solidification Temperatures (°C)	Thermal Conductivity ( $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ )
Capric Acid	CA	$\text{C}_{10}\text{H}_{20}\text{O}_2$	29.6–33.2	0.21
Lauric Acid	LA	$\text{C}_{12}\text{H}_{24}\text{O}_2$	41–41.5	0.15–0.37
Myristic Acid	MA	$\text{C}_{14}\text{H}_{28}\text{O}_2$	49–56.1	0.17–0.39
Palmitic Acid	PA	$\text{C}_{16}\text{H}_{32}\text{O}_2$	58.9–64	0.3
Stearic Acid	SA	$\text{C}_{18}\text{H}_{36}\text{O}_2$	53.8–70.8	0.159–0.35

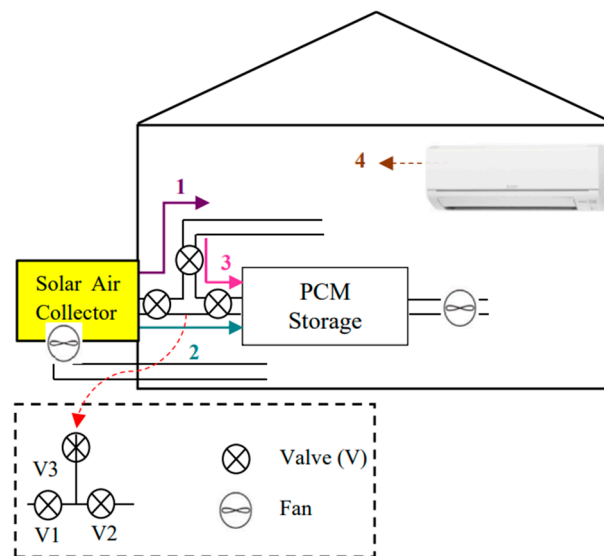
PCM can be molded into various shapes and forms, such as films, microencapsulated particles, fibers, and panels. Even though microencapsulation is the most popular technique that improves the thermal stability and durability of PCMs, it involves encapsulating the PCM in small polymer capsules, shifting them from their bio-based properties. When analyzing the energy of buildings with PCM integrated into them, it is clear that they depend on the thermal properties, climatic conditions, the building design, the material's melting point, their location, and their quantity [108]. The phase change materials could be either passively or actively embedded into the structure [109]. Within the passive mode, the PCM is implanted into the construction materials of buildings, such as the plaster or plaster-board, gypsum, or concrete, without any supplementary equipment. It can also be trapped in natural fibers (hemp, flax, etc.) following an in-shape stabilization process before using them to produce insulators for building walls [110]. Figure 8 represents the passive thermal storage system (PTSS) encompassing various applications, such as adding PCM to the building walls, floors, and roofs. They can also be integrated into insulation, façade, shutter, and shading systems [111,112].



**Figure 8.** Passive heating with the PCM in the walls, floor, ceiling, and roof [113].

On the contrary, PCM in active thermal storage systems (ATSS), as in Figure 9, entitles mechanical or electrical energy that enables the system to store and release heat upon demand, thus ensuring a more efficient heat transfer and reducing the energy consumption of buildings. Usually, in such a mode, the PCM gets utilized in the heating, cooling, and air conditioning (HVAC) sector or aquifers, boreholes, snow storage, pits, or tanks near the buildings. A photovoltaic module (PV)—powered fan was utilized to propel room air into the solar heater, warm it up, and return it to the room or the PCM storage unit. To

establish the airflow routes given by arrows (1–4) for heat exchange, electric valves (V1, V2, V3) were placed [113].



**Figure 9.** Representation of the different pathways to supply the PCM with heating/cooling energy [113].

Many properties and variables must be considered and fulfilled when selecting a PCM to ensure it is well-functioning. One of the primary concerns is the material's transition temperature, as it must be within the application's temperature range. If not, the PCM will only store the heat without undergoing a phase change. This so-called temperature difference between the transition temperature and cooling and heating temperature is crucial as it impacts the overall energy transfer rate to the storage system. Another factor is the latent heat, known as the enthalpy of phase change, of the phase transition. To ensure and accomplish a high energy storage density and maximize the energy stored in the phase transition, the latent heat must be as high as possible. Thermal conductivity, related to the conduction of the PCM to heat, must also be considered. If its thermal conductivity is measured to be too low, it will be challenging to charge the PCM or extract the energy from it in a reasonable amount of time. The PCM must be stable since these materials are being introduced to serve in the long run. This implies that the materials must not degrade over time and, thus, should not be affected by the ambient air or moisture to conserve their properties with their aging. The PCM must be stable over thousands of thermal cycles and not exhibit a major decrease in its latent heat or transition temperature over its lifetime. In addition, its continuous melting and crystallization should not degrade or alter the material. Some of the rising and promising PCMs possess supercooling drawbacks. Supercooling is called subcooling, undercooling, or supersaturation, meaning the persistence of the high-temperature phase below its transition temperature. If the system supercools beneath the minimum temperature of the PCM, this will prevent the stored latent heat from being regained. Thus, the PCM would serve as a sensible heat storage material after heating it for the first time.

As explained before, PCMs have a wide range of applications; however, they stand out in construction [114] as they are used for insulation due to their heat-storing and releasing properties. The PCM can be integrated into many building parts with various techniques, such as mixing it with construction material, such as mortar, concrete, or gypsum. Another way is the direct impregnation of the PCM with the building materials, such as into gypsum, concrete, or other porous materials, and in their study, Khudhair and Farid [115] explored and explained the numerous impregnation techniques. Finally, the PCM could be encapsulated in thin shells. The micro-encapsulation consists of surrounding

the PCM with a microscopic polymer capsule; these microcapsules will then form a powder that gets incorporated into the recipe of the construction building material. Here, it is imperative to direct special attention toward choosing the capsule's material to bypass any chemical reactions between the utilized tablets and the building material. The advantage of such a technique is that the PCM is now trapped in and hence cannot leak anymore, and the size of the capsules is small enough to prevent the extreme isolation of the solid crust of the PCM [102,104]. The research of Cao et al. [116] showed that with the incorporation of only 3.2% and 2.7% microencapsulated PCM into Portland cement and geopolymer concrete, the compressive strength decreased by 42% and 51%, respectively [107]. The present published research is based on studying conventional PCMs that sometimes exhibit poor heat flow properties and performance and have some gaps. This is why studies and investigations are shifting to developing composite PCM (C-PCM) and incorporating PCM with suitable fillers to improve conventional PCM's properties, effectiveness, and performance. The C-PCM is a heterogeneous mixture of two or more homogeneous phases bonded together, such as metal, polymer, ceramic, carbon, and fluid classes. On the other hand, the concept of PCM incorporated with fillers slightly differs from that of the C-PCM. Fillers can be generated from industrial and agro-industrial waste sources and are important since they enhance the performance of the PCM due to their high thermal conductivity properties [103]. Typically, for PCM incorporated with fillers, both the PCM and filler belong to the same group. Consequently, their combination does not produce a novel material due to their similar structures. Despite this, both PCMs lead to the same target: improving the material's performance in the TES system. Other gaps observed in the current studies on PCMs in buildings are cost analysis and economic evaluations. Most of the articles indeed emphasized the high capability of PCM for cooling applications, but few tackled the economic aspects or are still uncovered. The financial payback of the initial investment must be calculated to encourage the market and increase its uptake. Additionally, if tropical climates are a subject of study, apart from temperature, another important factor influencing thermal comfort is humidity. This is why the potential of PCMs to control the humidity levels in these conditions ought to be explored [103,112].

