INTERNATIONAL JOURNAL OF ENGINEERING MANAGEMENT AND SOCIAL SCIENCES (IJEMSS)

e-ISSN : 3139-065X

www.ijemss.com

editor@ijemss.com

Vol. 01, Issue 1, May 2026, pp : 16-26

Green Building Materials and Sustainable Construction

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ABSTRACT

The built environment is responsible for nearly 40 percent of global energy consumption and approximately 33 percent of greenhouse gas emissions, making the construction sector a central focus of global decarbonization efforts. Green building materials — encompassing bio-based, recycled, low-carbon, and energy-efficient products — offer a comprehensive pathway to reducing the sector's environmental impact across the full building lifecycle. This article provides an in-depth review of the most significant green building materials and sustainable construction strategies available today, including bamboo, cross-laminated timber, hempcrete, recycled steel and aluminum, low-carbon concrete, aerogel insulation, green roofing systems, and photovoltaic-integrated facade materials. The study examines their environmental credentials, structural and thermal performance, cost considerations, and deployment status globally. Challenges including standardization, supply chain development, and workforce upskilling are analyzed alongside policy frameworks driving adoption. The article concludes that the large-scale transition to green building materials is technically feasible, economically viable over whole-life cost horizons, and environmentally imperative.

Keywords: green building materials, sustainable construction, bamboo, cross-laminated timber, hempcrete, low-carbon concrete, aerogel insulation, LEED, GRIHA, embodied carbon, circular economy

1. Introduction

The construction industry occupies a paradoxical position in modern society. It builds the infrastructure on which human wellbeing, economic productivity, and social development depend — yet in doing so, it consumes vast quantities of natural resources, generates enormous waste streams, and releases greenhouse gases that accelerate climate change. Buildings and construction together account for 36 percent of global final energy use, 39 percent of energy-related carbon dioxide emissions, and approximately 40 percent of raw material consumption worldwide, according to the International Energy Agency and the United Nations Environment Programme.

The scale of construction activity is set to grow substantially over the coming decades. Global floor area is projected to double by 2060, driven by urbanization in South and Southeast Asia, Sub-Saharan Africa, and Latin America. This expansion represents both a profound challenge and a historic opportunity: if new buildings are designed and built with green materials and sustainable strategies, the construction sector could make a decisive contribution to meeting global climate targets. If conventional materials and methods continue to dominate, the sector's carbon footprint will grow to levels inconsistent with the goals of the Paris Agreement.

Green building materials are defined by their reduced environmental impact across the full lifecycle — from raw material extraction through manufacturing, transportation, installation, service life, and end-of-life — compared to conventional alternatives. They typically exhibit one or more of the following characteristics: renewable resource base, high recycled content, low embodied energy and carbon, enhanced thermal or acoustic performance, locally sourced supply chains, low toxicity, and recyclability or biodegradability at end of life.

Sustainable construction extends beyond material selection to encompass building design, energy systems, water management, waste minimization, site ecology, and building operation. This article focuses primarily on the material dimension while acknowledging that materials choices interact with and enable broader sustainable design strategies. Section 2 reviews the principal green building material categories. Section 3

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addresses sustainable construction strategies. Section 4 presents comparative performance data. Sections 5 and 6 examine economic and environmental dimensions. Section 7 addresses barriers and policy, and Section 8 sets out research and industry priorities.

2. Green Building Materials: Categories and Properties

2.1 Bamboo

Bamboo is among the most remarkable natural building materials available. A grass rather than a timber, bamboo reaches structural maturity in 3 to 5 years — compared to 25 to 80 years for structural timber species — and can be harvested without killing the plant, as new culms regenerate from the root system. Its tensile strength-to-weight ratio rivals that of structural steel, and its compressive strength exceeds that of many timber species and conventional concrete mixes.

Bamboo sequesters carbon at exceptionally high rates during its rapid growth phase, absorbing approximately 12 tonnes of CO2 per hectare per year in productive plantations. When harvested and used in long-life building products, this sequestered carbon remains locked in the structure for the building's service life. Life cycle assessments of bamboo construction consistently demonstrate negative net carbon balances for well-managed plantation systems, making bamboo one of the few structural materials with the potential to actively remove carbon from the atmosphere while serving a structural function.

