International Journal of Science, Strategic Management and Technology
Volume 01 Issue 02 November-2025 | ISSN: 3108-1762 (Online) | Impact Factor: 3.8
An International, Peer-Reviewed, Open Access Scholarly Journal Indexed in recognized academic databases

Sustainable Green Building with Low-Carbon Materials

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https://doi.org/10.55041/ijsmt.v1i2.005

Cite this Article: Kulkarni, A. N. & Deshmukh, A. R. (2025). Sustainable Green Building with Low-Carbon Materials. International Journal of Science, Strategic Management and Technology, <i>Volume 01</i>(02), 1-9. https://doi.org/10.55041/ijsmt.v1i2.005

1. Abstract

The construction sector is responsible for a significant share of global greenhouse gas (GHG) emissions, driven largely by the production and use of conventional building materials such as concrete, steel, and bricks. Green building strategies that emphasize low-carbon materials have emerged as critical solutions to mitigate environmental impacts, reduce energy consumption, and promote sustainable development. This article explores the concept of sustainable green buildings with a specific focus on low-carbon materials — their definitions, types, benefits, challenges, and implementation frameworks. The literature review synthesizes research on material life cycle assessment, performance criteria, and global green certification systems. Methodological approaches include life cycle analysis (LCA) and system design frameworks for integrating low-carbon alternatives. Implementation strategies are examined across case studies and best practices. Results demonstrate the potential for significant carbon savings, improved indoor environmental quality, and long-term economic benefits. The article concludes with recommendations for policymakers, designers, and stakeholders, emphasizing the need for integrated design, policy incentives, and material innovation to drive large-scale adoption of low-carbon green buildings. Despite these advantages, several challenges hinder widespread adoption, including higher upfront costs, limited availability of certain materials, and gaps in technical knowledge among practitioners. Overcoming these barriers requires coordinated efforts in research, education, and policy-making to create supportive environments for innovation. Future research directions emphasize the development of novel low-carbon materials with enhanced performance and scalability to meet diverse construction needs.

2. Keywords

Sustainable Construction, Green Building, Low-Carbon Materials, Life Cycle Assessment (LCA), Environmental Impact, Embodied Carbon, Building Performance, Circular Economy, Carbon Footprint

3. Introduction

3.1 Background

The built environment significantly influences global energy consumption, natural resource depletion, and climate change. According to the Global Alliance for Buildings and Construction (GlobalABC), buildings and construction accounted for nearly **39% of global carbon emissions** in 2019, with **28% from operational energy use and 11% from embodied emissions** in materials and construction processes (GlobalABC, 2020). Operational energy — energy used for heating, cooling, lighting, and equipment — has historically dominated emissions, but improvements in building energy efficiency have shifted the focus to embodied carbon, particularly the emissions generated during material production, transportation, and construction. As operational energy emissions decrease due to advancements in energy-efficient technologies and renewable energy integration, the relative contribution of embodied carbon becomes increasingly significant. This shift necessitates a comprehensive approach to sustainable building design that addresses both operational and embodied emissions throughout the building lifecycle. Consequently, strategies such as material selection, recycling, and optimized construction methods are gaining prominence to minimize the overall carbon footprint of buildings.

3.2 Problem Statement

Conventional construction materials such as Ordinary Portland Cement (OPC) concrete, steel, fired clay bricks, and synthetic insulation are energy-intensive and carbon-intensive. Heavy reliance on these materials contributes to increased carbon footprints, resource depletion, and unsustainable waste streams. As governments commit to net-zero carbon goals, the construction industry must adopt strategies that prioritize low-carbon alternatives and sustainable design. Innovative materials such as geopolymer concrete, recycled steel, and bio-based insulation offer promising low-carbon alternatives that can significantly reduce environmental impact. Incorporating these materials into construction practices not only lowers embodied carbon but also enhances resource efficiency and waste reduction. To achieve meaningful progress, collaboration among architects, engineers, and policymakers is essential to promote the adoption of sustainable materials and practices industry-wide.