One new emerging technique for the fabrication of PCMs is the Shape-Stabilization method [109]. Here, the PCMs are produced by choosing a porous building material and impregnating the PCM in it. As a consequence of the capillary force, hydrogen bonding interactions, surface tension, and other interactions between the confined PCM and the porous material, the PCM is now stabilized, and leakage problems during the phase change process are avoided. In order to infiltrate liquid or solid PCMs into the chosen porous support, either the two-step impregnation method, which involves impregnating liquid PCMs into the nanopores of the porous support, or the one-step in situ synthesis is used to manufacture the desired shape-stabilized PCM composite. The PCM can undergo a direct or vacuum impregnation process to fabricate the shape-stabilized PCMs. The composite's preparation process is broken down into three main steps, starting with the design and generation of the porous support, its incorporation in the PCM solution that gets absorbed into it, and finally, the solvent evaporates to acquire the final composite PCMs [117]. Like everything around us, utilizing the shape stabilization technique to incorporate PCMs into buildings possesses strengths and shortcomings. The former is due to its simplicity and low cost, a wide choice of support materials, containment and segregation of the liquid phase, attainment of a material having a high thermal conductivity, and ease in encapsulating a large fraction of PCMs (10–100%). The disadvantages however, are mainly recorded because of the diffusion of the PCMs to the surface, causing their progressive loss, and increasing the contact between the PCM and the environment, leading to corrosion or unfavorable reactions. As mentioned earlier, one of the good things about this practice is that it hosts a wide variety of materials, including polymers, porous materials, and nanomaterials, and the shape stabilization of PCMs is not limited. These materials are divided into porous and nanomaterials, micro-encapsulation, polymer matrices, and solid-solid PCMs [109,118].

In their article, Sawadogo et al. [30] noted the increase in the thermal conductivity of hemp concrete upon adding capric acid (CA) mainly due to the enhancement of the porous upon impregnation with PCMs. CA has replaced the air in the hemp shives/CA composites in which the thermal conductivity of CA is around  $0.21 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  at ambient temperature, which is ten times higher than air, about  $0.02 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ . Moreover, the fabricated composite's moisture buffer value (MBV) was measured and found to be  $2.23 \pm 0.23 \text{ g}/(\text{m}^2\cdot\%\text{RH})$ ; thus, it is classified as an excellent humidity regulator according to the Nordtest Project. In another study, Suttaphakdee et al. [119] used a PCM/recycled concrete block composite forming lightweight concrete having a density of  $1711\text{--}1812 \text{ kg}/\text{m}^3$  and compressive strength of  $33\text{--}53 \text{ MPa}$ , and Li et al. [120] synthesized a form-stable PCM to make cement composites with a density of  $1700\text{--}1900 \text{ kg}/\text{m}^3$  and a thermal conductivity ranging between  $0.72$  and  $0.88 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  [121]. Since the review focuses on bio-sources sustainable materials, in their paper, Boussaba et al. [122] conducted an experimental and numerical study of a bio-sourced composite material's characteristics. A vegetable non-cocoa oil was introduced to an insulating material made of clay and cellulose fibers using direct impregnation, and it constituted 56% by volume of PCM. The material showed good stability according to the chemical and thermal analysis, as the results exhibited good thermochemical stability even after 2000 cycles. The results of the differential scanning calorimetry (DSC) measured the temperatures to be  $34.83^\circ\text{C}$  and  $22.34^\circ\text{C}$ , the heat of fusion was recorded at  $60.41 \text{ J g}^{-1}$ , and finally, the solidification rate was  $62.39 \text{ J g}^{-1}$ . On the other hand, the mechanical properties of the composite material were reduced upon this impregnation, shifting its uses to non-building applications. Finally, the thermal conductivity increased upon adding recycled graphite by a factor of 415% ( $0.2$  to  $0.83 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ ). Another work by Dehmous et al. [123] synthesized a new thermal energy storage concrete (TESC) by impregnating lightweight aggregates with vegetable oil PCMs, added into the cement mortar, having a melting temperature between  $23$  and  $26^\circ\text{C}$ . Three main types of aggregates were used: bentonite, sepiolite, and silica gel impregnated using direct and vacuum techniques. Silica gel had superior rates than the other two (56%). However, sepiolite (32%) is preferred for practical reasons, according to the mechanical tests. In addition, the results showed an improvement of 24.4% and about 13.5% for their energy storage capacity and thermal conductivity, respectively [30].

### 3.9. Geomaterials

As the name suggests, geomaterials are natural resources derived from the earth's crust. They play a significant role in various geological processes and construction. Geomaterials date back to old times as they were among the first mineral raw materials developed, processed, and tested by humans. These materials encompass a wide range of resources that differ in their constitution and nature. Namely, materials such as clay rocks, minerals, soils, natural sands, gravel, and aggregates are present in the earth's surface and subsurface. Nowadays, since the main aim for all emerging materials and research is sustainability, geomaterials are the way to go as they decrease the utilization of the primary non-renewable resources, greatly minimize the environmental impacts on the natural systems, reduce the energy needed during their preparation and production and, most importantly, all the materials used in their manufacturing technologies produce fewer emissions of harmful substances into the nature. Their use in construction is possible after their proper and appropriate processing to be molded into a functionally varied group of mineral resources [124,125]. Geomaterials are highly linked to the man's skills to find, extract, and process them and are characterized by four functional attributes: accessibility, durability, workability, and serviceability. Starting with accessibility, the material being used falls under this criterion if it is found near the dwellings and is practical regarding the energy needed to transport it once extracted. The transportation distance was one of the most considered parameters for standard buildings and structures. In this regard, if the material was found close to the construction site, even if it is of lower quality, it was preferred over other durable ones, which must be transported over several tens of



kilometers. Using very local resources of raw materials for construction causes a decrease in the impact of consuming raw materials because the negative impacts of long-distance transportation are diminished. Moving on, a material's durability is its ability to withstand and resist the action of weathering and decay processes. It is also linked to the dynamic interactions between the material and its surrounding environment, which encompasses the gradual adaptation of materials to their environmental conditions, interactions between the materials used for construction, and the impact of a polluted environment. Thus, in brief, the accessibility of the material is dependent on the earth's processes plus the individual's ability to explore and extract the material; workability targets another point of view. Workability reflects the ability to comprehend and identify the properties of the raw material to process it into a desired composition and physical properties prior to its use. Finally, the term serviceability in construction combines multiple fundamental and technical properties relating to the physical nature and the mode of utilization, respectively. These properties secure the stability and proper functioning of the structure built in a certain environment over a desired period, directly ensuring its durability [126]. Problems can be faced in all materials during and upon their use, particularly with geomaterials; the major drawback is their decay. Decay is related and directly proportional to the serviceability of the material; this is why it is vital to pick the suitable material, trace the mechanisms of decaying, and weathering to prevent the causes of decay. In many studies, dust particles of different compositions were found to be the pollutants responsible for the decay as they induce the sulphation process, and they act as a source of contaminants that create water-soluble salts that call for that [126,127].

### 3.9.1. Earth

The most impactful sectors on the environment are the architectural, engineering, and construction (AEC) sectors, contributing to more than 37% of energy-related CO<sub>2</sub> emissions. The construction industry alone is responsible for a quarter of those emissions. Although many improvements and trials have been launched to reduce carbon dioxide emissions from buildings, it has been found that the fraction of stored carbon emissions is rising in the AEC sector, mainly due to the practices involving carbon-containing materials such as cement, steel, and others reducing or elevating the environmental impacts of these carbon-intensive materials is the way to go [128]. With these concerns comes the importance of the earth as a material. Earth is one of the oldest building materials used worldwide. In terms of geo-technique, earth possesses a mechanical behavior that combines cohesion and friction. Colloidal particles, mainly clay minerals, provide this cohesion, whereas friction is achieved by the contact between the particles of the earth, i.e., silts, sands, gravels, and stones. It is also characterized by its unsaturated porous medium that contains adsorbed water and capillary water, making it in equilibrium with the internal and external atmospheric relative humidity [129]. Earth materials have many benefits that encourage their use: they possess high hygrothermal properties, meaning they ensure high indoor air quality; have good environmental performances and hence decrease climate change impacts; and they are infinitely recyclable just by adding water, so the need for extraction and carbon-intensive materials is bypassed. Since soil highly varies between local cultures, various types of earth have been developed, such as cob, rammed earth (RE), compressed Earth Block (CEB), or adobe and wattle and daub [130]. They have been and still are being used due to their high availability, low cost, and environmental sustainability.

