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## GREEN BUILDING MATERIALS AND ENVIRONMENTAL PERFORMANCE

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### **Abstract**

*The environmental performance of buildings is strongly influenced by the materials selected for structural systems, envelopes, finishes, services, and maintenance activities. Conventional materials can require substantial extraction of raw resources, energy-intensive processing, long-distance transport, and repeated replacement during a building's service life. Green building materials offer an alternative approach by seeking to reduce these burdens while maintaining safety, durability, functionality, indoor environmental quality, and economic feasibility. Their value is not limited to low operational energy use; it also depends on embodied carbon, resource efficiency, toxicity, water demand, recyclability, local availability, and the capacity of a material to support long-term building performance.*

*This study examines the relationship between green building materials and environmental performance from a life-cycle and sustainable construction perspective. It considers materials such as supplementary cementitious binders, recycled aggregates, responsibly sourced timber, bamboo, compressed earth blocks, low-emission insulation, recycled metals, reclaimed products, and bio-based finishes. Attention is given to the way material choices affect carbon emissions, energy demand, water use, construction waste, thermal comfort, indoor air quality, maintenance requirements, and end-of-life recovery. The study also recognizes that no material is inherently sustainable in every context. Environmental outcomes vary according to product composition, local climate, transport distance, design detailing, construction quality, building use, maintenance practices, and disposal or reuse pathways.*

*The paper adopts a descriptive, analytical, and comparative approach based on published research, environmental product information, building-assessment frameworks, technical standards, and documented sustainable construction practices. It evaluates material options according to their capacity to lower environmental impacts across the building life cycle while meeting performance requirements. The analysis indicates that the strongest outcomes result from integrated decisions that reduce material demand, extend service life, use low-impact and locally appropriate products, minimize waste, and plan for disassembly, reuse, or recycling. Green building materials can therefore improve environmental performance most effectively when they are selected as part of a whole-building strategy rather than as isolated products.*

**Keywords:** *Green building materials; Environmental performance; Embodied carbon; Sustainable construction; Life-cycle assessment; Resource efficiency; Low-carbon materials; Circular economy; Indoor environmental quality; Building sustainability*

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### **1. INTRODUCTION**

Buildings shape environmental conditions throughout their life cycle. Materials are extracted from land and ecosystems, processed into products, transported to construction sites, installed in buildings,

maintained or replaced during use, and eventually demolished, reused, or discarded. Each stage can generate greenhouse-gas emissions, consume water and energy, create waste, contribute to pollution, and affect the health and

comfort of occupants. For many new buildings, operational energy remains important, but the relative importance of embodied impacts becomes more visible as building energy systems become more efficient. This makes material selection a central issue in the transition toward a low-carbon and resource-efficient built environment.

Green building materials are generally understood as products and assemblies that reduce environmental burdens while supporting required technical performance. They may contain recycled or renewable content, require less processing energy, have lower emissions, improve insulation or moisture control, emit fewer harmful chemicals, use responsibly managed resources, or permit recovery at the end of service life. However, the term should not be treated as a simple label. A product can have recycled content but a short service life, a low-carbon production process but high transport impacts, or a natural origin but inadequate durability in a humid or termite-prone climate. Sound decisions therefore require an assessment of environmental performance together with structural safety, durability, fire resistance, maintenance, cost, availability, and social suitability.

The construction sector is also affected by rapid urbanization, housing demand, infrastructure expansion, and the need to retrofit existing building stock. These pressures can increase demand for cement, steel, glass, aluminum, plastics, aggregates, timber, insulation, and finishing materials. Where material extraction and production are poorly managed, the result may include depletion of natural resources, dust and water pollution, habitat disturbance, high energy consumption, and a growing volume of construction and demolition waste. Green material strategies seek to address these impacts through efficient design, optimized quantities, substitution with

lower-impact products, reuse of existing elements, local sourcing, and circular procurement practices.

Environmental performance must be considered at the whole-building scale. A low-impact wall material may not improve overall performance if it is paired with inefficient glazing, excessive concrete use, poor orientation, unnecessary finishes, or building services that require high energy during operation. Similarly, a durable and repairable material can provide a lower life-cycle impact than a product with a lower initial footprint that needs frequent replacement. Designers, engineers, developers, manufacturers, and public authorities therefore need practical methods for comparing alternatives and documenting environmental claims.