Engineered bamboo products — including laminated bamboo lumber, bamboo strand woven board, and bamboo scrimber — have significantly extended the material's structural applications beyond traditional vernacular construction. These products offer dimensional stability, predictable mechanical properties, and compatibility with standard construction tools and techniques. Structural applications now include multi-story residential buildings, bridge decks, flooring, cladding, and internal partition systems. The INBAR (International Network for Bamboo and Rattan) estimates that over one billion people live in bamboo structures globally, predominantly in Asia, while engineered bamboo products are increasingly penetrating markets in Europe and North America.

2.2 Cross-Laminated Timber (CLT)

Cross-laminated timber is a mass timber product formed by gluing multiple layers of structural timber at perpendicular angles, producing large panels with high in-plane and out-of-plane structural capacity. Originally developed in Austria and Germany in the early 1990s, CLT has become the material of choice for mid-rise and high-rise timber construction globally. Buildings of up to 18 stories have been completed in CLT, and structural systems combining CLT floor plates with glulam columns and beams have been approved for structures exceeding 80 meters in several jurisdictions.

The environmental credentials of CLT are compelling. Each cubic meter of CLT stores approximately one tonne of biogenic carbon — carbon absorbed from the atmosphere during the tree's growth — while displacing approximately 1.1 tonnes of CO2 that would have been emitted by equivalent concrete or steel structural elements. A typical 8-story CLT residential building stores 180 to 250 tonnes of biogenic carbon while avoiding 300 to 450 tonnes of embodied carbon compared to a concrete-framed equivalent, yielding a net climate benefit of 480 to 700 tonnes of CO2-equivalent per building.

Beyond its carbon credentials, CLT offers superior construction speed — panels are precision-manufactured offsite and assembled rapidly on site — improved on-site safety through reduced wet trades and lifting operations, excellent acoustic performance between floors, and a warm aesthetic that contributes to occupant wellbeing. Fire performance, which was the primary regulatory concern limiting timber construction height, has been addressed through intumescent coatings, encapsulation with gypsum board, and the inherent char

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formation characteristics of mass timber that provide predictable, self-limiting fire behavior.

2.3 Hempcrete

Hempcrete is a bio-composite building material produced by mixing the woody inner core of the hemp plant (the shiv or hurds) with a lime-based binder and water. It produces a lightweight, highly insulating, vapor-permeable wall material with exceptional hygrothermal regulation properties. Hempcrete is not a structural material in the conventional sense — it cannot bear imposed loads — but serves as an insulating infill within a timber, steel, or concrete structural frame, or as an insulating render on existing walls.

Hemp cultivation sequesters carbon both in the biomass and in the soil. The shiv used in hempcrete retains the carbon sequestered during the plant's rapid growth (hemp reaches harvest maturity in 70 to 120 days), and when combined with lime, undergoes a slow carbonation process over decades that permanently mineralizes this carbon. Life cycle assessments consistently demonstrate that hempcrete walls are carbon negative over their service life, sequestering more CO2 than is emitted during their production and installation.

The hygrothermal performance of hempcrete is its most architecturally significant property. The material absorbs and releases moisture in response to internal humidity variations, moderating indoor air quality and reducing condensation risk. Its thermal mass combined with moderate thermal resistance produces buildings with reduced peak heating and cooling loads even at wall thicknesses comparable to conventional insulation systems. Growing interest in hempcrete is reflected in recent code updates in France, the United Kingdom, Australia, and several US states that now permit hempcrete construction under specific conditions.

2.4 Recycled Steel and Aluminum

Steel and aluminum are intrinsically recyclable — their elemental composition is unchanged by use, and both can be re-melted and recast indefinitely without degradation of structural properties. The environmental benefit of recycling versus primary production is dramatic. Primary steel production from iron ore via the blast furnace route emits approximately 1.8 to 2.2 tonnes of CO2 per tonne of steel; electric arc furnace (EAF) steelmaking from scrap emits just 0.4 to 0.7 tonnes per tonne — a reduction of 65 to 75 percent. For aluminum, the contrast is even starker: primary aluminum smelting requires approximately 11,000 kilowatt-hours of electricity per tonne, while secondary production from scrap requires only 700 kilowatt-hours — a 95 percent energy saving.

