Discover Sustainability

Review

Alternative construction materials: a point of view on energy reduction and indoor comfort parameters

Paul O. Awoyera[1] · John Effiong[2] · Vamsi Nagaraju[3] · Md. Aminul Haque[4] · Md Azree Othuman Mydin[5] · Kennedy Onyelowe[6]

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Abstract
The indoor comfort of occupied buildings has become essential, as it significantly affects the productivity and health of occupants. This review provides a comprehensive overview of air and thermal comfort studies in residential buildings using alternative materials. This study aims to provide the trends and the state of the research in this field, to summarize the optimization methods, and to offer a perspective on future studies. The results demonstrate that in comparison to traditional air conditioning systems, natural ventilation systems, and air purifying plants have the potential to reduce energy consumption and carbon emissions in buildings by up to 60%. Also, cross-laminated timber (CLT) buildings can achieve energy savings of up to 30% compared to conventional buildings due to their superior insulation properties and reduced thermal bridging. This review has provided highlights to help the building owners to promote a healthier environment, reduce energy consumption and achieve more comfortable indoor air quality. The study promotes incorporating innovative materials and use of natural ventilation systems, smart air conditioning systems and air purifying plants.

Keywords Thermal comfort · Air comfort · Alternative materials · Energy efficiency · Sustainability

Abbreviations

CO_2	Carbon dioxide
USA	United States of America
IEA	International energy agency
ASHRAE	American society of heating, refrigerating and air-conditioning engineers
IEQ	Indoor environmental quality
HVAC	Heating, ventilation, and air conditioning
VOCs	Volatile organic compounds
EP	Environmental protection agency
IAQ	Indoor air quality
Kg	Kilogram
GW	Gigawatts
L	Liter

✉ Paul O. Awoyera, awopaul2002@gmail.com | [1]Department of Civil Engineering, Prince Mohammad Bin Fahd University, Al Khobar, Kingdom of Saudi Arabia. [2]Department of Civil Engineering, Covenant University, Ota, Nigeria. [3]Department of Civil Engineering, SRKR Engineering College, Bhimavaram 534204, India. [4]Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hong Kong SAR, China. [5]School of Housing, Building and Planning, Universiti Sains Malaysia, 11800 Penang, Malaysia. [6]Dept. of Civil Eng, Michael Okpara University of Agriculture, Umudike 440109, Umuahia, Nigeria.

mK	Meter Kelvin
SEER	Seasonal energy efficiency ratio
MJ/m3K	Megajoules per cubic meter per Kelvin
PCMs	Phase change materials
EPS	Expanded polystyrene
PVC	Polyvinyl chloride
LED	Light emitting diode
HVACR	Heating, ventilation, air conditioning, and refrigeration
UV	Ultraviolet
R&D	Research and development
MJ/m2K	Megajoules per square meter per Kelvin
EUI	Energy use intensity
LCA	Life cycle assessment
GWP	Global warming potential
U-value	Thermal transmittance
SHGC	Solar heat gain coefficient
VOC	Volatile organic compound
PV	Photovoltaic
PMV	Predicted mean vote
PPD	Predicted percentage of dissatisfied
AMs	Alternative materials
CLT	Cross-laminated timber

1 Introduction

The heating and cooling systems in residential buildings requires notable amount of energy annually. From records, the European household emits nearly 5.5 tons of CO_2 annually, with around 61% of those emissions coming as result of heating [1]. Based on the estimated records [2], the United States, China and India's residential housing released CO_2 emissions of over 20% (2019), 15% (2020) and 10%(2019), respectfully. Still according to the report, in China, the residential sector accounted for about 15% of the nation's total CO_2 emissions in 2020, and in India, the residential housing's CO_2 emission in 2019 was estimated at 10% of the country's total.

As a result of the concurrent reduction in component self-weight, the construction industry is gravitating towards increasingly lightweight building elements with novel manufacturing process improvements and environmental benefits. However, the decreased capacity of building materials to store heat tends to lower the radiant temperature stability of interior surfaces, especially in environments with high temperatures and sun irradiance gradients. As a result, the user's perception of comfort diminishes. The indoor thermal environments are crucial for health and comfort. The environment has impact on wellness or a detrimental effect on occupant's health, and it is a cause for concern and an indication that the building has design or technical flaw [3]. Indoor comfort refers to the individual's satisfactory perception of their indoor environment [4]. The occupant's thermal comfort can also be referred to as the state of physical, emotional, and social stability that results from a person's ability to adapt to the environment's thermal equilibrium, temperature, and humidity [5]. The human body requires protection from the elements to maintain a stable internal temperature. Generally, a building's exterior exchanges heat with the interior and the wall as shield. Also, the rate of this heat exchange is determined by the thermophysical characteristics of the building materials, which contributes to one aspect of thermal comfort inside any building [6]. Buildings are primarily intended to house people, often to meet their various housing needs and, most significantly, to provide them with comfort, all of which impose certain indoor conditions. In addition, both residential and commercial building inhabitants need to feel safe and comfortable while living or working, as the case may be. Residential buildings generally require low energy usage compared to the more energy demands of commercial buildings. Handbook of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) [7], categorized buildings into various functional areas. These functional areas are dependent on their serving purpose. An indoor environment's specifications may vary based on the functional area, meanwhile the architecture's complexity is a result of these features. The unique qualities in functional sectors of both the commercial and residential structures contributes to healthy and pleasant indoor atmosphere for working and living. Thus, ensuring a better indoor quality could minimize airborne related infections by 9–20% [8]. Hence, there is an increasing requirement to keep indoor spaces in buildings comfortable.

New developments in building design that pertain to thermal comfort and air quality have been noted and reported over time. Considering the recent changes in global climate conditions as well as an outbreak of several pandemics, it is only important that building infrastructure is properly developed so as to meet the accommodation and functionality needs of users. Moreover, considering that people spend 80% to 90% of their time indoors [9], thus the concept of indoor environmental quality (IEQ) has become a very important consideration in a growing number of research studies for the past few years. Both psychological and physiological variables are affected by thermal comfort, particularly for variables like radiant temperature, ambient temperature, air velocity, humidity and clothing. Hence, there is a need for the indoor environment to be maintained within a specific range of temperature and humidity levels to achieve thermal comfort. Both heat loss and gain process can be prevented during winter and summer, respectively, by proper insulation [10, 11]. A comfortable home temperature can be maintained using heating and cooling systems in an entire year [4]. Also, there is a significant relation between IEQ and the amount of energy used in buildings because the operation of lighting, HVAC, and other systems in buildings are required to keep indoor conditions at an acceptable level. Therefore, it is essential to exercise control over IEQ to determine whether or not the reduction in energy consumption has a negative impact on comfort conditions [12]. According to the Environmental Protection Agency [13], poor indoor air quality could cause various health challenges such as allergies, headaches and respiratory issues. Thus, there is a need for building to be designed with proper ventilation, pollutant and filtration control to ensure quality indoor condition.

However, managing thermal comfort in multi-zone areas of buildings in real time can be difficult due to a variety of factors. For instance, different zones within a building may have varying occupancy levels and various activities occurring at the same time. As a result, maintaining a consistent thermal environment that meets everyone's comfort preferences is difficult. Moreover, individuals may have varying comfort preferences, which can be influenced by factors such as age, gender, clothing, and health conditions. Managing a multi-zone environment that caters to a wide range of preferences is a difficult task.