This paper focuses on green building materials and environmental performance, examining the major categories of sustainable materials, the criteria used to evaluate them, and the conditions that support credible adoption. The discussion emphasizes life-cycle thinking, climate-responsive design, material efficiency, circularity, health protection, and transparent performance data. It argues that material decisions should connect environmental responsibility with technical reliability and long-term value for building users and communities.

## **2. LITERATURE REVIEW**

Research on sustainable construction increasingly treats buildings as material systems rather than only as energy-consuming assets. Earlier green-building approaches often emphasized operational efficiency through better lighting, air-conditioning systems, renewable energy, and building controls. Recent literature shows that the environmental impacts embedded in materials can represent a substantial share of a building's total life-cycle impacts, especially in highly efficient new buildings. This shift has encouraged wider use of life-cycle

assessment, environmental product declarations, whole-life carbon assessment, material passports, and circular-design principles.

Life-cycle assessment provides a structured method for examining environmental impacts from raw-material extraction to manufacturing, transport, construction, operation, maintenance, refurbishment, demolition, and end-of-life treatment. It helps compare products using indicators such as global warming potential, energy demand, water use, acidification, eutrophication, resource depletion, and waste generation. However, results depend on the boundaries, data quality, service-life assumptions, transport scenarios, electricity mix, allocation methods, and end-of-life assumptions used in the study. For this reason, literature cautions against relying on a single environmental indicator or a generic product claim without considering local conditions.

A major theme in the literature concerns the reduction of high-impact conventional materials. Cement and steel are widely used because of their strength, durability, availability, and predictable performance, but their production can be energy- and emission-intensive. Researchers have examined blended cements, calcined clays, industrial by-products, recycled aggregates, optimized structural systems, high-strength materials used in smaller quantities, modular construction, and reuse of structural elements as ways to reduce impacts. These approaches must still satisfy design codes, quality-control requirements, and durability needs under local exposure conditions.

Bio-based and earth-based materials are another focus of research. Timber, bamboo, agricultural residues, cellulose insulation, cork, hemp-based products, and earth blocks can reduce reliance on virgin mineral resources when sourced and processed responsibly. Their

environmental advantages depend on sustainable land management, product treatment, moisture protection, fire performance, transport, and the ability to keep biogenic carbon stored over an appropriate period. The literature also highlights the importance of avoiding simplistic assumptions that all renewable materials are automatically low-impact or that all local materials are environmentally superior without accounting for production practices and performance.

Research on indoor environmental quality has broadened material assessment beyond carbon and energy. Paints, adhesives, sealants, composite boards, flooring, insulation, and cleaning products can release volatile organic compounds or other pollutants that affect occupant comfort and health. Low-emission products, careful ventilation design, moisture management, and verified product information are therefore important parts of green-material selection. This perspective is particularly relevant in schools, healthcare facilities, workplaces, and housing where occupants spend long periods indoors.

The literature also emphasizes market and governance barriers. Sustainable materials may face higher initial prices, limited supply chains, lack of skilled installers, insufficient testing facilities, unclear standards, conservative procurement practices, and unreliable environmental claims. Public procurement, building codes, green-rating systems, training programs, local manufacturing support, and digital material databases can help reduce these barriers. Adoption is most effective when environmental criteria are introduced together with quality assurance, performance testing, maintenance guidance, and transparent documentation.

## **2.1 GREEN BUILDING MATERIALS AND LIFE-CYCLE THINKING**

Green building materials are assessed not only by what they are made from but also

by how they perform across time. A material with low manufacturing emissions may have poor value if it fails early, creates high maintenance demands, or cannot be repaired. Conversely, a durable product with a moderately higher initial impact can be favorable when it reduces replacements, protects other building components, and remains recoverable at the end of use. Life-cycle thinking therefore connects production impacts with design life, exposure conditions, maintenance frequency, adaptability, and end-of-life scenarios.