In the construction sector, structural steel already incorporates substantial recycled content — typically 70 to 90 percent in regions with mature scrap collection infrastructure. Further gains are achievable through designing for disassembly, which facilitates the recovery of steel sections for direct reuse rather than recycling, preserving the embodied energy invested in rolling and fabricating structural sections. The Ellen MacArthur Foundation estimates that designing steel structures for deconstruction and component reuse could reduce embodied carbon by a further 25 to 40 percent compared to end-of-life recycling alone.

2.5 Low-Carbon and Green Concrete

Concrete is the construction material most in need of greening, given its production scale and carbon intensity. Low-carbon concrete strategies — substituting supplementary cementitious materials (SCMs) such as fly ash, ground granulated blast-furnace slag (GGBS), and silica fume for Portland cement clinker — have been reviewed in detail in prior literature. Beyond SCM substitution, several emerging approaches are expanding the low-carbon concrete toolkit.

Carbonation curing exposes fresh concrete to concentrated CO2, which reacts with calcium silicate phases to form calcium carbonate, permanently mineralizing CO2 within the concrete matrix. Commercial carbonation curing systems are now available and can sequester 20 to 30 kilograms of CO2 per cubic meter of concrete, partially offsetting the embodied carbon of the cement content. Carbon-cured concrete also demonstrates

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improved early strength and reduced water permeability compared to conventionally cured equivalent mixes.

Geopolymer concrete eliminates Portland cement entirely, using alkali-activated industrial by-products — typically fly ash or GGBS — as the sole binder. When activated with sodium hydroxide and sodium silicate, these materials form an aluminosilicate polymer network with mechanical properties comparable to conventional concrete but embodied carbon 40 to 80 percent lower. Geopolymer concrete is commercially available in Australia, the United States, and several European markets, with notable applications in bridge decks, precast elements, and industrial flooring.

2.6 Aerogel Insulation

Aerogel is an ultra-low-density solid material produced by replacing the liquid component of a silica gel with gas while preserving the solid nanoporous structure. The resulting material is 95 to 99.9 percent air by volume, giving it a thermal conductivity of 0.012 to 0.020 watts per meter-kelvin — two to five times lower than conventional mineral wool or rigid foam insulation products. This exceptional insulating performance allows equivalent thermal resistance to be achieved at a fraction of the thickness required by conventional insulation.

In building applications, aerogel insulation is particularly valuable where space is constrained: historic building renovation where wall thickness must be minimized, passive house construction in dense urban plots, industrial pipe insulation, and window frame profiles. Aerogel blankets, granules, and composite panels are commercially available from multiple manufacturers. The principal limitation of aerogel insulation is cost — production remains expensive despite process improvements, and aerogel products command a premium of 3 to 10 times the cost of conventional insulation per unit area. Research efforts focused on silica aerogel production from rice husk silica and waste glass show promise for reducing production costs and improving the sustainability of the raw material base.

2.7 Green Roof and Living Wall Systems

Green roofs — vegetated roof systems incorporating a waterproofing membrane, drainage layer, growing medium, and plant layer — provide a range of environmental benefits that conventional roofing cannot match. They reduce stormwater runoff by retaining and slowly releasing rainfall, provide thermal insulation reducing heating and cooling loads, moderate the urban heat island effect through evapotranspiration, extend roof membrane lifespan by protecting it from UV radiation and thermal cycling, and provide biodiversity habitat in urban environments.

Extensive green roofs, with shallow growing media (60 to 150 mm) planted with drought-tolerant sedum species, are the most widely adopted system, adding 60 to 150 kilograms per square meter to roof dead load and requiring minimal maintenance. Intensive green roofs support a wider range of plant species and can include trees and shrubs in deeper substrate profiles (300 to 1000 mm), delivering greater biodiversity and amenity value at higher structural and maintenance cost. Living wall systems extend the green surface concept to vertical facades, providing cooling through shading and evapotranspiration, improving air quality through particulate absorption, and contributing to acoustic insulation.