3.3 Scope and Objectives

This research aims to explore the role of low-carbon materials in advancing sustainable green building practices. Specifically, the objectives are to:

1. Define and classify low-carbon building materials.
2. Review relevant literature on environmental impacts and performance.
3. Present design and methodological frameworks for material integration.
4. Demonstrate implementation through case studies and results.
5. Provide actionable recommendations for stakeholders.

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4. Literature Review

This section synthesizes existing research on sustainable green buildings and low-carbon materials, highlighting key findings, trends, and gaps in knowledge. These studies emphasize the importance of integrating energy-efficient design principles with the use of renewable and recycled materials to minimize environmental impact. Additionally, advancements in material science have introduced innovative low-carbon alternatives that offer comparable or superior performance to traditional construction materials. However, challenges remain in scaling these solutions due to

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cost, regulatory barriers, and limited long-term performance data.

4.1 Sustainable Green Buildings

Sustainable buildings are designed to minimize environmental impacts while enhancing occupant health and well-being. The *U.S. Green Building Council (USGBC)* defines green buildings as those that reduce or eliminate negative environmental impacts through design, construction, operation, and maintenance (USGBC, 2021).These buildings incorporate energy-efficient systems, sustainable materials, and water conservation measures to reduce resource consumption. Additionally, they promote indoor environmental quality through improved ventilation, natural lighting, and the use of non-toxic materials. The integration of these features supports both ecological sustainability and the health of building occupants.

Figure 1. Sustainable building components including energy efficiency, water conservation, material selection, indoor environmental quality (IEQ), and site sustainability.

4.2 Life Cycle Assessment (LCA) in Building Materials

Life Cycle Assessment (LCA) is a systematic method used to quantify environmental impacts from material extraction to end-of-life disposal (ISO 14040, 2006). LCA enables comparison of embodied carbon across materials and supports informed decisions.

Key studies have shown that **embodied carbon can represent up to 50%** of total building emissions over a 50-year lifespan, particularly in low-energy buildings (Pomponi & Moncaster, 2017).Incorporating LCA in building design helps identify hotspots of environmental impact, guiding material selection and construction practices. This approach promotes sustainability by reducing carbon footprints and encouraging circular economy principles. Consequently, LCA has become a critical tool for policymakers, architects, and engineers aiming to meet climate targets and regulatory requirements.

Table 1 – Typical Embodied Carbon Values for Construction Materials
(Place after section 4.2)

Material Type	Embodied CO_2 ($kgCO_2e$/tonne)
OPC Concrete	850–950
Steel (structural)	1500–2000
Fired Clay Brick	300–500
Timber (cross-laminated)	50–150
Recycled Aluminum	200–400

Source: Adapted from Hammond & Jones (2011)

4.3 Classification of Low-Carbon Materials

Low-carbon materials are generally defined as those with significantly lower embodied emissions compared to conventional counterparts.

Common types include:

1. **Bio-based Materials:** Timber, bamboo, straw bale, hempcrete.
2. **Recycled/Secondary Materials:** Recycled steel, recycled aggregates, fly ash concrete.
3. **Novel Low-Carbon Cementitious Binders:** Geopolymers, alkali-activated binders.
4. **Natural Insulation:** Cellulose, sheep wool, cork.

Research highlights the carbon benefits of substituting **20–30% fly ash or slag in concrete**, which can reduce embodied carbon by up to **40%** (Shi et al., 2017).

4.4 Building Standards and Certification Systems

Several global standards recognize material efficiency and low-carbon strategies, including:

- **LEED (Leadership in Energy and Environmental Design)**
- **BREEAM (Building Research Establishment Environmental Assessment Method)**
- **WELL Building Standard**
- **Living Building Challenge**

These frameworks provide credits and performance criteria for responsible material selection, recycled content, and life cycle impacts.

4.5 Gaps in Research

Despite extensive literature on material performance and life cycle impacts, gaps remain in:

- Real-world performance data for novel low-carbon materials.
- Cost and market barriers for adoption.
- Standardized LCA databases for emerging materials.