#### Rammed Earth (RE)

Rammed earth (RE) is a subset of earth construction that has long been integrated into traditional structures. Its applications are growing due to its sustainability, availability, and low carbon emission. It is fabricated by creating a mixture of soil, gravel, sand, cement, or lime stabilizers. Layer by layer, rammed earth compacts at the optimum water content in a rigid formwork with a rammer until it becomes 6–10 cm thick. It has high thermal conductivity (1.65 W/m K) and a specific heat capacity of 1218.66 J·kg<sup>-1</sup>·K<sup>-1</sup>; however, its

thermal diffusivity of  $7.42 \times 10^{-7} \text{ m}^2/\text{s}$  suggests that it will delay heat flow even more than concrete [131]. Such engineered walls are implemented for both load-bearing and non-load-bearing structures, and two types of rammed-earth constructions are prominent: stabilized rammed earth (SRE) and unstabilized rammed earth (URE). The basic constituents for URE are soil, sand, and gravel. In addition to the main components, the SRE contains stabilizers like cement or lime, hence its name. The soil ingredient composition determines the compressive strength of URE, and clay plays the role of the binder. Its liability to loss of strength, also known as low compressive strength and erosion due to climatic changes, has limited its applications for structural purposes. Therefore, stabilizers like lime and cement are added to the soil to overcome the limitations. The chief advantages of constructions with rammed earth are (1) its environmentally friendly character, as they have a low energy intensity and carbon emissions; (2) its availability, since materials used are recyclable, and their bulk is available locally within a short distance from the construction area; (3) in the case of stabilized rammed earth walls, the wall thickness and its strength can be easily adjusted [132,133]. Finally, since energy-saving and insulation are our targets, these materials also have excellent thermal performance, contributing to building energy efficiency. As a result of its density ( $1540 \text{ kg/m}^3$ ), thickness, and soil layers, it can exhibit insulation properties and provide resistance to heat transfer through the walls, thus reducing their thermal conductivity. Moreover, climatic considerations must be regarded, as rammed earth material's efficiency depends on the local climate of their installed environment. In regions that experience extreme temperature variations, structures constructed with rammed earth can help buffer these temperature changes and their effect, providing a more comfortable interior environment. However, additional insulation measures are needed to attain optimal thermal performance in extremely cold or hot climates. Therefore, it is clear from the literature that the thickness, composition of the soil mix, and design considerations all impact the insulation performance of structures with rammed earth [130,132]. Additionally, RE structures exhibit hygrothermal [134] and acoustic insulation for residents.

### Cob

The inclination towards cutting the building industry's negative environmental and social impacts has renewed interest in earth construction. However, most literature and research papers presented rammed earth or adobe techniques and little tackled cob construction. Nonetheless, various vernacular earth construction processes depend on the cob comprising local materials, replacing rammed earth and adobe in specific geographical conditions [135]. Cob is one of the construction materials being used worldwide and is made up of clay-rich soil and natural fibers such as straw, sand, and water mixed in a plastic state [136]. It is considered a non-toxic and breathable natural material as it does not use chemical additives. It has good breathability, allowing moisture to flow in and out of the walls, preventing moisture buildup and mold issues. Given the reliance of this material in different construction modes, it possesses a wide range of applications. It can be found in numerous configurations, such as adobe bricks, circular, ovoid, and quenches, defined as a clay-based soil mix applied to a woven pattern of fibrous materials. Its malleability and ease of manipulation, low cost, and environmentally friendly building performance encourage further work on it to understand its opportunities [137]. Cob is an earth material subset offering structural stability and insulation properties. Many authors [138] have calculated and demonstrated that corresponding to the straw and water content and density, the thermal conductivity within earth buildings could vary from  $0.47$  to  $1 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ . In their article, Belarbi et al. [139] highlighted the properties of the cob building material in reference to other commonly used materials and upon the addition of straw (having a low thermal conductivity, between  $0.06$  and  $0.08 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  [140]). According to the lambda meter device, cob has a thermal conductivity of  $0.180 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ , which is lower than conventional materials such as concrete; however, it could reach a value of  $1.20 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ . The specific heat capacity measured for cob was between  $800$  and  $900 \text{ J/kgK}$  in accordance with the ones found in

the literature for raw earth materials (between  $800$  and  $950 \text{ J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$ ) [141]. At the end of the tests, the moisture buffer value (MBV) value for cob was  $1.4 \text{ g}/(\text{m}^2\cdot\%\text{RH})$  with an uncertainty of  $0.1$  [139] and a vapor permeability of  $1.08 \times 10^{-11} \text{ kg}\cdot\text{s}^{-1}\cdot\text{m}^{-1}\cdot\text{Pa}^{-1}$ . These values are per the values referenced in the existing literature. In his article, Zeghari et al. ranged the density of the cob based on its application. For structural walls, the density was from  $1107 \text{ kg}/\text{m}^3$  to  $1583 \text{ kg}/\text{m}^3$  and less than  $700 \text{ kg}/\text{m}^3$  for insulation. It was found that, for the mixes synthesized having a thermal conductivity higher than  $0.4 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ , the respective density and heat capacity was approximately constant; the average density is  $1519 \text{ kg}/\text{m}^3$ , and the average heat capacity is  $1205 \text{ J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$ . During their experiments, the cob integrated for insulation had a thermal conductivity of  $0.14 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ , and the one for construction was  $0.74 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  [142]. Cob structures exhibit high thermal mass related to their capability to absorb and store heat energy from the surrounding environment. This being said, during sunlight, cob walls absorb heat from the sun's rays, in contrast to nighttime, when they release the stored heat. This thermal inertia criterion induces a more stable and comfortable internal environment as it regulates the temperatures. Its composition provides natural insulation properties in which the straw particles act as a lightweight, low-conductivity material that reduces heat transfer in the wall. They also initiate air pockets within the cob, which boosts its thermal resistance properties and reduces heat flow [142]. Under the sustainability umbrella, cob is considered a sustainable building material since it embodies low energy levels. This embodied energy is defined as the total energy consumed during a material's life cycle, including extraction, processing, transportation, and construction. Since cob consists of locally available materials, it needs minimal processing, thus reducing the energy consumption correlated to the manufacturing and transportation steps. Finally, its hygroscopic [134] nature calls for regulating internal humidity levels at around  $50\% \text{ RH}$ . This minimizes the adverse effects on human health from mold spores, dust mites, etc. [143].

#### Adobe or Compressed Earth Blocks (CEBs)

Dating back to the old times, molded adobe production was developed in Mesopotamia 7000 years ago and is considered one of the most flexible ways of using earth constructions. These bricks have been employed for thousands of years and are undoubtedly one of the first man-made materials. The word "adobe" stems from a Spanish/Arabic origin [144] and describes construction materials, usually mud bricks or unburned bricks, assembled from moistened earth and sun-dried ( $\rho_a = 1300 \text{ kg}/\text{m}^3$ ). The drying time depends on the climatic conditions; however, the adobe blocks require several weeks or months to achieve the desired strength and moisture content [145,146]. The adobe bricks could be manufactured from a great category of soils and could be either earth or adobe [147]. The main raw materials that constitute adobe are coarse sand, soil, fibers, straw or sisal, and clay, which, when mixed with water to achieve a plastic consistency, could be cast into the desired form. The different components serve various purposes [148]. Clay-rich soil is the major component, as the clay content grants cohesion and binding properties to the mixture. The clay can vary in type and nature; however, soils with a high clay content are favored since they improve the strength and workability of the adobe. The added clay influences the humidity intake properties of the block, which causes the presence of moisture in the walls and its associated swelling. In this regard, the clay content should be enough to influence the workability but should not exceed a specific limit that causes swelling and shrinking, thus damaging the walls [147]. Sand is added to reduce shrinkage and enhance its structural stability. The sand acts as a filler and boosts the resistance to the compression forces. Straw or other organic fibers are mixed into the adobe. They target its tensile strength and reduce the cracking tendency when left to dry in the sun. These fibers distribute stress within the material and increase its resistance to deformation. Water is added to the mixture to make it practical and induce soil, sand, and straw bonding. A correct moisture content is important to guarantee the proper compaction of the materials and the formation of stable blocks.