Material efficiency is an important first principle. Reducing unnecessary floor area, avoiding overdesign, coordinating building services, selecting appropriate spans, using standardized components, and designing for future adaptability can lower environmental impacts before substitution is considered. Reuse of existing buildings, foundations, structural elements, doors, bricks, fixtures, and finishes can further avoid the impacts associated with new production. Where new products are necessary, specifications can prioritize lower-carbon binders, recycled inputs, certified renewable resources, low-emission finishes, and products supported by reliable environmental data.

The appropriate material palette varies by climate and building type. In hot climates, thermal mass, shading, reflective roofs, ventilated assemblies, and locally suitable wall systems can reduce cooling demand. In cold climates, insulation continuity, airtightness, moisture-safe detailing, and durable weather protection are central. Coastal, humid, seismic, fire-prone, and high-pollution environments require additional consideration of corrosion, moisture, biological decay, structural movement, and resilience. A green material must therefore be selected for its fit within an assembly and local exposure context rather than through an isolated product comparison.

## 2.2 ENVIRONMENTAL PERFORMANCE AND BUILDING ASSESSMENT

Environmental performance is commonly assessed using several connected indicators. Embodied carbon estimates greenhouse-gas emissions associated with materials and construction processes. Resource efficiency examines the use of virgin inputs, recycled content, renewable feedstocks, and material intensity. Water indicators consider extraction, manufacturing, and on-site consumption. Pollution indicators examine emissions to air, water, and soil, while health-related indicators consider chemical emissions, moisture risk, and indoor air quality. Circularity indicators address disassembly, reuse, repair, recyclability, and the ability to avoid landfill disposal.

Whole-building assessment avoids the risk of shifting impacts from one category to another. For example, lightweight materials may reduce structural demand and transport impacts, yet require additional acoustic, fire, or moisture-protection layers. Highly insulated envelopes can lower operational energy but require attention to service penetrations, durability, and end-of-life recovery. Recycled materials can reduce primary extraction but may need testing for contaminants or variation in quality. Balanced assessment therefore combines environmental data with functional performance, safety, affordability, availability, and maintenance planning.

Building-assessment frameworks have helped establish common criteria for responsible material use. Typical categories include life-cycle impacts, responsible sourcing, waste reduction, indoor environmental quality, adaptability, and innovation. Their influence has increased demand for environmental product declarations and supplier transparency. Nevertheless, the literature indicates that certification should support,

not replace, technical judgement. Project teams need to understand what product data represent, how comparable they are, and whether assumptions match the proposed building location, design life, and construction method.

### 3. OBJECT OF STUDY

The primary object of this study is to examine how green building materials contribute to environmental performance across the life cycle of buildings. The study treats environmental performance as the ability of a building and its materials to deliver required functions with lower carbon emissions, reduced resource demand, lower pollution risks, improved indoor conditions, and greater potential for repair, reuse, and recovery. It does not assume that a single material category can make a building sustainable. Instead, it investigates how design choices, material properties, procurement practices, construction methods, and end-of-life planning work together to influence outcomes.

The study considers the relationship between material selection and building performance at multiple scales. At product level, it examines composition, recycled or renewable content, manufacturing energy, emissions, toxicity, durability, and availability. At assembly level, it considers thermal, acoustic, moisture, fire, and structural performance. At building level, it considers material quantities, construction waste, operational energy interaction, maintenance needs, adaptability, and demolition or recovery options. At urban scale, it considers local supply chains, construction skills, waste-management capacity, and demand for resource-efficient development.

A key aspect of the research is the identification of material strategies that reduce environmental impacts without transferring burdens to occupants, contractors, or future users. The analysis compares low-carbon substitutes, recycled

materials, bio-based products, reclaimed components, and efficient design approaches against performance criteria such as safety, longevity, constructability, maintenance, affordability, and climate suitability. It also examines the importance of credible data, quality assurance, and responsible sourcing in preventing misleading environmental claims.

In addition, the study examines implementation across the design, procurement, construction, use, and end-of-life stages. Architects and engineers influence material demand through design. Contractors influence waste, workmanship, and installation quality. Manufacturers influence production impacts and product data. Owners and users influence maintenance, renovation, and replacement decisions. These roles must be connected if green-material choices are to provide reliable environmental benefits throughout the building life cycle.

### 3.1 MATERIAL SELECTION AND ENVIRONMENTAL CRITERIA

This subsection focuses on the criteria used to compare green building materials and select products that are appropriate for a project context.

