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# Sustainable Building Materials for Energy-Efficient Building Development – A Review

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## Abstract

Construction is one of the greatest consumers of raw materials and energy in the world hence sustainability is a key priority in the contemporary building development. With continued increase in the carbon emission globally, there has been a need to incorporate energy saving and environmentally conscious materials in curbing the effects of the buildings on their life-cycle. The transition is supported by sustainable building materials which reduce embodied energy, enhance thermal performance and permit more resource-efficient constructions. These resources can broadly be categorized into four primary groups, which are bio-based materials like bamboo, hempcrete, and engineered timber, recycled and low-carbon materials, such as reclaimed steel, recycled concrete aggregate, and polymer composites, high-performance insulation materials, and energy-generating/energy-saving materials, such as building-integrated photovoltaics, phase-change materials, and cool roofing technologies. Collectively, these innovations result in a considerable decrease in the operational energy demand alongside the advancement of the principles of the circular economy in the construction supply chain. Nevertheless, sustainable materials are not widely used due to cost constraints, government regulations, lack of technical expertise, and the discrepancy of the supply-chain across different regions of the world. Nonetheless, research and global sustainability models are focused on the fact that the large-scale expansion of sustainable material use is the most important in the long-term climate objectives, resilient infrastructure, and a low-carbon built environment.

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## 1. Introduction

The construction industry is undergoing a swift transformation as the aspect of sustainability takes center stage as a measure aimed at minimizing emissions, depletion of resources and the long term effects of the environment. Constructions occupy much of worldwide energy consumption and carbon emissions, so the material choice is essential in the promotion of energy-efficient constructions (Abera, 2024). Traditional building materials still popular (concrete, bricks, steel, etc.) are linked to high embodied energy and intensive extraction operations, which promote environmental degradation, as noted in investigations of low-carbon transitions (Ramakrishna et al., 2021). Consequently, sustainable building materials have become a vital issue in enhancing the thermal performance, minimal operational energy requirement, and global climate goals.

These materials are essentially recycled and reclaimed materials, as well as natural and bio-based materials such as bamboo, hempcrete, and engineered timber, which have significant environmental advantages over traditional ones (Asghari and Memari, 2024). The possibilities of sustainable design continue to develop with the introduction of new high-performance insulation and energy-generating technologies like the building-integrated photovoltaics (Kuhn et al., 2020). Nevertheless, the cost issues, gaps in policies, and lack of awareness of the industry among people still hinder widespread implementation even though positive outcomes have been demonstrated (Mewomo et al., 2023). This knowledge of these opportunities and constraints is critical towards the directing future of building development that is energy efficient.

## 2. Sustainable Building Materials: Concept and Definitions

### 2.1 Definition of Sustainable Materials

Sustainable building materials are those products which are designed, sourced, and used in a manner that reduces the environmental damage and improves the long term building performance. Such materials generally impress lower embodied carbon, less resource extraction and a better circle than conventional products and are aligned with the global objectives of eco-efficiency (Abera, 2024). They are natural, recycled, renewable and technologically enhanced materials which are specifically designed to minimize the environmental burdens throughout the life cycle of an entire building.

### 2.2 Criteria for Sustainability

Sustainability in materials choice is determined by three primary criteria, which are, low embodied energy, less pollution during production, and maximum durability and end-of-life recyclability. The following criteria serve the aspects of strategy of circular economy that will focus on the resource recovery and reduction of raw material dependency, which is one of the principles of research on critical raw material management (Karali & Shah, 2022). Other sustainability criteria include thermal performance and operational energy savings, which are increasingly being incorporated in modern buildings that are being equipped with insulation, composites, and bio-based materials with enhanced levels of efficiency.