Hence, this study aims to fill this gap by providing a thorough overview of thermal and air comfort in structures constructed with alternative materials. The objective is to identify trends in the field, describe its current state, highlight optimization techniques, and propose a new direction for future research.

1.1 Outline of the review article

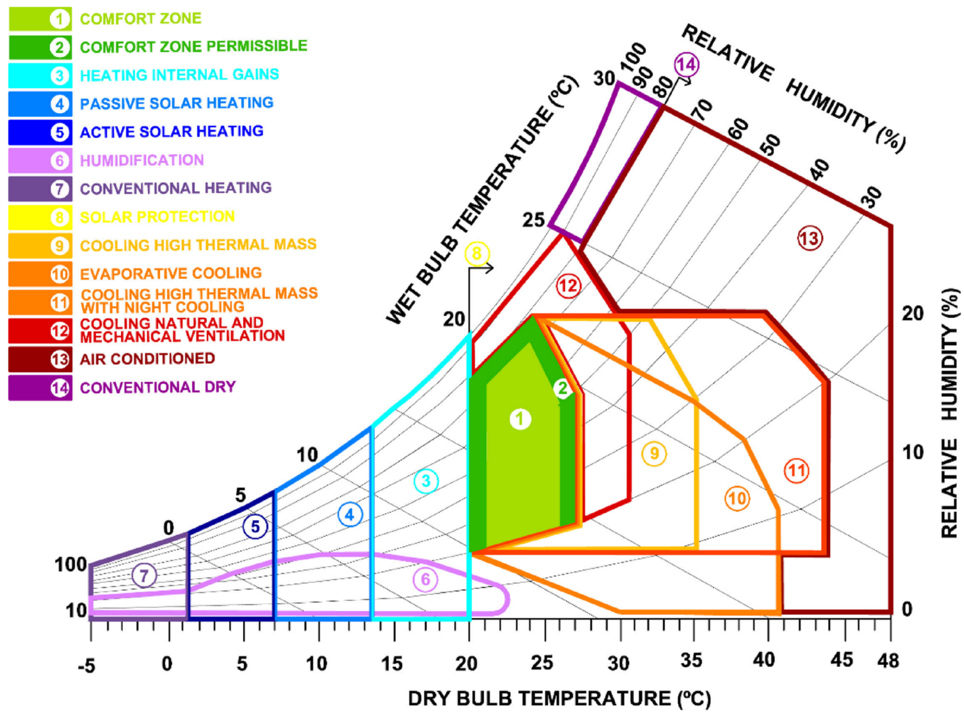
The study focuses on alternative Building Materials and addressing how indoor comfort parameters may be affected. The review paper seeks to offer a thorough investigation of the ways in which alternative building materials affect these metrics. To start, we present the idea of alternative building materials and highlight the role that indoor comfort parameters play in improving the well-being of occupants. After that, the paper goes into great detail to examine a number of indoor comfort characteristics, such as indoor air quality and thermal comfort.

With the above keywords, we ran thorough searches in a few databases to make sure everything aligned with the topic of our assessment. Several publications in journals, conference proceedings and books were reviewed. Also, citation analysis techniques were utilised to identify influential works and highly referenced articles within the discipline. The study also integrate the most recent research findings into our review by keeping up with new publications in reputable outlets.

2 Thermal and air considerations for indoor comfort

A complete strategy including thermal, air, and material concerns is needed to achieve indoor comfort. Adequate ventilation and air circulation are essential for promoting excellent indoor air quality, in addition to maintaining a tolerable temperature and humidity range [14]. Notably, the variables that affect air permeability and thermal insulation in this equation are construction materials. Adopting pollution control methods and putting filtration systems into place improve indoor air quality while reducing discomfort. The Givoni-adapted psychrometric chart, which shows suggested ranges for several factors crucial to thermal comfort, is explained in Fig. 1. It is critical to understand how the effectiveness of ventilation, indoor air quality, thermal comfort, and building materials affect the quality of life. Thus, an appropriate connection or consideration on the factor improves human health and emphasizes how they foster a healthier interior environment.

Fig. 1 Psychrometric chart adapted from Givoni [15, 16]



2.1 Thermal comfort indices and models for buildings

The Predicted Percentage of Dissatisfaction (PPD) and Predicted Mean Vote (PMV) are the two commonly considered indices for thermal comfort assessment in buildings. According to [4], these indices are part of the ASHRAE thermal comfort model, and are widely used in building design and the operation of HVAC (Heating, Ventilation, and Air Conditioning) systems. The predicted average response of a group of people to a thermal environment is represented by PMV, which is a numerical index. It uses a seven-point scale that ranges from – 3 (cold) to + 3 (hot) or in details as + 3, + 2, + 1 and 0 represent hot, warm, slightly warm and neutral, respectively, and, – 1, – 2 and – 3 represent slightly cool, cool, and cold, respectively[17]. A mathematical model is used to calculate PMV, which takes into account factors such as air temperature, radiant temperature, air velocity, humidity, and clothing insulation. A PMV value close to zero indicates a thermal environment in which the majority of people would be at ease. A positive value is a representation for a cool atmosphere, and a heated environment is indicated by negative values. However, PPD is a supplementary metric to PMV, which shows the anticipated proportion of individuals who would be unhappy with the thermal environment. The PMV departure from the ideal comfort level, which is often set to 0, is used to compute PPD. It shows the proportion of residents who are probably going to be unhappy with the temperature. For example, tenant population satisfaction is higher when PPD values are lower. The model for PMV is given by ISO 7730 as

$$\begin{aligned} PMV &= [0.303\exp(-0.036M) + 0.028] \times (M - W)3.05 \times 10^{-3}[(5733 - 6.99(M - W) - P_a] \\ &\quad - 0.42[(M - W) - 58.15] - 1.7 \times 10^{-5}M(5867 - P_a) - 0.0014M(34 - t_a) - 3.96 \\ &\quad \times 10^{-8}f_{cl}\left[(t_{cl} + 274)^4 - (t_{rm} + 274)^4\right] - f_{cl}h_c(t_{cl} - t_a) \end{aligned} \tag{1}$$

where, PMV = Predicted Mean Vote, M = metabolic rate (W/m^2), t_a = air temperature (°C), f_{cl} = clothing surface area factor, h_c = convective heat transfer coefficient (W/m^{2}K), t_{rm} = mean radiant temperature (°C), p_a = water vapour partial pressure (Pa), t_{cl} = clothing surface temperature (°C), and W = effective mechanical power (W/m^2);

However, PPD is given as

$$PPD = 100 - 95\exp(-0.03353PMV^4 - 0.2179PMV^2) \tag{2}$$

In general, a lower PMV value is associated with greater thermal comfort. PPD is frequently used in conjunction with PMV to account for differences in comfort preferences. A PMV close to zero, for example, may have a low PPD, indicating that a large proportion of occupants are likely to find the conditions satisfactory. Also, individual preferences for thermal comfort can differ, and these indices are models that attempt to predict the average response of a group. Various standards and guidelines, such as ASHRAE Standard 55 [4], specify acceptable thermal comfort ranges and criteria in various settings. These indices are used by designers and HVAC engineers to optimise building conditions for occupant comfort while taking energy efficiency and operational constraints into account.