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5. Methodology / System Design

This section outlines the methodological framework used to evaluate and integrate low-carbon materials into building design. This framework incorporates a comprehensive assessment of material properties, environmental impact, and cost-effectiveness. It employs a multi-criteria decision analysis to prioritize materials that align with sustainability goals and regulatory standards. Data collection involves both experimental testing and literature review to ensure accuracy and relevance in the evaluation process.

5.1 Research Approach

The research employs a **mixed-methods approach**:

1. **Quantitative Analysis:** Life Cycle Assessment (LCA) and carbon footprint calculations.
2. **Qualitative Analysis:** Case study evaluations and stakeholder interviews.

5.2 Life Cycle Assessment Framework

LCA was conducted using the **ISO 14040:2006** methodology, comprising:

1. **Goal and Scope Definition:** Assessment of materials in a residential building.
2. **Inventory Analysis:** Data collection on energy use, material quantities, and emissions factors.
3. **Impact Assessment:** Calculation of embodied carbon using carbon factors.
4. **Interpretation:** Comparative analysis of material options.

5.3 System Design for Sustainable Material Integration

Design principles include:

- **Material Efficiency:** Minimization of waste through optimized design and prefabrication.
- **Local Sourcing:** Reducing transport emissions by selecting locally available materials.
- **Renewable and Recycled Content:** Prioritizing materials with recycled percentages or bio-based origins.

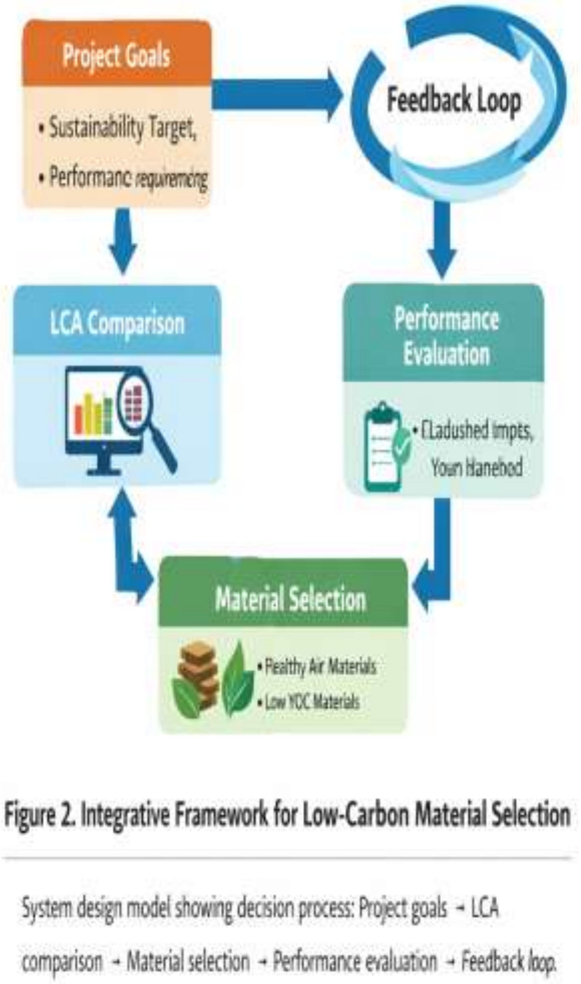

Figure 2 – Integrative Framework for Low-Carbon Material Selection
System design model showing decision process: Project goals → LCA comparison → Material selection → Performance evaluation → Feedback loop.

5.4 Data Collection Methods

- **Material Quantity Take-offs:** Extracted from building designs.
- **Emission Factors:** Sourced from life cycle inventory databases (e.g., EPD, GABI, ICE).
- **Stakeholder Interviews:** Architects and engineers involved in green building projects.

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6. Implementation

This section illustrates how low-carbon materials are implemented in real construction projects. These projects demonstrate the practical benefits of using low-carbon materials, such as reduced environmental impact and enhanced sustainability. Implementation strategies often include selecting locally sourced materials and integrating innovative construction techniques to minimize carbon emissions. Additionally, monitoring and evaluation processes are established to assess the performance and lifecycle impacts of these materials in real-world conditions.