- Assessment of embodied carbon, energy demand, water use, and resource intensity across manufacturing and transport stages.
- Evaluation of recycled content, renewable inputs, responsibly sourced raw materials, and avoidance of unnecessary virgin extraction.
- Identification of product durability, repairability, maintenance needs, and expected service life under local climate conditions.
- Examination of indoor environmental quality issues, including emissions from paints, adhesives, sealants, boards, and finishes.

- Review of thermal, acoustic, moisture, fire, structural, and weather-resistance requirements at assembly level.
- Assessment of supplier transparency, environmental product documentation, quality testing, and compliance with applicable codes.
- Consideration of transport distance, local availability, construction skills, and safe handling requirements.

### 3.2 BUILDING PERFORMANCE AND LIFE-CYCLE IMPACTS

This section examines how material choices influence environmental performance during construction, use, maintenance, renovation, and end-of-life stages.

- Analysis of material quantities and opportunities to reduce overdesign, off-cuts, packaging waste, and rework.
- Study of envelope performance, thermal comfort, cooling and heating demand, daylighting, and moisture control.
- Evaluation of maintenance intervals, replacement cycles, cleaning requirements, and the environmental burden of repairs.
- Assessment of construction and demolition waste, including reuse, recycling, downcycling, and landfill avoidance pathways.
- Identification of design-for-disassembly opportunities through mechanical fixings, modular dimensions, and accessible connections.
- Review of whole-life carbon trade-offs between initial impacts, operational energy, durability, and end-of-life recovery.

### 3.3 IMPLEMENTATION AND EVALUATION SCOPE

This subsection considers the practical systems needed to translate green-material goals into reliable project outcomes.

- Use of life-cycle assessment and whole-life carbon methods during early design and material procurement.
- Specification of low-carbon binders, recycled aggregates, certified wood, reclaimed components, and low-emission finishes where suitable.
- Integration of local climate, durability, moisture protection, fire safety, and structural performance into material selection.
- Development of procurement criteria that require verified environmental information and responsible sourcing evidence.
- Training of designers, contractors, and site teams in material handling, installation, waste segregation, and quality control.
- Planning for maintenance, adaptability, disassembly, product take-back, reuse, and material recovery at end of life.
- Consideration of affordability, local supply capacity, and the needs of occupants, workers, and surrounding communities.

### 4. RESEARCH METHODOLOGY

The present study adopts a descriptive, analytical, and comparative research methodology to examine green building materials and environmental performance. The methodology is designed to connect product characteristics, whole-building design, construction practice, operational conditions, and end-of-life planning. It focuses on the practical environmental performance of material choices rather than treating any single product as universally sustainable. Secondary information is drawn from peer-reviewed research, technical standards, environmental product guidance, building-assessment frameworks, policy documents, and documented sustainable construction practices.

The study follows a structured analytical framework that compares material strategies according to life-cycle

environmental relevance, technical suitability, durability, availability, installation requirements, cost implications, health considerations, circularity potential, and local climate compatibility. Particular attention is given to the relationship between initial material

impacts and long-term building performance. The framework recognizes that carbon reduction, resource efficiency, indoor air quality, safety, and affordability must be addressed together if sustainable construction is to be credible and scalable.

## 4.1 RESEARCH DESIGN

| Component       | Description                                                                                        |
|-----------------|----------------------------------------------------------------------------------------------------|
| Research Type   | Descriptive, Analytical, Comparative                                                               |
| Approach        | Material life-cycle and whole-building performance analysis                                        |
| Data Source     | Research articles, technical standards, environmental product data, and policy documents           |
| Analysis Method | Comparative assessment of green material strategies and performance criteria                       |
| Focus Area      | Environmental performance, resource efficiency, low-carbon construction, and circular material use |

## 4.2 STUDY DIMENSIONS AND MATERIAL-SYSTEM SELECTION

The study considers major dimensions of environmental performance for evaluating green building materials:

- Embodied carbon reduction through efficient design, lower-carbon binders, recycled inputs, and responsible procurement.
- Resource conservation through material optimization, reuse, renewable feedstocks, recycled content, and reduced virgin extraction.
- Operational performance through insulation, thermal mass, solar control, airtightness, moisture management, and durable detailing.
- Indoor environmental quality through low-emission paints, adhesives, sealants, boards, flooring, and moisture-resistant assemblies.
- Circularity through design for adaptability, repair, disassembly, reuse, recycling, and construction-waste prevention.
- Local suitability through climate compatibility, supply-chain feasibility, workforce skills, affordability, and code compliance.