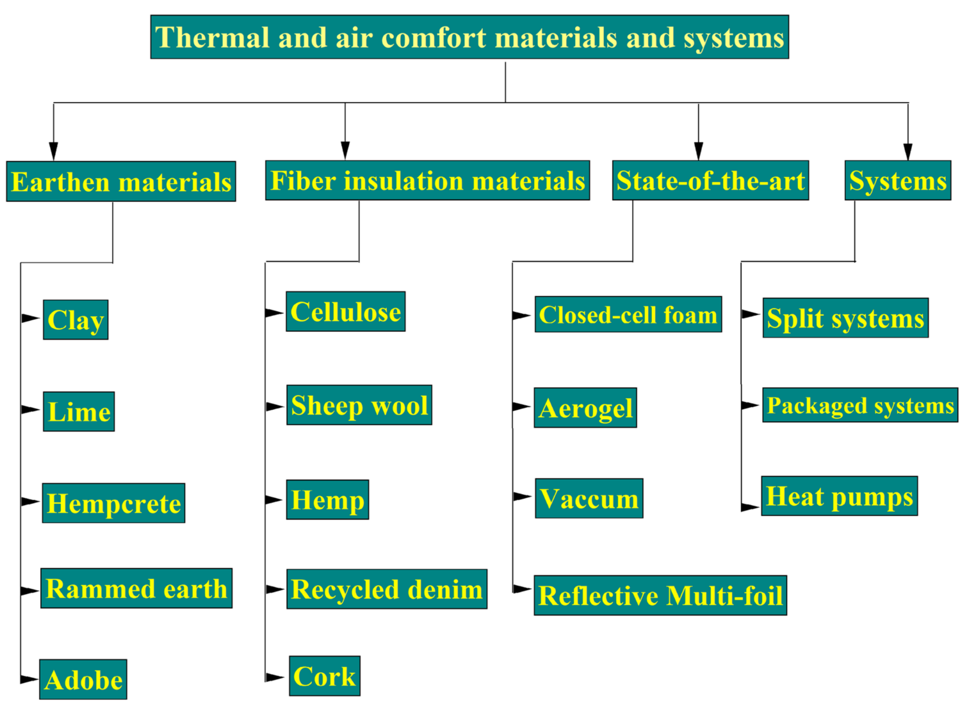
3 Conventional materials and systems for indoor air and thermal comfort

The widely accepted and commonly used options for thermal insulation and maintaining indoor air quality are the conventional materials and methods. Several research works have focused on materials and methods in buildings over time, demonstrating proven performance and reliability of the materials. They are considered industry standards and are typically readily available in the market. In general, four categories of materials and systems used regulating air and thermal comforts in buildings may be distinguished based on their origin, chemical makeup, availability, and unit scale. Figure 2 shows the various materials and systems that have been used for air and thermal comfort. These categories are not mutually exclusive, and many buildings use a combination of strategies and materials in order to conserve energy and provide the best possible thermal comforts.

3.1 Earthen materials in indoor comfort

The potential of earthen materials to make buildings' interiors more comfortable is huge [18]. Earthen materials have thermal mass, a main advantage it has over other materials, which allows them to store, absorb, and release heat, providing stable indoor temperatures and a more comfortable living environment. The earthen materials, in addition, exhibit excellent insulation properties [19], which is good for regulating heat exchange via walls and roofs [20]. Thus, indoor temperatures can be well maintained with the insulation, thereby minimize cost on energy, or cooling/mechanical heating. Also, the indoor humidity level can be regulated when earthen materials absorbs and release moisture to the external environment [21]. Mold's growth in earthen materials are minimized as it does not permit excessive moisture, thereby making the interior environment more healthier and comfortable. Additionally, the ability of clay materials to absorb and retain allergens and pollutants improves indoor air quality and lowers the risk of respiratory health issues. They further enhance indoor comfort by absorbing noise, creating a calmer atmosphere.

Fig. 2 Classification of air and thermal comfort materials and systems



CO_2 can be absorbed in a house by several earthen materials, this includes lime, clay, hempcrete, adobe and rammed earth [22]. The earthen materials exhibit several characteristics which affect their CO_2 absorption capacity. Earthen materials 'composition (presence of amounts of minerals and organic matter) and porosity are the key characteristics which influence their performance [23]. The moisture content of earthen materials is another important characteristic that affects the presence of microorganisms that aid carbon sequestation. Furthermore, because stable carbon compounds can form over time, the age of earthen materials might affect their capacity to sequester carbon.

Earthen materials 'properties are influenced by several factors such as raw materials used, The source and quality of the raw materials used to create earthen materials, compaction and curing processes, pore size and distribution. Clay has high moisture level and, consequently, their capacity to absorb CO_2 can also be influenced by environmental variables such as temperature and humidity. The potential of earthen buildings to sequester carbon can also be impacted by their design and construction. Factors such as the internal space placement, structural system, and shading devices used affects the porosity, moisture content, and water absorption of earthen materials. Moreover, other factors such as economic and sociocultural factors influence the design and construction of earthen buildings, and subsequently affect their carbon storage ability. Table 1 lists the factors that affect earthen materials' ability to lower CO_2 emissions and enhance thermal comfort.

3.2 Fibre insulation materials in indoor comfort

A building's envelope must have materials for thermal insulation since they stop heat loss and guarantee thermal comfort for its occupants [28–31]. Usually, the thermal conductivity of a material used for insulation determines how effective it is, also it is a measure of how well it can resist heat transfer. In order to retain the same internal temperature, a thinner layer is needed for materials with lower thermal conductivity values since they are more effective insulators. Conventional materials for insulation such as cellulose insulation, sheep wool insulation, hemp insulation, recycled denim insulation, and cork insulation, had a relatively low environmental impact, particularly with relation to consumption of energy and emissions of greenhouse gases [32]. However, the majority of these materials come from non-renewable resources, and their high embodied energy means that it takes a lot of energy to make them. This has stoked interest in investigating alternate insulating materials made from recycled or renewable fibres. As prospective substitutes for mineral insulating materials, natural fibres including jute, flax, and hemp have showed promise. Some researchers have demonstrated the potential applications of coconut fiber, as well as agricultural fibers derived from tomato, bean, and pea pods [33–35]. Natural fibres exhibit limitations when exposed to acidic attacks or high alkaline media. As a result, the fibers disintegrate, which may result in less insulation and structural stability [36, 37]. There are research works that explored various methods of pretreating these natural fibres or applying protective coatings to mitigate their vulnerability in harsh environments o address these challenges, [38–42]. The process of coating or pre-treating the fibers helps to enhance their resilience to alkaline or acidic media, thus allowing their suitability as long-lasting and efficient materials for building insulation. Natural fibre's full potential as sustainable alternatives to mineral insulation materials can be fully harnessed through the efforts. As a result, numerous research projects are investigating their suitability for building insulation. By exploring and utilizing these alternative materials, building insulation may be less harmful to the environment while yet providing the required levels of thermal comfort. Table 2 provides a summary of the sustainability of all the different alternative materials. [43–45].