2.8 Photovoltaic Building Materials

Building-integrated photovoltaics (BIPV) represent the convergence of material and energy system, replacing conventional building envelope elements with photovoltaic modules that generate renewable electricity while fulfilling their structural, weatherproofing, and aesthetic functions. BIPV products available commercially include photovoltaic roof tiles, glass-glass modules for structural glazing and skylights, spandrel panel replacements for curtain wall facades, and semi-transparent modules for shading canopies and atria.

The embodied carbon payback period for BIPV systems — the time required for electricity generation to offset production emissions — has fallen dramatically as solar cell efficiency and manufacturing process efficiency have improved. Current crystalline silicon BIPV modules typically achieve carbon payback within 1.5 to 3 years, while generating zero-emission electricity for 25 to 30 years thereafter. In high-solar-radiation regions such as

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Vol. 01, Issue 5, May 2026, pp : 1-6

the Indian subcontinent, Middle East, and Mediterranean, energy payback periods can be as short as 8 to 12 months.

3. Sustainable Construction Strategies

3.1 Passive Design Principles

Passive design strategies reduce building energy demand by working with climate rather than against it, minimizing the need for mechanical heating, cooling, and artificial lighting through building orientation, form, massing, and envelope design. The core passive design principles — solar orientation, natural ventilation, thermal mass, shading, and high-performance glazing — have been practiced in traditional vernacular architecture for millennia and are now rigorously codified in standards such as the Passive House standard (Passivhaus), ASHRAE 90.1, and the Indian National Building Code.

Passive house buildings achieve heating energy demand below 15 kilowatt-hours per square meter per year — typically 80 to 90 percent below conventional construction — through the combination of super-insulated envelopes with U-values below 0.15 watts per square meter per kelvin, triple-glazed windows, elimination of thermal bridges, airtight construction with controlled mechanical ventilation and heat recovery, and optimized solar gains. Over 65,000 certified Passive House buildings exist worldwide, demonstrating the replicability of the approach across diverse climates.

3.2 Design for Disassembly and Circular Economy

Conventional construction produces buildings that are difficult or impossible to disassemble at end of life without destroying most of the constituent materials. Design for disassembly (DfD) reverses this by specifying reversible connections, dry construction methods, standardized components, and material passports that document the identity and location of recoverable elements. Buildings designed for disassembly can recover 80 to 95 percent of their structural and envelope materials for direct reuse, dramatically reducing demolition waste and avoiding the embodied carbon of replacement materials.

The Dutch concept of adaptive reuse — designing buildings with generous floor-to-ceiling heights, regular structural grids, and adaptable service distribution to accommodate future changes in use without structural intervention — extends building service life by making adaptation economically attractive. Buildings that can evolve from residential to commercial to institutional use as urban needs change preserve their embodied carbon value over multiple use cycles, effectively amortizing production emissions over 200 or more years rather than the 50 to 80 year design life of conventional construction.

3.3 Water-Efficient Design

Sustainable construction addresses water consumption across three dimensions: reducing potable water demand through efficient fixtures and fittings, harvesting and treating non-potable water for appropriate uses, and managing stormwater to mimic pre-development hydrological behavior. Green building rating systems uniformly require water efficiency measures as a prerequisite for certification, reflecting the recognition that water scarcity is a co-equal sustainability challenge to climate change in many regions.

Greywater recycling systems collect, filter, and treat wastewater from washbasins, showers, and baths for reuse in toilet flushing, irrigation, and cleaning, reducing potable water demand by 30 to 40 percent in residential buildings. Rainwater harvesting systems collect roof runoff for non-potable uses, further reducing municipal supply demand. In water-stressed regions including much of India, Australia, and the southwestern United States, these systems transition from environmental aspirations to operational necessities.