**Each material option is assessed on the basis of:**

- Potential to reduce greenhouse-gas emissions and non-renewable resource demand across the life cycle.
- Ability to meet structural, thermal, acoustic, fire, moisture, and health-related performance requirements.
- Suitability for local climate, construction practice, maintenance capacity, and availability of replacement materials.
- Cost, installation complexity, product quality, service life, repairability, and exposure to failure or premature replacement.
- Credibility of environmental claims, including third-party documentation, responsible sourcing, and verified product information.
- End-of-life pathways, including deconstruction, reuse, recycling, recovery, and reduction of landfill disposal.

## 5. DATA ANALYSIS

The data analysis presents a qualitative evaluation of green building material strategies through six connected dimensions: embodied carbon, resource efficiency, operational interaction, durability, indoor environmental quality, and circularity. These dimensions help explain why a material that appears

environmentally favorable in isolation may perform differently when used in a complete building system. The analysis is therefore directed toward selecting combinations of materials and design practices that provide stable environmental benefits over time.

The first finding is that reducing material quantity is often as important as substituting one product for another. A structurally efficient layout, appropriate spans, coordinated service routes, standardized dimensions, and careful detailing can reduce the total amount of concrete, steel, masonry, finishes, and packaging required. This lowers extraction, manufacturing, transport, and waste impacts before alternative materials are considered. Material-efficient design also reduces construction time, storage needs, and the risk of damage or rework on site.

The second finding concerns the importance of low-carbon mineral materials. Blended cements, supplementary cementitious materials, calcined clay systems, recycled aggregates, and optimized concrete mixes can lower the carbon intensity of construction when they are supported by suitable mix design, curing, testing, and durability control. Their environmental benefit depends on availability, transport, performance under local exposure, and the avoidance of excessive cement content. The analysis indicates that concrete should be considered as part of an efficient structural system rather than evaluated only by the footprint of a standard mix.

Bio-based and renewable materials can contribute to environmental performance when sourced responsibly and detailed for durability. Timber, bamboo, cellulose insulation, agricultural-fiber boards, cork, and engineered wood products may reduce demand for energy-intensive mineral products and can support lightweight or prefabricated construction. Their

performance is strengthened when designers address moisture control, termite protection, fire safety, finishes, ventilation, and end-of-life recovery. The analysis does not support indiscriminate use; it supports verified sourcing and climate-appropriate assemblies that protect renewable materials from premature deterioration.

The third finding is that recycled and reclaimed materials provide value when projects prevent quality loss and minimize unnecessary processing. Reclaimed bricks, stone, timber, doors, fixtures, metal sections, and furniture can avoid new production and divert materials from disposal. Recycled aggregates, recycled steel, recycled aluminum, glass cullet, and recycled-content boards can reduce demand for virgin resources. However, the analysis highlights the need for inspection, testing, sorting, safe removal, dimensions compatible with the new design, and procurement schedules that allow time for recovery and reuse.

Envelope materials influence both embodied and operational performance. Insulation, reflective roof coatings, high-performance windows, shading elements, thermal breaks, ventilation cavities, and moisture-safe membranes can reduce cooling and heating demand when selected for the local climate. Their initial impacts should be balanced against expected energy savings, service life, replacement risk, and the impact of associated layers. The strongest solutions integrate passive design, orientation, shading, ventilation, daylight control, and suitable envelope materials rather than depending on a single technical product.

Indoor environmental quality is another critical dimension. Low-emission paints, adhesives, sealants, composite boards, flooring, and insulation can reduce exposure to pollutants during occupancy. Material specifications should consider chemical content, moisture resistance,

cleanability, ventilation needs, and the potential for mold growth. A product with low embodied carbon may still create environmental and health concerns if it releases pollutants, traps moisture, or requires high-toxicity maintenance products. Environmental performance therefore includes the health and comfort of building users.