### 2.3 Role of Buildings in Global Energy Use

The building industry has a significant role in the worldwide energy usage by making up significant proportions of operational and embodied energy demand. Materials, as the analysis of life cycles of residential buildings demonstrates, have a major environmental implication, which further supports the necessity to transition to low-carbon options (Dascalaki et al., 2021). Sustainable materials hence continue to be central in the realization of the energy-efficient development and minimization of the long-term environmental footprints.

## 3. Traditional and Greener Materials

### 3.1 Environmental Impacts of Conventional Materials

Traditional building materials like concrete, fired bricks and virgin steel prevail in the world of building and yet their use is related to high ecological effects. Their manufacturing procedures emit embodied carbs in large quantities, use a lot of natural resources, and lead to long-term emissions, which are captured in the analyses on the low-carbon material pathways (Ramakrishna et al., 2021). Besides, traditional materials can hardly be recycles, and extraction and production can put an enormous strain on the ecosystem, causing pollution, and exhausting rare resources. These restrictions accentuate the need to find alternative material systems that will cause less energy consumption at the manufacturing as well as functioning stages of structures.

### 3.2 Advantages of Sustainable Alternatives

The benefits of sustainable materials are enormous since they help to reduce the environmental impact and enhance the performance of buildings. The alternatives like reuse of concrete aggregate material and reuse of reclaimed steel can be used to minimize the waste streams and introduce construction circularity, which is highlighted in systematic reviews of reclaimed steel reuse (Bartsch, 2025). Bio-based materials, such as bamboo, hempcrete, and engineered timber, also offer additional opportunities to carbon sequestration and reduced processing energy (Asghari and Memari, 2024). Moreover, the use of superior insulation systems and energy-generating technologies, including BIPV, enhance thermal performance and minimise the use of operational energy (Kuhn et al., 2020). These alternatives collectively facilitate long term sustainability, resiliency, and environmentally-friendly development making them essential substitutes to traditional building products.

## 4. Types of Sustainable Building Materials

### 4.1 Low-Carbon & Recycled Materials

The most effective measures in reducing the embodied energy in building construction are the use of low-carbon and recycled materials which reuse the existing resources and also restrict the amount of virgin materials extracted. Recycled concrete aggregate (RCA), reclaimed steel and recycled plastics are some of the main examples which have been studied extensively in terms of their environmental advantages and performance capability. This decrease in carbon emissions of recycled materials correlates with the global approach of the circular economy to the minimum amount of waste and the maximum amount of resources recovery (Karali and

Shah, 2022). Not only do these materials decrease landfill pressure, but also facilitate low-energy production methods as opposed to the conventional options.

#### 4.1.1 Recycled Concrete Aggregate (RCA)

RCA comes about through crushing of demolished concrete and using it as an aggregate in new mixes. In the existing studies, it is demonstrated that RCA can be used to obtain similar structural performance in the case of appropriate use, but its mechanical characteristics differ depending on the material of origin (Lapyote Prasittisopin et al., 2025). This renders RCA as a significant alternative to natural aggregates, especially where there is no structure or moderately loaded.

#### 4.1.2 Reclaimed Steel

Steel is very much recyclable and the reclaimed steel elements will greatly decrease the embodied emissions since they do not undergo smelting process that requires a lot of energy. A systematic review points out that the reclaimed steel does not lose a bit of its structural integrity and provides huge benefits in terms of carbon savings but issues of certification and differences in sizes are present (Bartsch, 2025).

#### 4.1.3 Recycled Composites and Plastics

Recycled plastics composites have been increasingly receiving attention because of the developments in polymer engineering, as they enhance strength and durability. They are being used in decking, in panels, in railway sleepers, and show a high degree of resistance to moisture and corrosion (Esmaeili et al., 2023). These composite materials provide a lightweight, durable and low-maintenance choice that can fit in the contemporary sustainable construction.