Many factors influence the calculations of the ingredients' proportions, which can vary depending on climate, soil composition, and construction techniques. In such instances, a stable adobe has a high sand-to-silt-clay ratio while containing a small quantity of gravel. Soils generally suitable for constructing rigid adobe structures include a percentage of 70 and 80% sand and between 10 and 15% silt and clay. Soil containing large amounts of the latter gets mixed with additional sand to produce a good adobe. Adobe presents many advantages with these materials by serving as a building material [145]. Their thermal properties have a low thermal resistance ranging between 0.42 and 0.71 ( $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ ), or R-value, meaning they cannot resist heat transfer through the bricks. They can easily store radiated heat and release it when needed, making them suitable for counteracting temperature variations. The well-designed use of insulation causes a drastic increase in the energy performances of these walls. Moreover, adobe walls regulate humidity by soaking the environmental air moisture and releasing it into the structure [146]. Its water vapor permeability ranges from 1.0 to  $2.7 \times 10^{-11} \text{ kg}\cdot\text{s}^{-1}\cdot\text{m}^{-1}\cdot\text{Pa}^{-1}$  [141]. In addition, adobe materials fulfill the sustainability requirements as they are environmentally friendly. It is composed of local soil that bypasses the need for transportation and reduces toxic carbon emissions. The waste generated from adobe construction can be left at the extraction site without environmental hazards. Adobe materials are also classified as biodegradable and recyclable [147,149]. The compressed earth blocks (CEBs) are very similar to adobe in composition, just that a hydraulic press is used to compress and mold the earth mixture into uniform blocks instead of sun-drying individual bricks. CEBs have advantages offered through adobe construction, but improved strength and consistency are added. They are flexible in molding and can be easily stacked and mortared to create walls [130].

### 3.9.2. Aggregates

In addition to other substances, natural aggregates are granular materials created from smaller particles such as crushed stone, gravel, recycled materials, and sand that can either be loose and naturally occurring or obtained by crushing a bedrock [150,151]. On the basis of their origin, aggregates could be derivatives of (1) primary, naturally occurring sources derived through the disintegration and weathering of rocks to generate sand and gravel or crushed stone resulting from blasted and crushed rock masses or (2) secondary, manufactured/synthetic raw materials. The secondary aggregates could be further broken down into three categories: lightweight from mineral raw materials, by-products, and wastes from diverse industrial processes, and finally, construction and demolition wastes, also known as recycled aggregates [152]. Lightweight mineral raw materials: clay or claystone, perlite, and vermiculite. By-products and wastes from industrial processes: coal combustion products such as bottom ash, fly ash, and boiler slag. Construction and demolition waste: concrete, crushed bricks, crushed construction rubbish. Aggregates are chief components of many applications, such as road bases, bridges, dams, power plants, concrete, and asphalt. Thus, it is present in almost every part of the environment. It is counted to be the number one nonfuel mineral product worldwide in terms of volume and value. Their mode of utilization could be either inbound or unbound and are grouped based on their particle sizes into three categories: coarse aggregates, fine aggregates, or a combination of both. Fine and coarse aggregates integrate into concrete, occupying 75–85% of its mass [150]. By acting as load-bearing components, aggregates provide construction materials with stability, strength, and durability and interfere with the compressive and flexural strengths and resistance to wear and deformation of concrete and asphaltic materials. Thus, they contribute to construction elements' overall structural and mechanical properties and enhance their resistance to environmental factors. The key and principal parameters that describe the aggregates' properties are particle size and shape, referred to as geometrical characteristics, soundness, physical properties, mechanical performance, durability, mineralogical composition, petrographic description, and lastly, their resistance to weathering, harmful chemical reactions, and decay. Soundness refers to the ability of the aggregate to tolerate destructive forces generated from severe environmental and

climatic conditions like freezing, thawing, salt crystallization, and unwanted chemical reactions of the minerals in the rock [152,153]. The aggregates used in the construction sector must satisfy certain quality standards and specifications that guarantee consistency, performance, and safety. The American Society for Testing and Materials (ASTM) and European Standards (EN) target parameters such as particle size distribution, shape, strength, and durability of the aggregates.

### 3.9.3. Gypsum

Modern buildings are inclined to improve thermal efficiency by establishing thermal conditions, optimizing heat flows in and out of the premises, and enclosing structures. Energy-efficient construction and striving to find a suitable heat-insulating material that minimizes building heat loss are gaining attention daily. Therefore, using a suitable heat-insulating material reduces the thickness and the weight of walls as it lowers the percentage of conventional building materials like cement, metals, and bricks. By this, the energy efficiency of the building is enhanced [154]. Gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ) is one of the most common mineral binders and is considered a geomaterial. Its main component is calcium sulfate, which can either be present in a hydrous or non-hydrous compound, for instance, dihydrate ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ), hemihydrate ( $\text{CaSO}_4 \cdot 0.5\text{H}_2\text{O}$ ), and anhydrate ( $\text{CaSO}_4$ ). Unlike other lime and concrete binders, gypsum has a neutral pH [155,156]. It is a common mineral found in sedimentary rocks, usually in zones with a previous record of shallow seas or saltwater lakes. It can also be present in caves upon the evaporation of water.

Binders from gypsum are energy-saving materials since their calcination usually occurs between 135 and 180 °C at lower temperatures than when combined with cement and lime. Therefore, the fuel required for its calcination is lower; hence, little or no emissions of  $\text{CO}_2$  in manufacturing are generated. Moreover, gypsum sets and hardens rapidly; hence, gypsum-derived products do not demand accelerated curing. Accordingly, gypsum-based products could be classified as environmentally friendly materials. Gypsum has many properties that make it suitable for sustainable construction and offers many advantages as a building material. It is non-toxic, lightweight, has a density of 998 kg/m<sup>3</sup> [137], is highly soundproof, has excellent mouldability, and is fire-resistant. According to Espinoza-Herrera et al. [157], gypsum has a thermal conductivity ranging between 0.3004 and 0.353 W·m<sup>-1</sup>·K<sup>-1</sup>, a specific thermal conductivity of  $5.75 \times 10^{-2}$  W·m<sup>-2</sup>·kg<sup>-1</sup>·K<sup>-1</sup>, and a heat flux of 1164 W/m<sup>2</sup>, making them heat-insulating materials. In another study [158], based on Ciernicka et al.'s experiments, the specific heat for gypsum was found to be 1520 J·kg<sup>-1</sup>·K<sup>-1</sup>, along with a thermal diffusivity of 0.1923 mm<sup>2</sup>/s. Adamopoulos et al. tackled the mechanical properties in addition to the thermal properties. The gypsum they manufactured had a density of 870 kg/m<sup>3</sup> with a corresponding compressive strength of 2.51 MPa. As seen, the compressive strength is not as high as other building materials, which justifies why gypsum is usually coupled with other materials [159]. The water-gypsum ratio is one of the most important factors influencing the material's properties. Due to the water evaporation, capillary pores are formed that cause the gypsum to have a high water absorption rate. To reduce this ratio, high-range water reducers are introduced. Gypsum products have a low water resistance, mainly due to the high solubility of gypsum dihydrate. Lime, or a mix of cement and pozzolanic admixtures such as fly ash and blast furnace slag, is added to enhance and stimulate water resistance. In addition to the ratio, the humidity of gypsum products impacts the properties because any increase in moisture content causes irreversible plastic deformations upon application of a load. Gypsum products are highly durable, but their strength gradually decreases during alternate wetting and drying. Gypsum could be molded into blocks and panels and integrated into partitions and internal walls to replace the traditional ceramic bricks and concrete blocks. In plasters, it could be a replacement for lime and cement [156].