Finally, the analysis demonstrates that circularity depends on design decisions made early in the project. Buildings designed for long service life, flexible layouts, accessible services, separable layers, mechanical connections, and documented material information are more likely to support repair, renovation, reuse, and recycling. Where materials are permanently bonded into mixed assemblies, recovery is more difficult and demolition waste is more likely to be sent to landfill. Circular material systems can reduce future impacts when they are supported by deconstruction planning, local reuse markets, and safe waste-management practices.

## 6. DISCUSSION

The findings indicate that green building materials should be understood as part of a performance-based approach to sustainable construction. Environmental improvement is not achieved simply by selecting products marketed as natural, recycled, local, or energy efficient. It emerges when material choices are coordinated with building form, orientation, structure, envelope design, construction methods, maintenance plans, and end-of-life strategies. A product can contribute to a low-impact building only when it performs reliably within the relevant climatic, technical, and social context.

An important observation is that material strategies should follow a hierarchy. The first priority is to avoid unnecessary construction and reduce excess material demand. The second is to retain, retrofit, and adapt existing buildings and

components wherever feasible. The third is to use products with lower life-cycle impacts, higher recycled or renewable content, greater durability, and verified environmental information. The fourth is to ensure that materials can be repaired, reused, or recovered. This hierarchy helps avoid a narrow focus on product substitution while continuing high levels of waste and overconsumption.

The discussion also highlights the complementary relationship between low-carbon materials and climate-responsive design. In a hot climate, shading, air movement, roof design, insulation, thermal mass, and reflective surfaces can reduce cooling demand, but their effectiveness depends on appropriate material assemblies and construction quality. In a humid climate, moisture control and ventilation may be more important than simply increasing insulation. In cold climates, airtightness and thermal continuity need to be balanced with ventilation, durability, and moisture safety. Green material selection must therefore be based on building physics as well as environmental data.

Local context remains central. Transport distance, regional electricity mix, availability of recycled inputs, local manufacturing, waste-management capacity, and climate exposure can change the comparative performance of materials. A locally made earth block may have strong environmental value in a dry region when appropriate stabilization and weather protection are used. A recycled product may be less beneficial if it requires long-distance transport or intensive reprocessing. A bio-based material may be favorable when responsible forestry and fire-safe detailing are available. Project teams should therefore avoid copying material palettes from unrelated regions without local assessment.

Equity and affordability also require attention. Green material strategies should

not be restricted to premium projects or used only as a marketing feature. Low-impact approaches can be applied in affordable housing, schools, healthcare facilities, public buildings, and community infrastructure through material efficiency, local procurement, passive design, durable finishes, and waste reduction. Public procurement can create demand for credible environmental data and lower-carbon alternatives, while training programs can help local contractors and manufacturers build capability. The benefits of sustainable materials are broader when they improve comfort, reduce operating costs, support local livelihoods, and reduce exposure to harmful pollutants.

The role of government, professional bodies, and manufacturers is significant. Building codes and standards can set minimum performance levels for energy, moisture, fire safety, structural reliability, and product quality. Public agencies can support life-cycle assessment databases, environmental product declarations, recycling infrastructure, pilot projects, and procurement criteria. Manufacturers can improve transparency, disclose product composition, reduce production emissions, and provide guidance for installation and maintenance. Designers and contractors can ensure that environmental claims are tested against technical requirements rather than accepted without verification.

The study also suggests that measurement should be practical and proportionate. Large projects may use detailed whole-life carbon models and multiple environmental indicators, whereas small projects may rely on simplified benchmarks, verified product information, material take-offs, and local guidance. The purpose of assessment is not only to produce a score but to inform better decisions. A transparent process that identifies major material impacts, compares reasonable alternatives, and records assumptions can

be more useful than a complex assessment that cannot be understood or applied by the project team.

## 7. CONCLUSION

This study concludes that green building materials can make a meaningful contribution to environmental performance when they are selected through a whole-life, context-sensitive, and performance-based approach. Environmental impacts are influenced by material extraction, manufacturing, transport, construction, operation, maintenance, renovation, and end-of-life treatment. As a result, isolated product claims are not sufficient. Durable improvement depends on reducing unnecessary material demand, selecting lower-impact products where technically suitable, protecting occupant health, extending service life, and planning for reuse or recovery.