### 4.2 Biological and Natural Materials

Bio-based materials are products of renewable natural resources with such benefits as low embodied carbon, biodegradability, and high thermal performance. The storage of atmospheric carbon in them makes them especially efficient in climate-positive construction strategies. The recent fascination with bamboo, timber, hempcrete, and straw bale indicates the transition in the global movement toward building systems that are resource-efficient and regenerative (Abera, 2024). The materials also increase the indoor environmental quality as they are composed of natural materials and emit low chemical levels.

#### 4.2.1 Bamboo

Bamboo is a renewable material, which has the best tensile and compressive properties and is a fast growing plant. According to the latest reviews, properly bonded bamboo-based composites have outstanding structural stability, which is why they can be used as flooring, wall panels, and engineered products (Nkeuwa et al., 2022). Its ability to renew fast, and its ability to store carbon are its better-case scenario as a sustainable material.

#### 4.2.2 Timber & Cross-Laminated Timber (CLT)

Timber and CLT are becoming a more popular choice in mid- and high-rise construction following the innovation in engineered wood technologies. CLT panels have good strengthweight ratios and positive thermal characteristics. It is also observed in the recent research on polymer materials that bio-based polymers applied in timber processing contribute to its durability and resistance to fire (Cywar et al., 2021). This renders timber as a low-carbon substitution of concrete and steel.

#### 4.2.3 Hempcrete

Hempcrete is a type of lightweight breathable walling material made of hemp fibres mixed with lime. It has been found to have excellent insulation properties and positive moisture control with lower mechanical strength than traditional masonry (Asghari and Memari, 2024). It is most applicable in non-load bearing walls and sustainable housing.

#### 4.2.4 Straw Bale

Straw bale construction has a high insulation performance and low embodied energy. The structural analysis shows that load-bearing walls on straw bales can be successfully used in case they are plastered and reinforced appropriately (Peng et al., 2021). It is a good contender as affordable housing that is energy efficient because it is cheap and accessible.

### 4.3 High-Performance Insulation Materials

Insulation materials that are of high performance are essential in minimizing the energy that is used in buildings in terms of operation. Aerogels, cellulose insulation, and wool have high thermal resistance and can be used in supporting sustainability objectives. Such materials simplify the inside comfort with reduced heating and cooling requirements, and they are carbon-neutral of the global goals (Li et al., 2022).

#### 4.3.1 Aerogels

Aerogels are very light materials, and they are highly thermal conductive, which makes them the best choices on the facades and high performance envelopes. They have much higher levels of insulation than conventional materials.

#### 4.3.2 Wool & Cellulose Insulation

Natural materials that are good in buffering moisture are sheep wool and cellulose insulation. They are less embodying carbon, and they perform well thermally, which is why they are useful in cold and temperate climate areas. Environmental sustainability is also improved because of their biodegradability.

### 4.4 Materials that produce energy and use less energy

Net-zero buildings are supported by energy-generating and energy-saving materials. These are building-integrated photovoltaics (BIPV) systems, cool roof systems and phase-change systems. These technologies reduce the level of operational energy and increase envelope performance (Torchyniuk et al., 2024).

#### 4.4.1 BIPV

BIPV also incorporates the use of photovoltaic modules into the walls or roofs and operates as an energy generator and a building envelope element (Kuhn et al., 2020).

#### 4.4.2 Cool Roofing

Cool roofs reflect solar rays and lower the heat gain indoors and cooling loads.

#### 4.4.3 Phase-Change Materials (PCMs)

PCMs capture and emit thermal energy that regulates the temperature indoors and enhances comfort (Huang et al., 2021).

## 5. Selection of Materials in energy efficient buildings

The choice of the right materials plays a major role in enhancing the performance of the building and minimising overall energy use in the modern building. The type of materials used will have direct impacts on heating and cooling demand which constitutes a significant portion of energy expenditure within the operations of most climates. According to research on sustainable construction, the choice of materials is an important element that can help achieve the desired outcomes in terms of energy-efficiency goals (Abera, 2024), especially when one takes into account thermal resistance and the life-cycle aspects.