### 3.9.4. Clay

One of the most valuable old dating industries worldwide is the construction industry, and it is one of the leading materials in all market economies. It is generally known that the construction industry is based on several essential materials such as concrete, aggregates, cement, clay, etc., and the choice of the raw material is highly dependent on the application, required properties, environment, and, most importantly, the cost [160]. Intending to promote sustainability in construction materials manufacturing and the increasing demand for such materials to be formed using environmentally friendly techniques, clay materials have been a subject of great interest in recent years due to their ability to fulfill the many requirements and properties in several industrial and environmental fields. Zooming in on those materials, clays are naturally occurring sedimentary materials primarily composed of fine-grained minerals called clay minerals. In a broader sense, they are defined as hydrated aluminosilicates belonging to the phyllo-silicates family comprising two-dimensional infinite sheets [161]. As a consequence of its water content, geometry, and particle size, clay can develop plasticity and be molded into any form when it retains water and turns into a coherent, stiff, hardened, and non-plastic material upon its firing [160]. The justification for this serious attention invested in this material is its recyclability, simple accessibility, easy transportation, abundance in nature, means, and colloidal, physicochemical, mineralogical, mechanical, rheological properties [161], thermal, and acoustic [162]. Clay formation is straightforward and can occur either from the simple decomposition under erosion's effect or through the combination of substances transported by soil or water under the influence of degradation or aggradation. Many different types of clay exist, such as kaolinite, montmorillonite illite, bentonite, ball and fire clay, smectite, talc, chlorite, and vermiculite. Nevertheless, kaolinite, montmorillonite (MMT), and illite are the most frequently used [163]. Kaolinite is a material with the chemical composition  $\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$ . It is usually white and has a soft, earthy feel. It is produced from the weathering of aluminum silicate minerals. Rocks with kaolinite in their composition are called kaolin. Kaolin is a widely used material in many applications such as the paper industry, cracking catalysts, rubber and plastic fillers, cosmetics, oil adsorbents, medicine, and ceramics, and it is a raw material in the production of Metakaolin (MK) needed for the synthesis of geopolymer materials [164,165]. Clay containing kaolinite is the best type in tropical and subtropical environments [163]. Another major clay is the lightweight expanded clay aggregate (LECA) since the raw material is clay, which is abundant worldwide. Expanded clay is generated as a product of firing natural clay, which expands at 1000–1200 °C due to the action of the gases created inside it [166]. It is well known for its thermal and acoustic insulation and moisture impermeability. It is incompressible under permanent pressure and gravity loads, does not decompose in severe conditions, and is resistant to fire, freezing, and thawing [167]. The lightweight property is attributed to the relatively high proportion of pores. Due to the LECA's easy accessibility, it could be integrated into a wide range of applications, such as construction to manufacture concrete blocks, slabs, lightweight concrete, water treatment facilities, and the agricultural sector. In many studies, for instance, Sousa et al. [168] showed that by coupling normal-weight sand with 0.14 m<sup>3</sup> and 0.73 m<sup>3</sup> LECA, the thermal conductivity reached 0.5 W·m<sup>-1</sup>·K<sup>-1</sup>. The masonry units had high sound and thermal insulation. A. Bastos et al. [169] mentioned that within the mixture that contains 214 kg/m<sup>3</sup> of cement, the addition of 65%, 70%, and 80% LECA as coarse aggregates yielded thermal conductivities of 0.51, 0.44, and 0.33 W·m<sup>-1</sup>·K<sup>-1</sup>, respectively, in the concrete blocks. Zach et al. [170] demonstrated, with the hot-wire method, that the different types of LECA concrete showed thermal conductivities of 0.1376, 0.1521, and 0.1649 W·m<sup>-1</sup>·K<sup>-1</sup>. Graboïs et al. [171] mentioned that the incorporation of LECA as coarse aggregates having sizes in the range of 0.4–20 mm and 0.06–10 mm, instead of normal weight sand, can lower the thermal conductivity by 60% while increasing the specific heat by 3.62%. A high percentage of residential buildings are constructed using the clay brick materials. In his article, Alam et al. [172] performed hygrothermal transfer studies on a constructed clay brick wall in Egypt by measuring the hygrothermal properties and

performing experimental tests. It has a low thermal conductivity of  $0.41 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  and high specific heat of capacity  $C_p = 780 \text{ J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$ . That means clay can be considered as a good insulator since it takes time to absorb more heat before it actually heats up. The moisture diffusivity is  $D_w = 6 \times 10^{-10} \text{ m}^2/\text{s}$ , and the water vapor permeability is  $\delta v = 1.62 \times 10^{-11} \text{ kg}\cdot\text{s}^{-1}\cdot\text{m}^{-1}\cdot\text{Pa}^{-1}$ , which indicates its ability to transfer moisture under a certain vapor pressure gradient. This means that the permeability levels for the clay are not as high; however, it possesses a porous structure. The manufactured and tested clay brick wall, on the other hand, has a dry density of  $1980 \text{ kg}/\text{m}^3$  [139]. In conclusion, it is safe to say that the quantity of LECA and the thermal properties are proportional. As LECA's content in a mixture increases, the thermal insulation increases. Also, its thermal conductivity is lower than that of normal-weight aggregate. This is presumed because LECA has a lower density and a higher porosity than the normal weight aggregate, leading to a minor thermal conductivity or higher thermal isolation. The formed interconnected pores in the LECA pellets reduce the material's thermal conductivity since the air in pores is a good insulation material. The attractive thermal insulation properties of LECA in construction improve buildings' energy performance and influence energy reduction [173].

### 3.10. Emerging Green Materials

It is a consensus that one of the sectors that most negatively affects the environment is the building sector, which calls for the extraction of more than 40% of the natural resources in industrialized countries, the consumption of at least 70% of the electricity, 12% of potable water, and the vast production of the waste ranging between 45 and 65% that is being disposed to landfills [174]. Moreover, the building sector contributes 30% of the greenhouse gases and many harmful emissions due to their operation, material exploitation, and transportation [175,176]. These are expected to rise even more due to the rise of the global population from 6.5 billion in 2005 to approximately 9.0 billion in 2035. Even in non-industrial buildings, its building materials and furnishings account for the release of 60% of total volatile organic compounds (VOCs) in which conventional building materials produce formaldehyde and other toxic or irritating chemicals that react with ozone to produce secondary emissions [177]. Consequently, a bad indoor environment quality is faced because of the integrated materials, which causes health problems for individuals in offices, homes, and buildings. In this scenario, improving the environmental impact of buildings is a primary concern. Previously, attention was focused on energy-saving in the operation phase of the construction, like the energy needed for heating, cooling, ventilation, lighting, etc., which led to an improvement in this direction [174,175]. Nowadays, the environmental impact of building materials, starting with raw materials extraction, their manufacturing process, and transportation to the construction site, all within the pre-use phase of the building, is also being considered. This impact could be quantified through parameters identified in the Life-Cycle Assessment (LCA) procedure. This being stated, the construction of green buildings is taking the lead in the building sector. To check if the building is green or not, various certification codes certify the building. Leadership in Energy & Environmental Design (LEED) is the most common [175,176,178].

Green building materials are classified as eco-friendly with little or no effect on the environment and are harmless to human health in their production cycle. They comprise renewable resources rather than non-renewable ones. Therefore, these materials must be of a natural origin and withstand heat, humidity, and other environmental aspects. The reuse, reduce, and low emissions features characterize them and could be divided into ecological, healthy, recycled, and high-performance materials. Their high performance is a crucial feature as it targets improving the quality and efficiency of a building by ensuring soundproofing, water permeability, and energy savings [179]. The change in the weather patterns, shifting to hotter summers and short winters, and insufficient monsoons, calls for the preservation of the city's ecology, and resources and energy sources are now highly needed to reduce these negative environmental impacts [178]. Green building materials

are numerous: bamboo, hempcrete, geopolymers, cork, recycled plastic and glass, earth, mycelium, and lime are the most used [179,180].