The analysis demonstrates that material-efficient design, lower-carbon cement systems, recycled aggregates, reclaimed components, responsible timber and bamboo, low-emission finishes, suitable insulation, and climate-responsive envelopes can strengthen sustainability outcomes. These measures should be supported by life-cycle assessment, verified product information, quality testing, appropriate detailing, construction quality control, and maintenance planning. The environmental benefits of green materials are highest when they are integrated into whole-building strategies that consider structural efficiency, passive design, indoor environmental quality, and circularity.

The study further concludes that durability and local suitability are essential. A material that reduces initial impacts but fails early, creates moisture or health problems, or cannot be maintained may increase total environmental burdens. Material choices must therefore respond to climate, exposure, building use, skills, supply chains, code requirements, and the

ability to repair or replace components. Environmental performance should be evaluated alongside safety, serviceability, affordability, and user comfort.

Another important conclusion is that transparent information and responsible procurement are necessary for credible implementation. Environmental product declarations, responsible sourcing evidence, testing data, product composition information, and clear maintenance guidance can help project teams compare alternatives and avoid misleading claims. Public authorities and institutions can support this process through standards, procurement policy, training, and investment in recycling and reuse systems.

## 8. REFERENCES

1. United Nations Environment Programme. (2024). Global Status Report for Buildings and Construction: Beyond Foundations. Nairobi: UNEP. <https://www.unep.org/resources/report/global-status-report-buildings-and-construction>
2. Intergovernmental Panel on Climate Change. (2022). Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report. Cambridge University Press. <https://www.ipcc.ch/report/ar6/wg3/>
3. World Green Building Council. (2019). Bringing Embodied Carbon Upfront: Coordinated Action for the Building and Construction Sector to Tackle Embodied Carbon. London: WorldGBC. <https://worldgbc.org/advancing-net-zero/embodied-carbon/>
4. International Organization for Standardization. (2006). ISO 14040: Environmental Management - Life Cycle Assessment - Principles and Framework. Geneva: ISO.
5. International Organization for Standardization. (2006). ISO 14044: Environmental Management - Life Cycle Assessment - Requirements and Guidelines. Geneva: ISO.
6. International Organization for Standardization. (2017). ISO 21930: Sustainability in Buildings and Civil Engineering Works - Core Rules for Environmental Product Declarations of Construction Products and Services. Geneva: ISO.
7. European Committee for Standardization. (2019). EN 15804: Sustainability of Construction Works - Environmental Product Declarations - Core Rules for the Product Category of Construction Products. Brussels: CEN.
8. Royal Institution of Chartered Surveyors. (2023). Whole Life Carbon Assessment for the Built Environment. 2nd ed. London: RICS. <https://www.rics.org/whole-life-carbon-assessment>
9. United States Environmental Protection Agency. (2024). Sustainable Management of Construction and Demolition Materials. Washington, DC: EPA. <https://www.epa.gov/smm/sustainable-management-construction-and-demolition-materials>
10. Ashby, M. F. (2013). Materials and the Environment: Eco-informed Material Choice. 2nd ed. Oxford: Butterworth-Heinemann.

Finally, the study suggests that future construction strategies should connect green material selection with adaptive reuse, low-carbon design, local manufacturing, resource efficiency, and circular building practices. Buildings that use fewer materials, last longer, maintain healthy indoor conditions, and allow components to be repaired, reused, or recovered can reduce environmental pressure while providing durable value for occupants and communities. Such an integrated approach can help move the construction sector toward a more resilient, low-carbon, and resource-conscious future.