### 5.1 Thermal Performance

The thermal performance indicates how a material can resist heat transfer and thus, influence the comfort of an indoor and loads to HVAC. Research indicates that when used in walls and envelope assemblies, cellulose, aerogel, and hempcrete offer high thermal stability, which means that it is not relying on mechanical technologies (Li et al., 2022).

### 5.2 Embodied Energy & Life-cycle Assessment

Embodied energy comprises of extraction, manufacturing, transport, and disposal impacts. Life-cycle assessments show that the use of recycled aggregates and bio-based materials can substantially reduce carbon emissions in lieu of traditional concrete and steel, which is in line with the approach to circular resources (Dascalaki et al., 2021).

### 5.3 Durability and End of Life

Recycleable materials like reclaimed steel and engineered timber minimize frequency of replacement and generation of wastes. The fact that they can be recycled at the end of their lives supplements natural materials such as bamboo, which biodegrades with minimal environmental impact (Nkeuwa et al., 2022).

### 5.4 Cost–Benefit Evaluation

Sustainable materials become economical in terms of long-term savings in operations and cost of maintaining the equipment, but initial costs might be higher. New materials are being studied with high financial returns in place of constructing lifetimes (Mogaji et al., 2024) when the energy costs are taken into account.

## 6. Sustainable Materials Case Studies

International architecture projects are used to showcase the benefits of sustainable material use in enhancing performance and minimizing emissions as a large scale application. There is case evidence that material innovation can directly contribute to the outcome of energy-efficient buildings (Abera, 2024), especially in climates with a high heating or cooling load.

### 6.1 Passive House Standards (Europe)

European Passive House structures combine high-performance insulation and airtight envelopes in order to minimize the amount of heating by up to 90 percent. Both residential and commercial projects have relied on aerogel and cellulose insulation to meet these goals (Li et al., 2022).

### 6.2 Bamboo Applications (Asia)

Engineered bamboo composite finds extensive application in Southeast Asia in structural and non-structural applications. Their tensile strength and quick renewability is sustainable to buildings as demonstrated in composite bonding research (Nkeuwa et al., 2022) in schools and community buildings.

### 6.3 Hempcrete Walls (UK)

The case studies in the UK have shown that the hempcrete is effective in terms of moisture control and thermal comfort. It has low density which combines with insulation performance that makes it suitable to use in eco-housing although it has a limited structural capacity (Asghari and Memari, 2024) to non-load-bearing purposes.

### 6.4 CLT High-Rise Buildings (Japan/Canada)

Several mid-rise and high rise buildings in Japan and Canada have been built with the use of cross-laminated timber. The advantage of these structures is the use of engineered polymers that allow increasing the durability (Cywar et al., 2021) instead of high-carbon steel and concrete.

### 6.5 Solar-integrated buildings (UAE)

BIPV is becoming more predominantly utilized in the UAE in the facades of buildings and the roofs. Such systems reduce energy requirements (cooling) by producing electricity on-site (Kuhn et al., 2020), which promotes the national renewable energy targets.

## 7. The Problems and Obstacles to Adoption

Mass adoption of sustainable materials has several barriers that are interrelated, which restricts the widespread use of sustainable materials in the global construction markets. Among the challenges which have been mentioned most of the time is the increased initial price of sustainable options, a factor which puts off developers with short budgets. Research indicates that novel or bio-based substances can be difficult to process or sometimes need imported materials, which raises upfront costs (Mewomo et al., 2023) though over time will lead to cost savings.

### 7.1 High Initial Cost

Initial expenses on hempcrete, engineered timber, BIPV and hi-tech insulation systems are still more expensive than normal ones.

### 7.2 Unawareness and Competent Workforce

Numerous contractors have not been trained in installation methods of bamboo composites, hempcrete or CLT. It has been identified that a lack of technical knowledge has been slowing adoption (Mogaji et al., 2024) and perceived risk.