4 Benefits and challenges of conventional materials in meeting relevant indoor comfort considerations

4.1 Benefits associated with conventional materials for indoor comfort

The conventional construction materials have been used for centuries, and they possess several benefits that make them relevant for meeting indoor comfort requirements. The heat storage and absorption in conventional materials such as concrete, brick, and stone exhibit high thermal mass. Consequently, there is balance in indoor temperature regulation of warmness and coolness during the winter and summer, respectively. Thermal mass can greatly reduce indoor temperature fluctuations and improve thermal comfort, according to research [50–52]. Traditional construction materials such as plaster, wood, and gypsum board improve indoor acoustic comfort by dampening sound absorbing. Also, it has been shown by studies that materials with high sound absorption coefficients can significantly reduce noise levels

Table 1 Factors affecting aspects and features of earthen materials to reduce CO_2 and improve thermal comfort

S. No	Parameter	Features of parameters	Factors influencing parameters	References
1	Porosity	Surface area and porous structure	Size and distribution of pores, as well as the compaction and curing of earthen materials	[24]
2	Moisture content	Presence of microorganisms that facilitate carbon sequestration	Environmental factors including humidity and temperature	[25]
3	Composition	Minerals and organic matter	Source and quality of raw materials	[26, 27]
4	Age	Formation of stable carbon compounds over time	Exposure to environmental conditions, maintenance, and repair	[27]

Table 2 Summary of various alternative materials sustainability

Material	Source	References	Thermal conductivity (W/mK)	Global warming potential (kg CO_2-eq/kg)	Demand of water (L/kg)
Cellulose insulation	Recycled newspaper	[44]	0.032–0.04	0.04–0.25	1.1–1.7
Sheep's wool insulation	Sheep wool	[46]	0.034–0.04	0.11–0.23	0.15–0.45
Hemp insulation	Fibres from hemp plant	[47]	0.04–0.05	0.15–0.34	0.2–0.5
Recycled denim insulation	Denim fabric from old jeans	[48]	0.039–0.044	0.10–0.14	0.3–0.5
Cork insulation	Bark of the cork oak tree	[49]	0.032–0.04	0.10–0.24	0.3–1.5

and improve speech intelligibility [53, 54]. Moreover, the conventional materials such as clay natural stone, and wood do not emit harmful toxins or volatile organic compounds (VOCs) that may affect quality of indoor air. Several health challenges such as respiratory issues and headaches may arise due to a persistent exposure to high levels of VOC [55]. Other materials such as brick, stone, and concrete are conventional materials that are extremely durable and resistant to extreme weather, insects, and other environmental factors. This can help ensure the long-term performance of a building, reducing maintenance costs and ensuring the comfort of its occupants [56]. All things considered, traditional materials have a track record of improving indoor comfort and health. While newer, innovative materials can also offer benefits, it's important to consider the advantages of traditional building materials when designing and constructing buildings.

4.2 Challenges associated with conventional materials for indoor comfort

Conventional materials such as concrete, steel, and glass have been widely used in the construction of buildings. However, they have certain disbenefits or challenges when it comes to meeting relevant indoor comfort considerations. Common materials like concrete and steel are great heat conductors because of their high thermal conductivity. They can therefore lead to considerable heat absorption in the summer and loss in the winter, making it difficult to maintain a comfortable indoor temperature. This may lead to higher heating and cooling energy costs as well as unsustainable environmental effects. There is inadequate thermal resistance with the conventional materials, as they do not exhibit sufficient insulation. The single-pane glass windows, for instance, exhibit low insulation properties, resulting to significant heat loss. Uncomfortable indoor temperatures, temperature swings, and drafts can result from inadequate insulation. Generally, concrete and steel are not effective sound-isolating materials. This can result in exterior noise pollution, which can be a major cause of discomfort for those living in buildings. Similarly, sound transmission between rooms and floors within a building can be disruptive and bothersome. There is negative impact from conventional materials on indoor air quality. This is common with materials such as carpets, furniture, and paints, which can release volatile organic compounds (VOCs), and potentially may lead to poor indoor air quality and occupants discomfort. Also, an inadequate building ventilation can result in stagnant air that potentially results to poor health condition. The conventional materials are environmentally unsustainable. They may not be recyclable or biodegradable, which results in substantial waste and environmental damage, and their manufacture and transportation increase carbon emissions. Despite the numerous benefits (affordability, strength and durability) associated with the conventional materials, they are deficient in indoor comfort requirements. Newer, more sustainable materials with better insulation, soundproofing, and air quality properties may be better suited to meet the evolving needs of modern buildings.

4.3 Sustainability of conventional indoor comfort materials

The efficiency of the system, the energy source, the manufacturing method, and the material utilised to make standard products for indoor comfort can all have a significant impact on their sustainability. It is essential to consider the materials' embodied energy, their end-of-life disposal, and their overall impact on carbon emissions and energy usage. The conventional indoor comfort tools such as windows and HVAC systems, have varying degrees of sustainability in terms of their reusability, carbon emissions, energy usage, and recyclability.

Materials such as mineral wool, foam, fibre glass and cellulose are commonly used for insulation [57]. Cellulose is made from recycled newspaper and can also be recycled. Foam insulation, on the other hand, is typically made from petroleum-based products and is not easily recyclable. The energy required to make, transport, and install insulation is included in the embodied energy of insulating materials, which is an important factor to take into account.

Depending on the type of system, the energy source used, and the system's efficiency, the sustainability of HVAC systems can vary significantly. Traditional HVAC systems that use fossil fuels, such as natural gas or oil, have a high carbon footprint and contribute to climate change. Energy-efficient HVAC systems, such as those with high Seasonal Energy Efficiency Ratios (SEER), can significantly reduce energy usage and associated carbon emissions. Additionally, windows are essential for thermal comfort since they minimize heat loss while letting in natural light and warmth.

4.4 Sustainability gaps in the utilizations of conventional indoor comfort materials

Several gaps in sustainability are associated with the utilization of conventional materials for building's air and thermal comfort. Several of the conventional materials used for insulation and other building components have limited recyclability, which can contribute to waste and increase environmental impacts. The manufacturing, transportation, and installation of conventional building materials can result in significant carbon emissions. The production of cement, which is required to create concrete for building foundations, releases a significant amount of carbon dioxide. The International Energy Agency found that the building industry is responsible for about 30% of the world's carbon emissions [2]. Materials such as low-carbon concrete can potentially lower emissions in buildings. The conventional building materials may not always be designed with energy efficiency in mind, which can result in higher energy usage and associated carbon emissions. The older windows may not be well-sealed and may allow air to escape, resulting in higher heating and cooling costs. The US Department of Energy research revealed that single-pane windows switching out for Energy Star-rated ones yielded significant savings in annual energy costs for homeowners [2]. Generally lasting 15 to 30 years, asphalt shingle roofs may require more frequent replacements than other roofing materials like slate or metal. Some insulation materials may contain formaldehyde, which can cause respiratory irritation and other health problems. Using sustainable alternatives, such as low-VOC insulation or natural materials, may help reduce these health concerns. Finally, Recognizing these sustainability gaps is crucial in order to provide the required upgrades and potentially environmentally suitable substitutes. Sustainable alternatives and greater research and development may help address these gaps and improve the sustainability of building materials and practices.

5 Alternative materials utilized for indoor comfort based on recent studies

The use of alternative building materials is a potential means of increasing indoor comfort, thus by lowering energy, improving insulation, appealing interior space, and fostering a more hospitable and. The beneficial effects of alternative materials on energy use and thermal insulation are compiled in Table 3, and Fig. 3 illustrates the several ways that alternative materials are used in building construction to improve air and thermal comfort. The subsequent discussion explores the impact of various alternative materials on the thermal performance and energy consumption.

An extremely porous, lightweight substance known as aerogel makes a great insulator, helping to maintain a comfortable indoor temperature. Aerogel insulation can reduce thermal energy consumption by up to 40% [58]. Another material is PCM, which is good at absorbing and releasing heat, thus helping to regulate indoor temperature. Bio-based PCMs are often utilized as thermal and air comfort materials. They are derived from renewable resources and offer sustainable alternatives. Materials such vegetable oil derivatives, bio-based polymers, and cellulose-based PCMs are potentially sustainable. These materials show promise in applications such as building insulation and thermal energy storage. Incorporating PCMs into building envelopes is capable of minimizing consumption of energy by 44% [59–61].