4. Comparative Environmental Performance

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e-ISSN : 3139-065X

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Vol. 01, Issue 5, May 2026, pp : 1-6

Table 1 presents a comparative summary of the environmental performance, structural characteristics, and deployment status of the principal green building materials reviewed in this article:

Material	Embodied Carbon (kg CO2e/m3)	Renewable/Recycled	Thermal Performance	Structural Use	Commercial Maturity
Bamboo (engineered)	Negative to 50	Renewable	Moderate	Structural	Commercial
Cross-Laminated Timber	-250 to -100 (net)	Renewable	Moderate-Good	Structural	Commercial
Hempcrete	Negative (carbon sink)	Renewable	Good	Infill/Insulation	Growing
Recycled Steel (EAF)	400-700	95% recyclable	Low (conductor)	Structural	Fully commercial
Geopolymer Concrete	100-180	Industrial waste	Low	Structural	Commercial (niche)
Aerogel Insulation	300-500	Silica-based	Excellent	Insulation only	Commercial
BIPV Modules	250-400 (offset by gen.)	Recyclable	Moderate	Envelope/Energy	Commercial
Green Roof System	Variable	Renewable (plants)	Good	Non-structural	Fully commercial

Table 1: Comparative environmental and structural performance of green building materials

5. Green Building Rating Systems

5.1 LEED (Leadership in Energy and Environmental Design)

LEED, developed and administered by the US Green Building Council, is the world's most widely used green building certification system, with over 100,000 certified projects in more than 175 countries. LEED evaluates buildings against criteria across eight categories: location and transportation, sustainable sites, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality, innovation, and regional priority. Points are awarded for each measure, with total scores determining certification level: Certified (40 to 49 points), Silver (50 to 59), Gold (60 to 79), and Platinum (80 or above).

The materials and resources category within LEED rewards the use of products with recycled content, regional sourcing, rapidly renewable materials, and certified sustainably managed timber. It also incentivizes construction waste diversion from landfill and the creation of building material passports. The energy and atmosphere category — the most heavily weighted in LEED — rewards reduced operational energy through passive design, efficient mechanical systems, on-site renewable energy generation, and commissioning.

5.2 BREEAM (Building Research Establishment Environmental Assessment Method)

BREEAM, developed by the Building Research Establishment in the United Kingdom in 1990, is the oldest green

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Vol. 01, Issue 5, May 2026, pp : 1-6

building rating system and the most widely used in Europe and the United Kingdom. BREEAM assessments cover new construction, in-use buildings, and major refurbishments, evaluating performance across categories including energy, health and wellbeing, innovation, land use, materials, management, pollution, transport, waste, and water. Certification levels — Pass, Good, Very Good, Excellent, and Outstanding — reflect increasing performance thresholds.

BREEAM places particular emphasis on material environmental profiles through its Green Guide to Specification, which rates over 1,500 construction specifications based on life cycle assessment data. The system also requires consideration of responsible sourcing of materials, recognizing chain-of-custody certification schemes such as FSC (Forest Stewardship Council) for timber and BES 6001 for responsible sourcing of construction products more broadly.

5.3 GRIHA (Green Rating for Integrated Habitat Assessment)

GRIHA is India's national green building rating system, developed by The Energy and Resources Institute (TERI) and adopted by the Government of India as the national standard for green buildings. GRIHA is specifically calibrated to Indian climate conditions, material availability, construction practices, and regulatory frameworks, addressing the limitations of international rating systems that may not adequately reflect local conditions in the Indian context.

GRIHA evaluates buildings across 34 criteria covering site planning, construction management, energy, water, indoor environment, and social dimensions. The system places particular emphasis on passive design strategies suited to Indian climate zones, locally sourced materials including fly ash bricks, stabilized compressed earth blocks, and bamboo, and the reduction of potable water use through rainwater harvesting and greywater recycling. As of 2024, over 7.5 billion square feet of built-up area in India is registered under GRIHA, reflecting strong policy support and institutional adoption.

6. Economic Analysis of Green Building

6.1 Cost Premium and Payback

Green buildings have historically commanded a construction cost premium of 2 to 10 percent over conventional equivalents, reflecting the higher cost of certified materials, specialist systems, enhanced commissioning, and third-party certification fees. However, research spanning multiple markets and building types consistently demonstrates that this premium is recovered through operational savings — reduced energy and water bills — within 3 to 10 years, with significant net present value savings over the building's service life.