### 7.3 Policy & Regulatory Gaps

The building codes in several areas are old and do not appreciate the use of other materials. This brings about delays in approval and deterrence of innovation.

### 7.4 Material Availability & Supply Chain

Recycled plastics, bio-polymers and natural fibres have supply limitations. The literature of circularity research proves that the lack of consistency in supply chains impedes low-carbon transformations (Karali & Shah, 2022).

### 7.5 Climate and Technical Limitations

Certain natural materials demand adaptation to climatic conditions; e.g. straw bales must be left in dry places, whereas timber buildings depend on humidity conditions. Structural use of hempcrete is also limited by mechanical limitations of hempcrete determined in reviews (Asghari and Memari, 2024).

## 8. International Policies and Sustainability Plans

The global policies and sustainability frameworks are vital in hastening the use of sustainable building materials. LEED, BREEAM, and Green Star can also be used as examples of the certification that puts low-carbon materials, life-cycle optimisation, and high-performance envelopes as their priorities, impacting the choice of materials on the largest markets (Abera, 2024). The systems encourage performance-based design through the use of recycled aggregates, timber, natural insulation, and renewable energy technologies.

### 8.1 LEED, BREEAM, Green Star

These rating systems encourage carbon embodied reduction, circularity, and energy-efficient materials with compulsory credits.

### 8.2 UN SDG 11 & SDG 12

SDG 11 focuses on sustainable cities, SDG 12 is concerned with responsible consumption. Their objectives are in line with bio-based and recyclable material consumption (Steinhäuser et al., 2022).

### 8.3 National Regulations (USA, EU, India, UAE)

GRIHA rating system in India and the Green Deal of the EU stimulate materials with a lifecycle, and the UAE is encouraging BIPV and low-carbon building codes to lower cooling loads (Kuhn et al., 2020).

## 9. Discussion

The literature demonstrates that sustainable materials highly influence a decrease in embodied carbon, enhancement in thermal performance, and a circular construction. The real-life application is, however, workable under the assumption of financial feasibility, regulatory support in addition to supply-chain readiness. The fact that bamboo, CLT, hempcrete, and energy-generating system have been successfully implemented in the case studies in Europe, Asia, and the Middle East is a positive sign of a massive potential of going global (Abera, 2024). However, due to the numerous challenges, such as the high price, the lack of awareness, and the unsuccessful regulation, the transition processes are slowed down (Mewomo et al., 2023). These limitations should be addressed in an effort to make sure that sustainable materials will be employed to serve the purpose of a full contribution towards developing low-carbon and energy-efficient buildings.

## 10. Recommendations

### 10.1 For Policymakers

The governments are advised to revise building regulations in order to incorporate sustainable materials, offer financial support to the low-carbon materials, and reinforce national testing and certification.

### 10.2 For Construction Firms

Companies are advised to implement life cycle costing, recycle aggregates and natural insulation, and invest in training of employees on new material technologies.

### 10.3 For Architects/Engineers

The designers need to consider using CLT, bamboo composites, and hempcrete at the initial design stage and focus on passive solutions with high-performance building envelopes.

### 10.4 For Manufacturers

The manufacturers are required to increase the supply chains of natural fibres, intensify standardisation, and come up with hybrid bio-based and recycled composites.

## 11. Conclusion

Sustainable building materials are critical in minimizing environmental effects, enhancing thermal performance and promoting energy-efficiency at the global level. Recycled, bio-based, high-performance insulation and renewable energy systems have shown evidence showing definite benefits over traditional materials. Despite the obstacles of cost, lack of awareness and regulatory loopholes, current studies and international policy frameworks are contributing to the speed up of adoption. The wider adoption will require concerted efforts of governments, industry practitioners, and manufacturers to enhance the supply chains and better standards. Sustainable materials will be able to greatly accelerate the development of low-carbon, resilient, and energy-saving buildings in the world as long as the innovation continues and the regulation is favorable.

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