Plant-based materials like hempcrete, mycelium, and corkcrete are renewable, have low environmental impact, and provide good insulation. They can also be used to create a unique and modern indoor aesthetic. Materials such as bamboo, cork, rice husk, and hemp can serve as good alternative to the conventional materials. These materials are renewable, biodegradable, and have low embodied energy, making them environmentally friendly choices [62–67]. Vegetation covers green roofs, which can act as insulation and lessen the amount of heat that enters the structure. By adding a layer of insulation on the roof's surface and collecting and evaporating solar radiation, they effectively reduce heat input. According to [68], Up to 5 °C can be saved inside thanks to green roofs, depending on the type of vegetation, thickness, and moisture content of the soil.

High-performance windows can reduce heat loss and gain, helping to maintain a comfortable indoor temperature. Using high-performance windows can reduce energy consumption by up to 35% [69, 70]. The principles of operation of

Table 3 A description of how alternative materials are used in building construction

Reference	Type of alternative material	Evaluation method	Application scenarios	Thickness	U-value (W/m^2 K) without alternative material	U-value (W/m^{2}K) with alternative material	Energy demand reduction, %	Location
[73]	Aeropan (aerogel-based product containing silica 40–55%, PET/glass fibre 20%-45% and additives 0%-15%)	Simulations	Internal and external insulation	10 mm	1.498	0.749	20.18 to 29,73% reduction in heating energy	Madrid, Spain
[74]	Aerogel based coating (plaster)	Real time application	Internal wall	12 mm	≈1.22 (march)	≈ 0.9 (march)	–	Turin, Italy
[75]	aerogel based rendering	Real time application	Facade	6 cm	1	0.30	–	Berlin, Germany
[76]	aerogel based rendering	Real time application	Outer wall	5–6 cm	1.37 to 0.96	0.40 to 0.35	–	Sissach/Switzerland
[77]	Aerogel Plaster	Real time measurement at laboratory	Inner wall	5 mm	2.14	1.73		Italy
[78]	Green roof	Real time application		0.150 m	0.241	0.190		Ancona, Italy
[79]	Green roof (peanut and sedum)	Real time application	With and without thermal insulation	0.100 m			Up to 45%	Hong Kong
[80]	Green roof	Real time application	Well insulated		0.26–0.4	0.24–0.34	2%	Athens, Greece
			Moderately insulated		0.74–0.80	0.55–0.59	3–7%	
			Non insulated		7.76–18.18	1.73–1.99	31–44%	
[81]	Green roof	simulations		Up to 30 cm			31.6	Athens, Greece
							5.97	La Rochelle, France
							8.17	Stockholm, Sweden
[82]	Green roof	simulations	Green roof with up to 20 cm insulation		≈0.38 to 0.41	≈0.35	11.89 to 15.45%	Greece
[83]	Hempcrete	simulations	Exterior wall	310			37.6% reduction in cooling energy	Toronto, Canada
[84]	PCM	Pilot scale at cubical	Wall and roof				55.33 to 58.33	
[85]	High energy-efficient windows with silica aerogel	Simulation	Windows containing aerogel, with aluminium and wood frame	4 mm	2.7–1.6 (only windows)	(1.1–1)	≈36 to ≈15% in heating energy	Paris, France
[86]	low-E windows	Simulation	Double and triple glazed windows with low-E coating		2.309 (only window)	1.780 to 0.688(only window)	Up to 65.5% in heating energy	Berlin, Germany

Fig. 3 Various alternative materials in building construction **a** Hemepcrete [87]; **b** aerogel rendering [88]; **c** green roof [89]; **d** phase changing materials (PCM) [84]

various smart windows and window types are shown in Fig. 4. Coatings for photocatalysis that frequently incorporate titanium dioxide (TiO2), have been investigated for their ability to improve indoor air quality. When exposed to light, these coatings have the ability to convert harmful pollutants like nitrogen oxides (NOx) and volatile organic compounds (VOCs) into less harmful ones. They can be used to maintain a healthier indoor atmosphere on surfaces like walls, tiles, and furniture [71, 72].

5.1 Thermal ability of alternative materials

Conductivity and volumetric heat capacity are two essential thermal characteristics of earthen and insulating materials. Insulation materials should have a lower thermal conductivity than frequently used construction materials to provide reduced heat transfer through building envelopes. High thermal mass materials can postpone and reduce indoor peak temperature by bringing indoor and outdoor temperatures into close proximity and lowering the danger of summer overheating. The ability of a material to store thermal energy is measured by its volumetric heat capacity. Figure 5 classifies insulators according to their volumetric heat capacity and thermal conductivity, with the most sophisticated insulators exhibiting the lowest thermal conductivity. Earthen insulation materials such as clay, sand,