### 3.10.1. Bamboo

Bamboo plants are being deeply studied as a green material due to their many benefits and fast regeneration. It is a resourceful and adaptable natural material used in construction for centuries. Bamboo is gaining interest as it is a fast-growing, sustainable, renewable, recyclable, and biodegradable plant. It is capable of shooting up to 91 centimeters in just 24 hours. This rapid growth allows its sustainable and abundant supply without exerting unnecessary strain on natural resources. Moreover, bamboo cultivation needs less water, insecticides, and fertilizers than other plants. Also, no harmful chemicals are required for its processing, like in other building materials, causing bamboo to have a significantly lower environmental impact than many traditional construction and manufacturing materials. It is characterized by low density, falling between 200 and 850 kg/m<sup>3</sup> [181], and high mechanical strength, having compressive, tensile, and flexural strengths between 51–56 MPa and 150–263 MPa, and 210.3 MPa, respectively [182,183]. Noting that the durability of bamboo is relatively low, it can be commonly used in manufacturing composites. It made its way through construction due to its multiple uses, such as structural support: being strong enough to support heavy loads, and it can be used to build entire structures, flooring and decking, wall and ceiling coverings, roofing, fencing, screening, and furniture.

On the other hand, bamboo has a low thermal conductivity (0.55–0.59 W·m<sup>−1</sup>·K<sup>−1</sup>), meaning it is an excellent heat insulator [184]. It maintains warm buildings in the winter and cool in the summer, thus decreasing energy consumption and costs and improving comfort levels. It is also a good sound insulation material that reduces noise pollution from outside buildings and between rooms. This is very useful in commercial buildings, where noise reduction is essential for the comfort and productivity of the residents. From a sustainability point of view, bamboo is a renewable resource that multiplies without demanding a high input of water or fertilizer. It is also biodegradable and can be composted at the end of its useful life. Integrating bamboo for insulation can help reduce the environmental impact of construction projects. Finally, it is distinguished by its fire resistance properties. It has natural fire-resistant assets, which causes it to prevent the spread of flames in case of a fire. This makes it a safe choice for insulation in buildings [40,185,186].

### 3.10.2. Geopolymers

Geopolymers are inorganic polymeric materials generated from mixing a dry solid with an alkaline solution and sometimes, if needed, other materials. The solution is usually sodium or potassium hydroxide or silicate, which are soluble alkali metals. The major component is the source material, which must be rich in Silicone (Si) and Aluminium (Al) [187]. Since aluminum is an abundant substance, there exist many raw materials to create geopolymers, such as calcinated clays, specifically kaolinite, which was the first widely used material in geopolymer synthesis, industrial waste (such as slag and fly ash) [188], waste glass [189], aluminum mine tailings, natural silicoaluminates, red mud, and zeolites. They harden quickly, achieving 70% of the final compressive strength in the first 4 hours. Geopolymers possess volume stability, a lower shrinkage ratio than Portland cement, high strength, excellent durability and attainment of their properties almost after decades, low thermal conductivity, and high fire resistance. These properties make them suitable for many applications, such as thermal insulation [190], fire-resistant materials, low-tech building materials, cement and concrete [191], low-energy ceramic tiles, repair infrastructures, strengthening composites, etc. [192]. Geopolymer foams are porous materials introduced in buildings to achieve thermal insulation [193]. They are formed by adding a foaming agent such as hydrogen peroxide, NaOCl, silica fumes, or metal powders (aluminum) to our paste. These agents increase mortars' porosity by releasing gases [194]. The heat conductivity of a geopolymer is usually in the range of 0.24 W·m<sup>−1</sup>·K<sup>−1</sup> to 0.3 W·m<sup>−1</sup>·K<sup>−1</sup>, compared to the lightweight refractory bricks with a conductivity of

$0.3 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  to  $0.438 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  [192]. In their article, Vaou and Panias [195] showed that the thermal conductivity of foamy geopolymeric materials as a paste is indirectly proportional to the quantity of the foaming agent. It was lowered substantially from  $0.053 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  to  $0.03 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  when hydrogen peroxide ( $\text{H}_2\text{O}_2$ ) content increased from 0.7% to 2.02% [190]. In order to improve their insulation properties even more, additives to the geopolymers were introduced, and positive results were obtained. For instance, upon coupling it with a potassium titanate whisker (PTW), improvements in the thermal insulation of the metakaolin-based geopolymer were observed. The results indicated that adding PTW could significantly enhance the porous geopolymer's thermal insulation and compressive strength properties [194]. Also, Huang [196], in his article, prepared an aerogel and geopolymer composite that turned out to be a hydrophobic, lightweight, and superb thermal insulating matrix. He achieved a thermal insulation value of  $0.0480 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ , and the composite materials exhibited great potential in the field of thermal insulation. Based on research, due to their low thermal conductivity and improved mechanical properties, geopolymers have a great application when fireproof or adiabatic insulation is required. In addition, they are molded into foamed plates and integrated as thermal insulation in the construction field [197].

### 3.10.3. Recycled Glass

By definition, glass is a solid material formed by exposing a mixture of normal sand (silicon dioxide), soda (sodium carbonate), and limestone (calcium carbonate) to a high temperature until a liquid is formed and left to cool to ensure that solidification occurs without crystallization. Glass could be transparent, translucent or brittle, with the simplest being composed of only soda, sand, and lime. It is one of the materials that individuals depend on as it exists through various manufactured products like sheet and float glass, bottles, glassware, laminated and toughened glass, heat-resistant glass, and many more [198]. Glass has many applications, such as energy saving and insulation, construction, containers and vessels, nanotechnology, etc. [199,200]. However, in its present form, glass is not a green material as tremendous amounts of  $\text{CO}_2$  get released during manufacturing. Moreover, due to glass's excessive dissolving temperatures and the decay of nitrogen compounds in the batch substances, nitrogen oxides ( $\text{NO}_x$ ) influence the acidification and development of serious air pollution, also known as SMOG. Numerous problems arise due to its contamination of the water bodies, its basis on un-replenishable raw materials, and its generation of solid wastes and volatile organic compounds [201]. In order to satisfy the 'Green' conditions, glass has to be recycled. Therefore, the most interesting type is recycled glass, which possesses different forms obtained from various sectors [198]. Glass is an infinitely recyclable material that does not lose its quality and value along the processes. Its remanufacturing is environmentally friendly since it lowers the quantity of needed raw materials and cuts the total energy consumed during the manufacturing process, as the recycled glass's melting point is way beneath the original raw materials that make up the glass [202]. Accordingly, many applications have arisen to integrate this recycled glass, such as green polymer and translucent concrete, as a raw material for geopolymers, foamed waste glass, ultra-lightweight fiber-enforced concrete, production of hot mix asphalt, and geopolymeric tiles [201]. Suitable and proper insulation is a critical issue that helps minimize the transmitted heat flow, saving heating/cooling energies and lowering the associated emissions from fossil fuel combustion. The traditional insulators in the market are usually from primary raw materials, such as minerals, rocks, and fossil fuels (organic foams). The emergence of secondary or renewable raw materials is paramount to fulfilling ecological and sustainability requirements, and insulating materials from natural sources or recycled materials are being increasingly evaluated [203]. The literature showed that glass could be altered to form foams. Glass foams [204,205] are reported to be thermally insulating, lightweight, compression-resistant, sound insulation, non-flammable, and water and steam-resistant. They are appealing for their chemical and thermal stability, low density, high surface area, and permeability due to their high porosity, freeze-thaw tolerance, and