A comprehensive 2022 study by the World Green Building Council analyzing 62 green commercial buildings across 12 countries found average energy cost savings of 25 to 35 percent relative to national building energy codes, average water cost savings of 30 to 50 percent, and premium rental rates of 5 to 10 percent over non-certified comparable buildings. Capitalized at prevailing commercial property yields, these rental premiums represent an increase in asset value of 7 to 14 percent, substantially exceeding the construction cost premium.

6.2 Whole-Life Cost Considerations

Whole-life costing — accounting for construction, maintenance, energy, water, refurbishment, and end-of-life costs over a building's full service life — consistently demonstrates the financial superiority of green construction even where upfront premiums are present. Reduced maintenance costs, extended component service lives, and lower operational energy and water expenditure compound over decades to produce substantial whole-life savings.

Materials selection is central to whole-life cost performance. Durable materials with lower maintenance

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Vol. 01, Issue 5, May 2026, pp : 1-6

requirements — high-quality timber cladding with appropriate detailing, for instance — may cost more initially than PVC alternatives but avoid the periodic replacement costs and environmental impact of shorter-lived products. Life cycle assessment and whole-life costing should be conducted concurrently in the design stage, enabling informed decisions that balance upfront cost against long-term financial and environmental performance.

6.3 Green Building and Property Markets

The relationship between green certification and property market performance has been extensively studied over the past decade. Consistent findings across major markets including the United States, United Kingdom, Australia, and Singapore demonstrate that LEED- and BREEAM-certified commercial buildings achieve rental premiums of 4 to 11 percent, sale price premiums of 5 to 15 percent, and lower vacancy rates than non-certified comparable buildings.

In India, green-certified office buildings in major cities including Mumbai, Bengaluru, and Hyderabad have attracted foreign institutional investment at preferential terms, as global real estate investors increasingly require sustainability certification as a prerequisite for investment. The Securities and Exchange Board of India's Business Responsibility and Sustainability Reporting (BRSR) framework, which requires listed companies to disclose sustainability metrics, is accelerating the corporate occupier demand for certified green buildings.

7. Challenges and Barriers to Adoption

7.1 Material Availability and Supply Chain

The geographic distribution of green building materials is uneven. Bamboo construction expertise and supply chains are concentrated in Asia, where over 80 percent of global bamboo species grow, limiting accessibility in other regions. CLT manufacturing capacity, while growing rapidly, remains insufficient to meet projected demand in rapidly urbanizing markets, and the long lead times and specialist logistics of large-format CLT panels constrain adoption in markets without established supply chains.

Hempcrete construction requires a supply chain encompassing hemp cultivation, retting, shiv separation, and lime production — a chain that is immature or absent in many markets. Regulatory barriers to hemp cultivation, arising from its association with cannabis despite the negligible THC content of industrial hemp, have historically constrained supply in the United States and several Asian markets, though legislative changes in recent years are opening the way for domestic hemp supply chain development.

7.2 Skills and Workforce Development

Many green building materials require construction techniques unfamiliar to the conventional building workforce. CLT joinery, hempcrete casting, green roof waterproofing, and BIPV installation all demand specialized skills that are not routinely covered in standard construction vocational training. This skills gap results in higher labor costs for green building projects, slower construction progress, and quality risks that can undermine the performance benefits that the materials are designed to deliver.

Addressing the skills gap requires systematic reform of construction vocational training curricula to incorporate green material handling, passive design detailing, and energy system integration as core competencies rather than specialist electives. Industry bodies including the Confederation of Indian Industry, the UK Green Building Council, and the US Green Building Council are developing competency frameworks and training programs, but the pace of curriculum reform lags behind the pace of material and technology innovation.