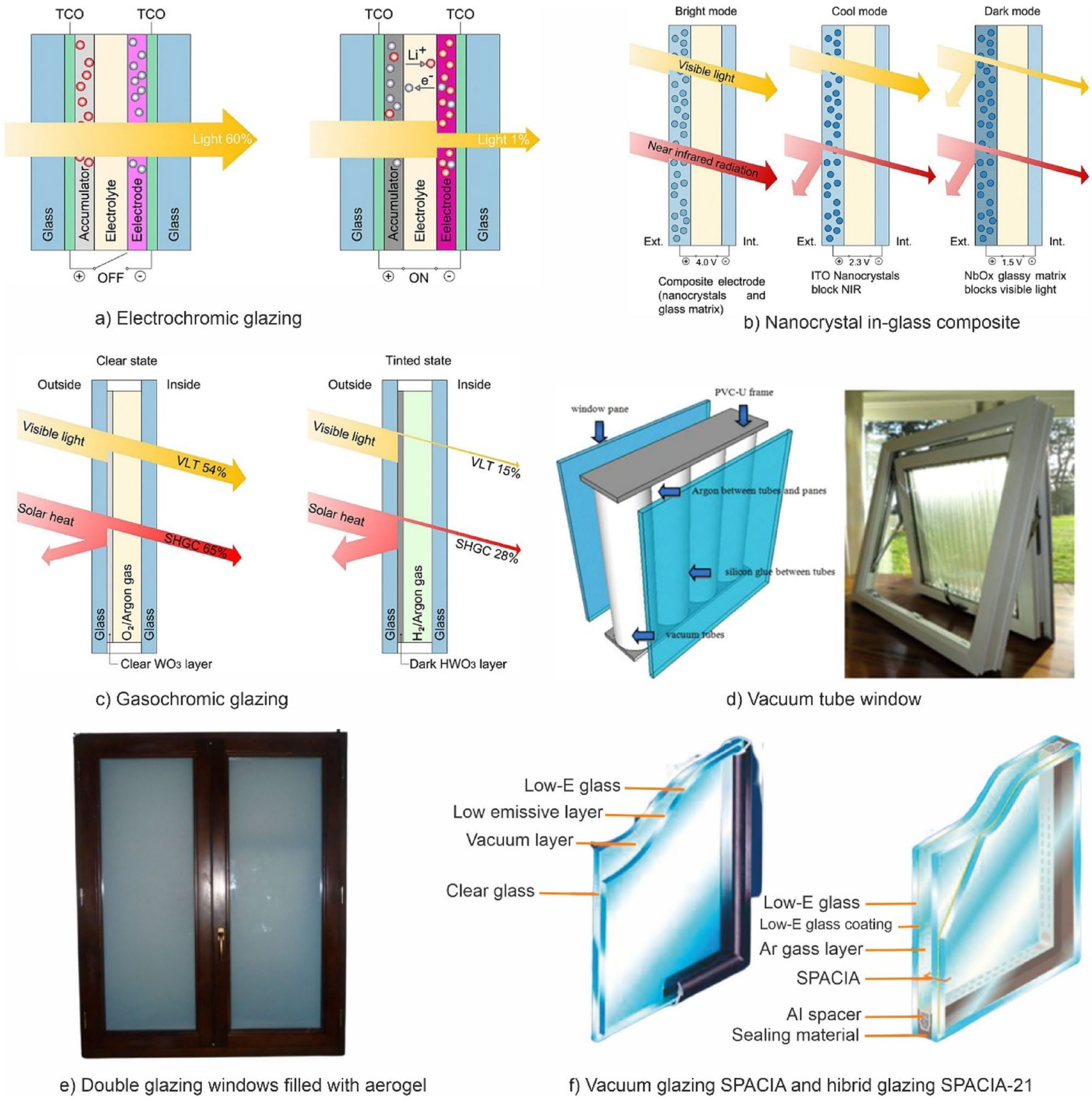


Fig. 4 Different type of thermal insulating windows **a** electrochromic glazing [90]; **b** nanocrystal glazing [90]; **c** gasochromic glazing [90]; **d** vacuum glazing [91]; **e** aerogel filled glazing [85]; **f** SPACIA [91]

and soil, have low thermal conductivity (0.1–0.8 W/mK) that effectively reduces heat flow through building components, but their low volumetric heat capacity (1.0–2.5 MJ/m^{3}K) leads to inefficient storage and slow heat release, potentially affecting indoor temperatures [92]. In contrast, fibre insulation materials made from compressed fibres or particles of materials such as glass, rock, or plant fibres exhibit higher thermal conductivity (0.03–0.08 W/mK) that improves heat flow reduction and higher volumetric heat capacity (1.5–2.5 MJ/m^{3}K) that enables efficient storage and slow heat release, helping to maintain comfortable indoor temperatures [93]. However, the particular application, the required degree of thermal insulation, the cost, and the availability of materials all influence the choice of insulating material [94]. Aerogel, for instance, shows low thermal conductivity, and it enables thinner walls with saving more floor space and insulation.

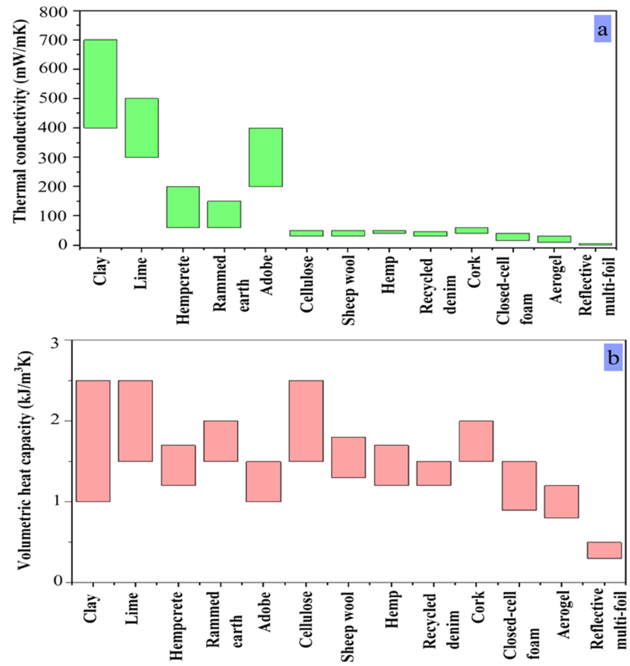


Fig. 5 **a** Thermal conductivity of various alternative materials [28, 94, 95], **b** Volumetric heat capacity of various materials [28, 95, 96]

5.2 Effectiveness of alternative materials in indoor comfort considerations

The relevant indoor comfort requirements can be achieved with alternative materials that give sustainable and energy-efficient solutions, and improve reduce heat loss and thermal insulation and maintain a comfortable indoor temperature. This can be achieved by using materials such as phase change materials (PCMs), green roofs, insulating plant based materials, hygroscopic materials, high performance windows, photocatalytic coatings and smart air conditioning systems.

5.2.1 Thermal insulation criteria

By absorbing and releasing thermal energy during phase transitions, phase change materials (PCMs) are efficient temperature regulators for indoor environments. To enhance thermal insulation and lower energy use, they can be added to construction materials like gypsum boards, cement and plaster [97]. As reported by Kuznik et al. [98], PCM-based materials can reduce energy consumption for cooling by up to 25% and heating by up to 50%. Sharshir et al. [99] presented an overview of the use of PCM in buildings and reported that the incorporation of PCM with bubble injection can reduce temperature penetration by up to 28%. They also reported that integrating PCM into building construction can lower indoor temperatures by approximately 2.80 °C during the melting and solidification hours. Similarly, Figueiredo et al. [97] observed a decrease of 4 °C in indoor temperature in rooms integrated with PCM. They also reported that integrating PCM reduced thermal comfort by 2.61% during the heating season and by 7.23% during the cooling season.

Green roofs help to minimise heat gain by providing a layer of insulation on the roof surface, and by absorbing and evaporating solar radiation. Depending on the type of plant, soil moisture levels, and thickness, green roofs can lower indoor temperatures by up to 5 °C [68]. This may result in less energy being used for cooling, which can be up to 50% in the summer. The authors [68, 100, 101] studied the thermal insulation of green roofs with substrate thicknesses of 10 cm and 20 cm in comparison. According to the study, energy consumption dropped by 31% and 37%, while heat transfer decreased by 59% and 96% compared to a conventional roof. According to Saadatian et al.[102], green roof installation might minimize need for cooling system by 32–100%, reduce roof surface temperatures by 30–60 °C, and block up to 60% of solar radiation.

The use of insulating materials that minimises heat loss through roofs and walls, and preserve a pleasant interior temperature include cellulose, mineral wool, and expanded polystyrene (EPS). According to Aditiya et al. [103], up to 64% less energy is needed to heat a space when insulating materials are used. Also, by minimising the intrusion of outdoor air, insulating materials and systems can also enhance the quality of the air inside buildings [104]. New-generation thermal insulation materials exhibit significant potential in enhancing building thermal comfort, even with thinner layers compared to conventional insulation. According to a study [105], the application of a 6 cm aerogel render can reduce the U-value by 70%, while a 5/10 cm aerogel render layer can lower heat losses by 80–90%.

In addition, the size and style of windows have a big impact on a building's thermal comfort. Furthermore, the type of window has a significant impact on its thermal performance [106]. New generation windows, such as those equipped with vacuum glazing and improved U-values, are potentially capable of reducing the energy consumption of buildings. Hee et al. [106] observed a remarkable 63% improvement in the U-value by incorporating aerogel-filled windows. Feng et al. [107] reported that use of gasochromic smart windows can lower the HVAC loads by up to 30%. Aliakbari et al. [108] also observed decrease of 3.64% in annual energy consumption by the use nano insulation in windows.