longer lifespan compared to conventional thermal insulating materials [206]. In their article, Yu et al. [207] investigated the engineering properties of ultra-lightweight fiber-reinforced concrete (ULFRC) in which they replaced the natural aggregates with expanded waste glass to manufacture a material with low thermal conductivity (around  $0.165 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ ) and insulating properties and a low density to be integrated into buildings that involve load-bearing devices, floating structures, or insulating materials [201,202]. In addition to the above, glass powder was also integrated into the concrete as per the article of Boukhelf et al. [208], in which the effect of the semi-replacement of cement by materials derived from the waste glass on the concrete's hygrothermal behavior was investigated. Glass powder has a density of  $2710 \text{ kg/m}^3$ . According to the SEM tests, the glass powder (GP) has multi-sized and irregularly shaped particles, varying from  $8 \text{ }\mu\text{m}$  to  $50 \text{ }\mu\text{m}$ . Upon substituting 20% and 30% of cement with glass powder, the porosity of the concrete increased by 7.9 and 16.7%, respectively. This is mainly because the fineness of the GP is lower than that of cement substituted and due to the formation of new ranges of micro and macro pores. Regarding the compressive strength of the synthesized material, it was lower than that of concrete alone (36–41 Mpa); however, it remains sufficient for structural application as a consequence of the dilution resulting from the substitution of cement—a more reactive powder with GP—a less reactive powder. Concerning the hygrothermal properties, the porosity increase for concretes with GP led to a decrease in the thermal conductivity by 3.7% and 8.9%, for the addition of 20% and 30% GP. The incorporation of glass powder increased the concrete moisture storage capacity ( $C_m$ ), which is attributed to the effect of porosity on this intrinsic mass transfer parameter; however, its lower permeability slows down the diffusivity and storage of moisture. Finally, the results feature a significant upward shift in water vapor permeability  $\delta$  with the replacement of cement by 30% GP from  $9.51 \times 10^{-13} \text{ kg} \cdot \text{s}^{-1} \cdot \text{m}^{-1} \cdot \text{Pa}^{-1}$  to  $2.87 \times 10^{-12} \text{ kg} \cdot \text{s}^{-1} \cdot \text{m}^{-1} \cdot \text{Pa}^{-1}$ . This is justified by the changes in the microstructure of concrete.

#### 3.10.4. Lime

Dating back, lime is a binding material used for building infrastructure; however, cement binder has replaced it to meet the needs of speedy construction. The lime mortar hardens through a carbonation reaction that calls for atmospheric  $\text{CO}_2$  to enter the lime's porous medium and connect with the moisture present inside it, thus converting calcium hydroxide ( $\text{Ca}(\text{OH})_2$ ) to calcium carbonate ( $\text{CaCO}_3$ ). Many factors affect the carbonation process: the ambient temperature, relative humidity, nature of used raw material, aggregate-to-water ratio, and  $\text{CO}_2$  concentration. Of the many materials that emerged nowadays, lime is considered green since its sustainability and eco-friendly properties characterize it. It is renewable, abundant, and recyclable since it is made of limestone, a naturally occurring mineral in the earth's crust that does not affect the natural reserves with a  $3340 \text{ kg/m}^3$  density. It possesses low embodied energy, as its production needs significantly less than other building materials, such as cement. Even though the calcination process needs elevated temperatures, it is still lower than the energy production of cement. Lime can absorb carbon dioxide, leading to a reduced carbon footprint since it re-absorbs the  $\text{CO}_2$  it generates during its formation in the kiln during the carbonation process. For this reason, lime building materials are counted as carbon neutral [209]. In a mixture, lime is added due to its plasticity and workability. The major drawback of lime is that in pure lime mortar, its setting and hardening processes are slow because they depend on the reaction of calcium hydroxide with atmospheric carbon dioxide. Many additives have been added to the lime matrix to improve this feature and its durability, workability, and thermal properties [210]. Sandaka et al. [211] found that the thermal conductivity at the decomposition temperature range  $900\text{--}1200 \text{ }^\circ\text{C}$  varies between  $0.4$  and  $0.9 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ . One of the added materials is the hemp shives, the inner part of the hemp stalk, which are chemically similar to the wood pulp due to their lignin content. Hemp shives are a byproduct of hemp cultivation, as their primary purpose is to obtain fiber and seeds. They are characterized by their superior moisture and smell absorption capabilities. Because of their porous nature, they could be



employed as fillers in thermal insulating biocomposites, thus contributing to the material's moisture-regulating capabilities and low thermal conductivity [212].

Many studies showed that the formed hempcrete's hygrothermal and mechanical properties depend on many factors. The essential elements are the compaction level, binder-to-hemp ratio, water content, and binder mix design [213,214]. In their article, Lawrence et al. [215] found the thermal conductivity of hemp and lime mixtures to be in the range of  $0.06\text{--}0.11\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  when the dry densities ranged from 200 to  $400\text{ kg}/\text{m}^3$  and hemp/binder ratios varied between 1:1, 1:1.5, and 1:2. When the values for the hemp/binder ratio and densities were increased, higher thermal conductivity was measured. The mixture's water content and thermal conductivity are directly proportional, so any increase in water content tends to increase the thermal conductivity of the hempcrete mixes. In order to further improve the properties of the hemp-lime, recycled crushed brick as a pozzolan is being added to the mix to increase composites' availability, performance, and thermal and moisture properties while reducing their environmental impact [216]. Another additive to the lime is waste paper (AWP) aggregates. After processing the waste paper into aggregates, it was mixed with lime and water to design lightweight bricks (AWPL) for building insulation. The mix's mechanical and insulating properties were tested to check their suitability. The AWPL materials exhibited a noticeable deformation without breaking under a compressive load. Good adhesion between the fiber and the matrix is due to the cellulosic fibers responsible for its fibrous structure and high porosity. It is also recorded that the lime content increases this adhesion. Moving on to its thermal properties, the thermal conductivity of the different types of AWPL increased from  $0.097\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  to  $0.12\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  with the increase in porosity. The experiments showed that all samples have low thermal conductivity and that the AWPL materials could be insulating materials [217]. A detailed listing of the exploited values from the existing research for green and geomaterials is tabulated in Table 4 below.

### 3.10.5. Cork

One of the naturally occurring emerging vegetable resources that are sustainable and renewable is harvested periodically every 9–12 years and can be used to improve energy efficiency and thermal insulation in buildings. Cork is the cork oak tree's outer layer in Southern Europe and Northern Africa [218,219]. Three types of cork are generated during its life cycle, mainly virgin cork ( $\rho = 160\text{--}240\text{ kg}/\text{m}^3$ ) from the first stripping, reproduction cork ( $\rho = 120\text{--}180\text{ kg}/\text{m}^3$ ) from the second stripping, and reproduction cork from later strips [220]. This material has various characteristics that make it popular in the industrial sector. Its lightness, elasticity, impermeability to gases and liquids, excellent thermal insulation, and acoustic properties are all due to its cellular structure. It has a macro-porous structure, attributed to its good insulation capacity [218,219,221]. Algeria is one of the major cork producers, reaching 1900 tons/year of granular material and 5600 tons/year of powder cork. The corresponding waste is either dumped in disposal landfills or incinerated, encouraging new applications, such as incorporating natural and expanded cork granules in cementitious composites. Recently, virgin cork has been used as aggregates in concrete at different volumes, remarkably improving cement's porosity, capillary absorption, and thermal conductivity while decreasing its workability and plastic viscosity. Having said this, cork concretes may be utilized in nonstructural applications such as filling blocks and insulation screeds [220,222]. Authors discussed that the compressive strength of these lightweight screeds fell between 0.12 and 1.98 MPa at 28 days, while their thermal conductivity oscillated between  $0.195\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  and  $0.318\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  depending on cement amount. In their study, Borges et al. [223] formulated cement mixtures with fly ash and expanded cork and/or clay. It was shown that the quantity of cork was inversely proportional to the mortars' thermal conductivity and mechanical properties, passing them as thermal mortars. Also using expanded cork, Novais et al. [224] also incorporated them as lightweight aggregates yielding products having a density of  $260\text{ kg}/\text{m}^3$  and thermal conductivity of  $0.072\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ . In their recent article, Tedjditi et al. [220]

used virgin cork to fabricate and develop a novel lightweight concrete. The materials, in accordance with the other articles, showed good thermal properties, low density, and weak mechanical properties. Depending on the aggregate cork size that could be within any range, 0–4 mm, 4–8 mm, and 8–16 mm, the apparent density of the cork was between 83.8 and 88.9 kg/m<sup>3</sup>, the particle density 184–223 kg/m<sup>3</sup>, the range for the water absorption was 68.89–168.67%, and finally, the inter-particle porosity was varying between 54.5 and 61.4, respectively. The cork has a low thermal conductivity of 0.045 W·m<sup>−1</sup>·K<sup>−1</sup>, a thermal diffusivity of 1 × 10<sup>−6</sup> m<sup>2</sup>/s, and a specific heat of 350 J·kg<sup>−1</sup>·K<sup>−1</sup>, so it could be a good candidate for thermal insulation. Its water diffusion coefficient ranges between 1 × 10<sup>−11</sup> and 4 × 10<sup>−10</sup> m<sup>2</sup>/s [219]. Upon its addition to the cement, the compressive strength went between 0.48 and 8.35 MPa; therefore, the virgin cork composites show good mechanical properties as non-structural materials. Also, for high amounts of virgin cork (50, 75, and 100%), the produced concrete had a thermal conductivity ranging the produced concrete had a thermal conductivity ranging between 0.041 and 0.56 W·m<sup>−1</sup>·K<sup>−1</sup> [220]. A detailed listing of the exploited values from the existing research for green and geomaterials is tabulated in Table 4 below.