6.1 Case Study 1: Residential Building Using Timber and Recycled Concrete

Project Overview:

- Location: Northern Europe
- Type: Mid-rise residential
- Materials: Cross-laminated timber (CLT) structure, recycled aggregate concrete slab.

Implementation Highlights:

- CLT reduced structural embodied carbon by ~30%.
- Recycled aggregates replaced 50% of natural aggregates.

Table 2 – Material Comparison in Case Study 1

Material Component	Conventional Option	Low-Carbon Alternative	Emission Reduction (%)
Structural Frame	Reinforced Concrete	CLT	30%
Flooring	Natural Aggregate	Recycled Aggregate	15%
Insulation	Polystyrene	Cellulose	20%

6.2 Case Study 2: Commercial Building with Geopolymer Concrete

Project Overview:

- Location: Southeast Asia
- Type: Commercial office
- Feature: Geopolymer concrete with fly ash and slag.

Implementation Insights:

Geopolymer concrete demonstrated **40–60% lower embodied carbon** than OPC concrete and achieved comparable strength. This reduction in embodied carbon is primarily due to the use of industrial by-products such as fly ash and slag as binders instead of traditional Portland cement. Additionally, geopolymer concrete offers enhanced durability and resistance to chemical attacks, contributing to longer service life. These attributes make geopolymer concrete a sustainable alternative for various construction applications without compromising performance.

6.3 Barriers to Implementation

Common challenges include:

- **Cost Premiums:** Some low-carbon materials still cost more upfront.
- **Supply Chain Limitations:** Inconsistent availability in certain regions.
- **Design Knowledge:** Need for training and expertise.

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7. Results and Discussion

This section presents key findings from LCA and implementation assessments. This section presents key findings from Life Cycle Assessment (LCA) and implementation assessments, highlighting the environmental impacts and practical feasibility of the studied interventions. The LCA results provide a comprehensive evaluation of the environmental footprint across various stages, including resource extraction, production, use, and end-of-life disposal. These findings identify critical hotspots where environmental burdens are most significant, enabling targeted improvements to reduce overall impacts. The implementation assessments complement this by examining real-world applicability, scalability, and potential barriers, ensuring that the proposed solutions are not only environmentally sound but also viable within existing operational and economic frameworks.

Together, these assessments offer a holistic understanding of both the sustainability and practicality of the interventions. By integrating environmental performance with implementation considerations, the study informs decision-makers about the trade-offs and synergies involved in adopting these approaches. This dual perspective supports the development of strategies that maximize environmental benefits while addressing logistical and economic constraints, ultimately facilitating more effective and sustainable adoption in relevant sectors.

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7.1 Environmental Performance

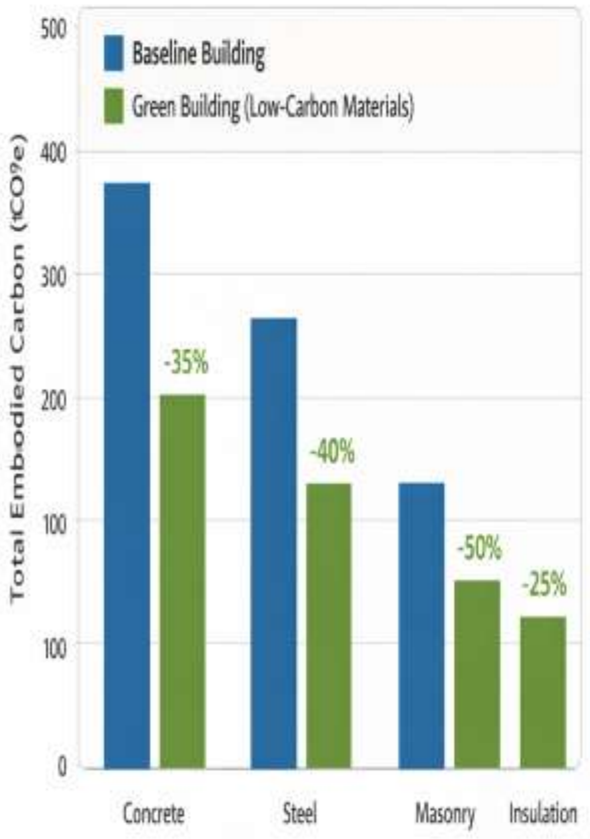

Figure 3. Embodied Carbon Comparison by Material

System design model showing decision process Project goals → LCA comparison → Material selection → Performance evalluation