11. Cabeza, L. F., Rincón, L., Vilariño, V., Pérez, G., & Castell, A. (2014). Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. *Renewable and Sustainable Energy Reviews*, 29, 394-416. <https://doi.org/10.1016/j.rser.2013.08.037>
12. Dixit, M. K., Fernández-Solís, J. L., Lavy, S., & Culp, C. H. (2012). Need for an embodied energy measurement protocol for buildings: A review paper. *Renewable and Sustainable Energy Reviews*, 16(6), 3730-3743. <https://doi.org/10.1016/j.rser.2012.03.021>
13. Pomponi, F., & Moncaster, A. (2016). Embodied carbon mitigation and reduction in the built environment: What does the evidence say? *Journal of Environmental Management*, 181, 687-700. <https://doi.org/10.1016/j.jenvman.2016.08.036>
14. Hammond, G., & Jones, C. (2011). Inventory of Carbon and Energy (ICE), Version 2.0. University of Bath, Department of Mechanical Engineering.
15. Habert, G., Miller, S. A., John, V. M., Provis, J. L., Favier, A., Horvath, A., & Scrivener, K. L. (2020). Environmental impacts and decarbonization strategies in the cement and concrete industries. *Nature Reviews Earth & Environment*, 1, 559-573. <https://doi.org/10.1038/s43017-020-0093-3>
16. Scrivener, K. L., John, V. M., & Gartner, E. M. (2018). Eco-efficient cements: Potential economically viable solutions for a low-CO<sub>2</sub> cement-based materials industry. *Cement and Concrete Research*, 114, 2-26. <https://doi.org/10.1016/j.cemconres.2018.03.015>
17. Provis, J. L. (2018). Alkali-activated materials. *Cement and Concrete Research*, 114, 40-48. <https://doi.org/10.1016/j.cemconres.2017.02.009>
18. Geng, Y., & Doberstein, B. (2008). Developing the circular economy in China: Challenges and opportunities for achieving leapfrog development. *International Journal of Sustainable Development & World Ecology*, 15(3), 231-239. <https://doi.org/10.3843/SusDev.15.3:6>
19. Ajayi, S. O., Oyedele, L. O., Bilal, M., Akinade, O. O., Alaka, H. A., Owolabi, H. A., & Kadiri, K. O. (2015). Waste effectiveness of the construction industry: Understanding the impediments and requisites for improvements. *Resources, Conservation and Recycling*, 102, 101-112. <https://doi.org/10.1016/j.resconrec.2015.06.001>
20. Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production*, 114, 11-32. <https://doi.org/10.1016/j.jclepro.2015.09.007>
21. Kibert, C. J. (2016). *Sustainable Construction: Green Building Design and Delivery*. 4th ed. Hoboken, NJ: John Wiley & Sons.
22. Ding, G. K. C. (2008). Sustainable construction - The role of environmental assessment tools. *Journal of Environmental Management*, 86(3), 451-464. <https://doi.org/10.1016/j.jenvman.2006.12.025>
23. Zuo, J., & Zhao, Z.-Y. (2014). Green building research-current status and future agenda: A review. *Renewable and Sustainable Energy Reviews*, 30, 271-281. <https://doi.org/10.1016/j.rser.2013.10.021>
24. Ortiz, O., Castells, F., & Sonnemann, G. (2009). Sustainability in the construction industry: A review of recent developments based on LCA. *Construction and Building Materials*, 23(1), 28-39. <https://doi.org/10.1016/j.conbuildmat.2007.11.012>
25. Sartori, I., & Hestnes, A. G. (2007). Energy use in the life cycle of conventional and low-energy buildings: A review article. *Energy and Buildings*, 39(3), 249-257. <https://doi.org/10.1016/j.enbuild.2006.07.001>

26. Pacheco-Torgal, F., & Jalali, S. (2012). Earth construction: Lessons from the past for future eco-efficient construction. *Construction and Building Materials*, 29, 512-519. <https://doi.org/10.1016/j.conbuildmat.2011.10.054>
27. Ramage, M. H., Burrige, H., Busse-Wicher, M., et al. (2017). The wood from the trees: The use of timber in construction. *Renewable and Sustainable Energy Reviews*, 68, 333-359. <https://doi.org/10.1016/j.rser.2016.09.107>
28. van der Lugt, P., ThangLong, T., & King, C. (2018). Bamboo construction: A sustainable alternative for the built environment. In: *Bamboo: The Plant and its Uses*. Cham: Springer.
29. Moe, K. (2010). *Thermally Active Surfaces in Architecture*. New York: Princeton Architectural Press.
30. World Health Organization. (2010). *WHO Guidelines for Indoor Air Quality: Selected Pollutants*. Copenhagen: WHO Regional Office for Europe. <https://www.who.int/publications/i/item/9789289002134>