**Table 4.** Summary of the Geo/Green material’s thermal insulation and other properties.

Type	Raw Materials	Density (kg/m <sup>3</sup> )	Thermal Conductivity (W·m <sup>−1</sup> ·K <sup>−1</sup> )	Specific Heat Capacity J·kg <sup>−1</sup> ·K <sup>−1</sup>	Thermal Diffusivity (m <sup>2</sup> /s)	Moisture Buffer Value g/(m <sup>2</sup> ·%RH)	Vapor Permeability kg·s <sup>−1</sup> ·m <sup>−1</sup> ·Pa <sup>−1</sup>	References
Rammed Earth	A mixture of Soil, Gravel, Sand, Cement, or Lime Stabilizers.	1540	1.65	1218.66	7.42 × 10 <sup>−7</sup>	NOT APPLICABLE	NOT APPLICABLE	[130–134]
Cob	A Clay-rich Soil and Natural Fibers (Straw, Sand, and Water)	1519	0.18 to 1.20	800–950	NOT APPLICABLE	1.4	1.08 × 10 <sup>−11</sup>	[134–143]
Adobe	Sand, Soil, Fibers, Straw or Sisal, and Clay	1300	0.42–0.71	NOT APPLICABLE	NOT APPLICABLE	NOT APPLICABLE	1.0 to 2.7 × 10 <sup>−11</sup>	[130,141,144–149]
Gypsum	Calcium Sulfate	870	0.3004 and 0.353	1520	1.923 × 10 <sup>−7</sup>	NOT APPLICABLE	NOT APPLICABLE	[154–159]
Clay	Hydrated Aluminosilicates	1980	Clay, Dry to Moist	780	NOT APPLICABLE	NOT APPLICABLE	1.62 × 10 <sup>−11</sup>	[160–173]
			Clay, Saturated					
			Fire-clay Brick					
Bamboo	Bamboo Plant	200 to 850	0.55–0.59	NOT APPLICABLE	NOT APPLICABLE	NOT APPLICABLE	NOT APPLICABLE	[40,181–186]
Recycled Glass	A mixture of normal Sand, Soda, and Limestone	2710	0.045–1.05	NOT APPLICABLE	NOT APPLICABLE	NOT APPLICABLE	NOT APPLICABLE	[198,208]
Lime	Calcium Oxides and Hydroxides	3340	1.26–1.33	NOT APPLICABLE	NOT APPLICABLE	NOT APPLICABLE	NOT APPLICABLE	[209–217]
Cork	cork oak tree’s outer layer	Virgin Cork: 160–240	0.195–0.318	350	1 × 10 <sup>−6</sup>	NOT APPLICABLE	NOT APPLICABLE	[218,224]
		Reproduction Cork: 120–180						

#### 4. Discussion

This scientific, comprehensive review article provides an overview of the state-of-the-art, sustainable, environmentally friendly materials used in building construction. The article focuses on the hygrothermal characteristics, thermal conductivity, and insulation properties adopted by these tackled materials, their moisture buffering value (MBV), and energy performance upon their integration into the building. Hemp, wood, earth, recycled glass, bamboo, cork, straw, geopolymers, and many more materials are discussed and

detailed. With the increase in population worldwide, the rise of environmental problems and energy efficiency challenges associated with the building sector are seen. Hence, the increasing demand for sustainable construction materials such as green, bio-sourced, or geomaterials is crucial to solve and reduce such issues. This review serves as a data set for understanding the present state of theoretical and experimental investigations. It highlights their potential as renewable, low-energy, and eco-friendly alternatives to be introduced in building envelope applications. When used for building applications, all these materials are fabricated and designed to have optimum energy-saving performance, thermal insulation, reduced impact on natural resources, reduced waste and pollution, and boost a more sustainable and healthier lifestyle. This collective review includes all families of sustainable materials that are possible candidates to be invested in and introduced in the building for thermal insulation and energy conservation. Depending on the situation, they can be introduced in many ways, usually invested in cooling or heating. They are being proposed as solutions for managing and conserving energy, cutting substantial sums of money spent in this direction.

## 5. Conclusions

In conclusion to what was stated above, an increase in the population is definitely calling for an increase in building and energy demand. Fossil-fuel-based materials may indeed satisfy that demand; however, they negatively impact and harm the environment and affect populations worldwide. This work addresses a highly innovative subject that significantly transforms the facades of buildings and addresses energy problems in a healthy, safe, and economical manner. Overall, integrating green materials, geomaterials, or bio-sourced materials in buildings can successfully target improving energy performance and insulation, and infrastructures will be environmentally friendly and energy efficient. The building's cost-effectiveness depends firstly on the type of sustainable material that will be used, its application, environmental and weather conditions, and the structure's location, which can be a significant challenge. Even though some of these materials are relatively more expensive than the conventional ones, their benefits in the long run will outshine their price. As presented above, it is clear that all three types are suitable for insulation and have good thermal resistance. For green materials, for example, their efficiency as insulators depends on considerations such as density, thickness, and installation technique. They also promote reducing greenhouse gas emissions as they do not demand raw materials associated with energy-intensive manufacturing processes. They use recycled materials that aid in diverting waste from landfills and lowering the carbon footprint associated with insulation products. On the other hand, geothermal efficiency depends on the material's thermal conductivity, porosity, and moisture retention properties. They can provide superior insulation in specific applications, like earthen construction techniques.

Nonetheless, their insulation effectiveness may vary depending on the material and construction method. There is no direct link between these materials and the diminishing GHG levels, as the raw materials for this category are naturally occurring. However, once introduced in the construction sector, they can maintain and indirectly contribute to reduced emissions if they are locally sourced, necessitate less transportation energy, and are associated with low-carbon construction like earthen construction. Lastly, depending on the specific material used and the density, bio-sourced materials in all types act as effective insulators having good thermal resistance properties. They often have a lower carbon footprint when compared to traditional insulation materials. Since their raw materials are produced from renewable sources, they have carbon stored within during their growth, offsetting the carbon they emit during manufacturing and installation. Also, since bio-sourced materials encompass agricultural byproducts, these can help cut waste and associated methane emissions from their decomposition. The best-case scenario is using a combination of these materials that have similar properties and are compatible with the building's design and construction methods to create sustainable building practices like reduced energy consumption, energy-efficient designs for heating and cooling, and proper sealing.

These energy-saving materials mitigate climate change, reduce carbon emissions, and minimize resource depletion as they depend on natural resources and utilize innovative technologies. Not only do they benefit on an environmental level, but they also possess looked-for properties such as thermal insulation, high strength, and durability, and they are replacing conventional substances in many sectors, such as construction, automation, packaging, and more. With these renewable alternatives, energy savings in different applications are easily calculated, consequently reducing energy consumption and elevating their overall efficiencies. To choose wisely, many experiments must be performed to evaluate the materials' mechanical, chemical, and thermal properties, followed by a series of characterization techniques such as the Heat Flow Meter, Hot Wire Conductivimeter method, Absorption/Desorption Tests, Water Porosity Tests, Calorimeter and the Gravi-Test, which are performed once the material is synthesized to check its performance on thermal, moisture, and durability levels to finalize the choice fully. Investing in research that advances this field is critical nowadays as it influences the circular economy approach, ameliorates manufacturing processes, and advances the lifestyle and unique environments. The research goes one step further by considering coupling these materials and integrating them into other energy-saving solutions that possibly cover the whole building construction spectrum.

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