5.2.2 Indoor air quality

Indoor air comfort can be achieved with alternative materials which is effective for relevant indoor comfort considerations and improving indoor air quality, reducing energy consumption, and enhancing thermal comfort. Some examples of materials in this category are hygroscopic materials, purifying plants, high-performance windows, smart air conditioning systems, and photocatalytic coatings.

The quality of indoor air can be improved and interior contaminants can be eliminated with the help of air purifying plants. According to Wolverton and Bill [109], up to 87% of indoor air contaminants, including formaldehyde, trichloroethylene, and benzene, can be eliminated by purifying plants. Air purifying plants can also enhance thermal comfort by reducing the need for mechanical ventilation systems, and by increasing humidity levels [9, 110].

There is a unique ability in hygroscopic materials such absorption and moisture release from the surrounding air, thus helping to maintain indoor humidity. By maintaining optimal humidity levels, these materials contribute to thermal comfort and inhibit the growth of mold and mildew, thus enhancing indoor air quality. These materials systems can reduce energy consumption for cooling by up to 30%, and for heating by up to 5% [111, 112].

High-performance windows are equipped with advanced glazing technologies that reduce heat transfer, minimize air leakage, and offer better insulation. By keeping the indoor temperature stable and reducing the need for heating or cooling, these windows help lower energy consumption and create a more comfortable indoor environment [69, 70].

Applied to surfaces like windows or walls, photocatalytic coatings are made to degrade dangerous pollutants in the presence of light. These coatings employ a photocatalyst, usually titanium dioxide, to start a chemical reaction that turns pollutants into innocuous chemicals, such as nitrogen oxides and volatile organic compounds. This helps improve indoor air quality by actively reducing pollutants in the air [113, 114].

By modulating cooling and heating based on occupancy and ambient circumstances, smart air conditioning systems are successful at increasing thermal comfort and minimising energy usage. According to [115], smart air conditioning systems can reduce energy consumption for cooling by more than 45%, and for heating by up to 30%. Smart air conditioning systems are capable of improving the indoor air quality by controlling humidity levels and reducing the possible risk of mold growth [116]. Table 4 summarizes of the potential benefits of alternative materials/systems for thermal and air comfort in buildings.

These alternative materials/systems for air comfort in indoor buildings are effective in meeting relevant indoor comfort considerations by reducing energy consumption, improving indoor air quality, and enhancing thermal comfort. By incorporating materials/systems building owners can promote a healthier and more comfortable indoor environment, while also reducing energy consumption and promoting sustainability.

5.3 Sustainability of alternative materials for indoor comfort

5.3.1 Carbon emissions

Alternative materials are potentially sustainable for ensuring thermal comfort in buildings, and varies in terms of their carbon emissions, depending on the technologies and specific materials used.

Table 4 Summary of the potential benefits of alternative materials/systems for thermal and air comfort in buildings

Alternative Materials	Percentage Reduction in Energy Consumption (Cooling)	Percentage Reduction in Energy Consumption (Heating)	Temperature Reduction (in °C)	Percentage Reduction in Indoor Pollutant Concentrations	References
PCMs (gypsum boards, cement, and plaster)	Up to 25%	Up to 50%			[59, 98]
Green roofs	3% to 50%	Up to 45%	Up to 5 °C (depending on the type of vegetation, thickness, and moisture content of the soil)		[68, 100, 117]
Plant based materials (hemp, rice, husk, cork, bamboo)		41.8% to 61.87% with respect to the perimeter wall and ranges from 82.64% to 91.47% with respect to internal partitions	Up to 6 °C (for warmer room conditions)	35% to 75%	[9, 118, 119]
Hygroscopic materials (earth brick, hemp brick, clay plaster and wood)	Up to 30% (in a HVAC controlled environment)	Up to 5% (in a HVAC controlled environment)			[111, 112]
High performance windows	Up to 47%				[69, 70]
Photocatalytic coatings	Up to 30%	Up to 54%	Up to 4.3 °C (for inner surface temperature)		[113, 114]
Smart air conditioning systems	More than 45%	Up to 30%			[115]

The air purifying plants and natural ventilation systems are typically regarded as low-carbon systems and are sustainable solutions for boosting thermal comfort and indoor air quality. The energy consumption and carbon emissions associated with mechanical ventilation and air conditioning systems can be reduced through the use of natural ventilation systems and air purifying plants [9, 109, 110]. On the other hand, smart air conditioning systems that are powered by electricity may have a higher carbon footprint, depending on the source of the electricity used. Also, employing renewable energy sources, such solar or wind power, to power smart air conditioning systems can lower the carbon emissions [115, 116, 120]. Moreover, both the energy design and building envelope needed for heating or cooling may be reduced by the use of designed insulating materials. Factors such as the material's lifespan, production method and disposal methods can have different influence on the sustainability of insulation materials. A building's carbon emission and energy use can be minimized by 50% using passive cooling methods and natural ventilation than in traditional air conditioning systems [121, 122]. Studies [15, 111, 123] have shown that natural ventilation and passive cooling systems can help to create a more comfortable indoor environment by reducing the risk of sick building syndrome and improving indoor air quality. On the other hand, if they are driven by electricity derived from fossil fuels, some alternative materials and technologies for indoor air comfort, such air purifiers and mechanical ventilation systems, may have a higher carbon footprint. In such cases, the carbon emissions associated with these systems can be reduced by using renewable energy sources, such as solar or wind power, to power the systems ([116, 124].

5.3.2 Energy usage

The energy consumption of thermal comfort alternative materials (AMs) employed in structures can be used to assess their sustainability. The energy-saving passive design techniques like high-performance glass, optimising building orientation, and adding shading devices can lower the amount of energy needed for heating and cooling [122]. The use of air conditioning and heating systems can be decreased by minimizing heat gain in the summer and heat loss in the winter, which can be achieved by using passive design features such insulation and high thermal mass materials [125–127] revealed that the indoor thermal comfort can be maintained in building by utilizing natural ventilation for its benefits of maintaining the ambient temperature and humidity conditions. Another study by [128] showed that daylighting could improve the indoor environment by supplying natural light and boosting occupant well-being, which can reduce the need for artificial lighting. In some AMs, the energy consumption rate may be higher for thermal comfort, particularly for cooling and heating. [124] in their study, observed that by combining renewable energy sources like solar and geothermal, lowers energy demand and carbon footprint. Other studies [115, 116, 120] have shown that passive design techniques, natural ventilation, daylighting, and renewable energy sources can offer sustainable options for preserving indoor comfort while lowering energy usage, which is another factor in the to be considered for sustainability. Also, the sustainability of AMs varies based on the various factors such as the material's properties, the building design, and the climate of the region. In addition, [58, 62, 65, 129] revealed that the materials exhibit the potential to reduce energy consumption by providing better ventilation, insulation, and thermal comfort.

Cross-laminated timber (CLT), a sustainable and renewable building material formed from layers of wood panels, is one example of such a substance. CLT has a reduced embodied energy and carbon footprint than conventional building materials such as steel and concrete, as revealed by [130] in a study on the operational heating and cooling energy consumption of office buildings in China. The excellent insulating qualities and less thermal bridging of CLT in buildings can save up to 30% more energy than conventional buildings [130].

Another potential materials is the Phase change materials (PCMs). They exhibit potential to both absorb and release thermal energy, as they transform from solid to liquid or vice versa. [131] revealed that the use of PCM in building envelopes can cut heating and cooling energy consumption by up to 50% by reducing temperature swings inside the building, according to a research done on a Beijing office room. Moreover, factors such as material melting point, latent heat capacity, and structural location and orientation were highlighted by the study as aiding PCM's effectiveness.