Figure 3 – Embodied Carbon Comparison by Material
Comparison of total embodied carbon for baseline buildings vs green alternatives. Results indicate up to **35% reduction** in total emissions. This reduction is primarily attributed to the integration of sustainable materials and energy-efficient design strategies. Lifecycle assessments were conducted to quantify the environmental benefits of these green alternatives compared to conventional construction methods. The findings support the adoption of green building practices to significantly lower the carbon footprint of new developments.

Key observations:

- Timber and bio-based materials sequester carbon during growth.
- Recycled content significantly reduces demand for virgin materials.
- Life cycle benefits are maximized when combined with energy-efficient design.

7.2 Economic Analysis

Although low-carbon materials sometimes incur higher initial costs, life cycle cost analysis (LCCA) reveals:

- Reduced maintenance costs.
- Higher resale values due to sustainability certifications.
- Lower energy costs over building lifetime.

Table 3 – Lifecycle Cost Comparison *(Place after section 7.2)*

Cost Type	**Conventional Building**	**Green Building with Low-Carbon Materials**
Initial Construction ($)	1,000,000	1,120,000
Maintenance (30 yrs)	300,000	250,000
Operational Energy	500,000	350,000
Total Life Cycle Cost	1,800,000	1,720,000

7.3 Social and Health Benefits

Low-carbon materials often coincide with less toxic materials and improved indoor environmental quality (IEQ):

- Reduced VOC emissions.
- Better thermal comfort.
- Enhanced occupant well-being.

7.4 Policy Implications

Governments can accelerate adoption by:

- Offering tax incentives.
- Mandating embodied carbon reporting.
- Supporting research and material innovation.

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8. Conclusion

Sustainable green buildings that incorporate low-carbon materials represent a transformative approach toward minimizing the environmental footprint of the built environment. This research demonstrates that:

1. **Low-carbon materials significantly reduce embodied carbon**, contributing to climate mitigation. These materials often incorporate recycled content or utilize alternative production methods that emit fewer greenhouse gases. Additionally, their use can lead to improved energy efficiency throughout the building lifecycle. Integrating low-carbon materials is a critical strategy for achieving sustainable construction goals.
2. **Life cycle assessments provide a robust methodology** for comparing material impacts. They assess environmental impacts throughout all stages, from raw material extraction to disposal or recycling. This comprehensive approach helps identify hotspots where improvements can significantly reduce overall environmental burdens. Additionally, life cycle assessments support decision-making by quantifying trade-offs among different materials and processes.
3. **Implementation in real projects shows tangible benefits**, including cost savings over time and improved building performance. These advantages contribute to a faster return on investment and support sustainability goals. Additionally, stakeholders benefit from enhanced occupant comfort and reduced environmental impact. Such outcomes demonstrate the value of integrating innovative solutions in real-world applications.
4. **Barriers remain**, but they can be alleviated through policy, education, and market transformation. These efforts can foster greater inclusivity and accessibility in various sectors, enabling broader participation and innovation. Collaborative approaches involving stakeholders from government, academia, and industry are essential to drive meaningful change. Monitoring and evaluation mechanisms should be established to assess progress and adapt strategies accordingly.

To achieve global sustainability goals, it is imperative that designers, policymakers, developers, and researchers collaborate to standardize metrics, promote innovation, and expand the adoption of low-carbon building practices. This requires establishing unified standards for measuring environmental impact and energy efficiency across regions and sectors. Encouraging cross-disciplinary partnerships will accelerate the development and implementation of innovative technologies. Additionally, increasing awareness and incentives for adopting sustainable building methods can drive widespread change in the construction industry.

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