In addition, green roofs are also a sustainable material, which can aid in lowering building energy use. Green roofs, which are covered in plants, can improve air quality, offer insulation, and lessen the effects of urban heat islands. The annual energy consumption can be reduced with green roofs by up to 45% and 46% for cooling and, respectively, in a building by reducing heat transfer through the roof and improving the building's thermal comfort, depending on the level of insulation, according to a study to assess the potential of green roofs on a nursery school in Greece

[117]. Overall, alternative materials for air comfort in buildings can be sustainable in terms of their energy usage, but their effectiveness depends on various factors, such as the material's properties, the building design, and the climate of the region.

5.3.3 Recyclability

The material and the recycling method are two factors that can be influence the recyclability of alternative materials for air comfort. Some materials are highly recyclable and can be reused in a variety of construction applications, whereas others may have limited recycling options. In general, recyclable materials that are renewable, biodegradable, or comprised of recycled materials are more sustainable. Insulation made from recycled paper and cardboard is an example of a material that is both recyclable and environmentally friendly. A study conducted by the U.S. US Environmental Protection Agency (EPA) revealed that cellulose insulation exhibit high recycling potential, thus making up to 75% of the material to be recoverable for reuse [30]. Cellulose insulation also has a low embodied energy compared to other insulation materials, further increasing its sustainability [30].

Another example is recycled materials such as recycled steel, which can be used for building structures and HVAC systems [132, 133]. The initial and ongoing embodied phases of the case building, where virgin materials were used, accounted for 39.1% of the structure's life cycle energy use and 28.1% of its life cycle greenhouse gas emissions, according to a study to determine how the use of recycled materials instead of virgin materials affects the installation of renewable energy systems for the energy transition of buildings. Due to the usage of recycled materials, the total embodied energy and greenhouse gas emissions were reduced by 12.2% and 11.7%, respectively. As a result, the case building's life cycle energy use and greenhouse gas emissions reduced by 4.9% and 3.3%, respectively, when recycled materials were employed in place of virgin materials. This suggests that employing recycled materials may aid in energy conservation in buildings [132].

Natural ventilation systems, which rely on natural air flows and passive cooling techniques to provide air comfort in buildings, are highly sustainable in terms of recyclability. Ventilation and cooling are provided by these systems without any mechanical components or materials, but only rely on natural forces such as wind and temperature differentials. As a result, natural ventilation systems have no end-of-life disposal issues and are highly recyclable.

Some common alternative materials include natural fibers, recycled materials, and biodegradable materials. One example of a sustainable alternative material for thermal comfort in buildings is wool insulation. Both sources produce waste that is notably different in terms of both its properties and volume. Manufacturing waste has a defined composition and is frequently reintroduced into its manufacturing process, making it cleaner. By using this technique instead of coke, the cost of raw materials can be reduced. Additionally, a recent study examined the melting behaviour of fresh raw materials and used rock wool, coming to the conclusion that using differential scanning calorimetry (DSC) to remelt used rock wool is 23% more energy-efficient [134].

Similarly, a comparative analysis of different insulation materials suggests that cellulose insulation, along with hemp exhibit better environmental impact. They are considered more environmentally friendly compared to non-renewable solutions such as XPS and PUR. While materials like EPS, stone wool, and glass wool are also environmentally preferable, they are slightly less impact-full than cellulose and hemp.

5.3.4 Reusability

Alternative materials for thermal comfort in buildings are becoming increasingly popular as a means of reducing energy consumption and environmental impact. However, the materials sustainability depends on their reusability, among other factors. Wool is a typical insulation material, which is natural and renewable material.

PCMs, materials that can store and release heat energy, can also aid the temperature regulation in buildings. PCMs can be made from a variety of materials, including paraffin wax, salt hydrates, and fatty acids. The reusability of PCMs depends on the specific material used. For instance, paraffin wax phase change materials (PCMs) can be repeatedly re-solidified without impairing their capacity to store heat, whereas salt hydrate phase change materials (PCMs) can degrade over time and lose their capacity to do so [135]. Hence, PCM's reusabilityvaries depending on the material used.

Plant-based air filters are a sustainable alternative to traditional synthetic air filters. They are made from natural materials, such as coconut fibers, and can be composted at the end of their lifespan. Plant-based air filters can also be cleaned and reused, reducing waste and the need for frequent replacements. A study found that plant-based air filters can remove up to 90% of particulate matter from the air [136]. Also, electrostatic air filters draw and collect airborne particles using an electric charge. They may be cleaned and re-used numerous times, which minimises waste and the requirement for constant replacement. In addition, electrostatic air filters use less energy than conventional air filters, making them a more environmentally friendly choice [137].

There is also geothermal heating and cooling that utilizes constant temperature from the earth to warm and cool buildings. They are a more environmentally friendly alternative to conventional heating and cooling systems because they consume less energy and produce fewer emissions than conventional systems. In addition, geothermal systems have a lifespan of several decades and require very little maintenance, which makes them an investment that is both long-term and sustainable [138].

Water is used in evaporative cooling systems to cool the air within a building. Due to their lower energy consumption and emissions, they are a sustainable substitute for conventional air conditioning systems. In addition, evaporative cooling systems outlive conventional air conditioning systems and require less maintenance [139]. Since these materials can be cleaned and reused, less waste and frequent replacements are required, making them extremely sustainable. Because they consume less energy and emit fewer emissions than conventional heating and cooling systems, geothermal and evaporative cooling systems are also sustainable substitutes.

6 Conclusions

This study explores how alternative building materials and HVAC affect the indoor comfort in a building and its parameters. Conclusions drawn from the study are presented as follow:

- Generally, achieving indoor comfort requires taking into account both thermal and air variables. The interdependence between factors such as the thermal comfort, ideal ventilation, and indoor air quality contribute to improved human health.
- The capacity of structures made of earth to store carbon depends on how they are designed and constructed. For instance, temperature and humidity are two environmental variables that can affect the moisture content of clay materials and, consequently, their capacity to absorb CO_2.
- Traditional insulating materials like cork, cellulose, hemp, recycled denim and sheep wool have a very small environmental impact, notably in terms of energy consumption and greenhouse gas emissions. However, the production of these materials frequently requires a large amount of energy due to their high embodied energy and dependence on non-renewable resources.

7 Possible recommendations for future studies

There is still a need for further research and development to fully understand the potential and effective utilizations of alternative materials and their impacts on the indoor comfort in buildings. The current review recommends some issues for future studies and utilization of alternative materials for indoor comfort, which are as follows:

(a) Future studies can include life-cycle assessments of alternative materials to fully understand their environmental impacts, considering the production and transportation to disposal. Life-cycle assessments can help identify areas for improvement and provide a basis for comparison between different materials.
(b) The energy consumption of buildings made of alternative materials can be modelled, and their effects on indoor comfort can be assessed, by further investigations by using building energy simulation. As a result, it wil be possible to locate potential problems with the materials and improve their application in various cases. Building energy simulation can also be used to determine the cost- and energy-effectiveness of various materials.
(c) Future studies can also include cost-effectiveness analysis of alternative materials. With this, it will be possible to identify materials exhibiting much sustainability benefits. Such analysis will not only consider the upfront material costs but also the long-term costs of operating and maintaining buildings with these materials.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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