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Vol. 01, Issue 5, May 2026, pp : 1-6

7.3 Regulatory and Code Barriers

Building codes in many jurisdictions have not kept pace with innovations in green building materials. Structural design codes for mass timber are absent or conservative in many markets outside Europe and North America, limiting permissible building heights and requiring costly engineering justification for straightforward applications. Performance-based building codes, which evaluate materials and systems against functional outcomes rather than prescribing specific products or methods, provide a more accommodating framework for innovation but require more sophisticated engineering analysis and regulatory competence than prescriptive codes.

Embodied carbon regulation — mandating maximum permitted embodied carbon in new buildings — is beginning to emerge in jurisdictions including the Netherlands, Denmark, Finland, and several US cities, creating a regulatory driver for low-carbon material selection. India's Bureau of Energy Efficiency has incorporated embodied energy considerations in the Energy Conservation Building Code, and further strengthening of embodied carbon requirements is anticipated in future code revisions.

8. Policy Frameworks Driving Adoption

Policy interventions across multiple levels of government are accelerating the adoption of green building materials and sustainable construction practices:

- Green public procurement mandates require government-funded construction projects to meet minimum green building standards, leveraging the substantial purchasing power of the public sector to create market demand and demonstrate viability at scale
- Carbon pricing mechanisms including emissions trading schemes and carbon taxes increase the financial cost of high-carbon conventional materials, improving the relative economic competitiveness of low-carbon alternatives
- Green building incentives including tax credits, density bonuses, expedited planning approval, and concessional finance reduce the effective cost premium of green construction and shorten payback periods
- Minimum energy performance standards for new buildings and major renovations, progressively tightened on a scheduled trajectory toward near-zero energy standards, drive demand for high-performance envelopes and systems
- Extended producer responsibility regulations for construction products require manufacturers to take back and recycle products at end of life, incentivizing design for recyclability and stimulating secondary material markets
- Research and innovation funding directed toward scaling green material supply chains, reducing production costs, and developing performance characterization and testing standards

India's Smart Cities Mission, the Housing for All initiative, and the National Action Plan on Climate Change all incorporate green building requirements that are driving adoption at significant scale. The Bureau of Energy Efficiency's Energy Conservation Building Code has been progressively strengthened and now applies to commercial buildings above 100 square meters in conditioned floor area, with residential applications under development. State-level green building policies in Maharashtra, Tamil Nadu, Karnataka, and Andhra Pradesh supplement national frameworks with local incentives and requirements.

9. Future Directions

The trajectory of green building materials development points toward several transformative developments over the next decade:

- Mass timber construction will extend to increasingly tall buildings as structural performance data accumulates, fire codes are updated, and manufacturing capacity scales, with 30 to 50 story CLT and hybrid timber-concrete buildings anticipated in major urban markets

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editor@ijemss.com

Vol. 01, Issue 5, May 2026, pp : 1-6

- Carbon-negative material systems combining biological carbon sequestration with long-life structural applications will move from demonstration to mainstream, driven by embodied carbon regulations and voluntary net-zero building commitments
- Digital material passports, enabled by building information modeling and blockchain traceability, will allow the identity, location, and condition of every recoverable material in a building to be tracked throughout its life, facilitating component reuse at end of life and enabling circular economy business models
- Smart building envelopes integrating photovoltaics, electrochromic glazing, phase-change thermal storage, and biosensing into unified facade systems will transform the building envelope from a passive barrier to an active energy and environmental management system
- Mycelium-based composites, grown from agricultural waste substrates inoculated with fungal mycelium networks, are emerging as a bio-based alternative to rigid foam insulation and packaging materials with particularly low embodied energy and full biodegradability
- 3D-printed construction using low-carbon concrete, geopolymer, or earthen material feedstocks will reduce construction waste, enable complex structural geometries that optimize material efficiency, and accelerate construction timelines in labor-constrained markets

The convergence of bio-based materials innovation, digital design and manufacturing, circular economy principles, and tightening regulatory requirements creates conditions for a fundamental transformation of the construction sector's environmental performance over the next two to three decades. Achieving this transformation will require sustained collaboration between materials scientists, structural engineers, architects, regulators, investors, and the construction workforce — but the technical building blocks are increasingly in place.

10. Conclusion

The transition to green building materials and sustainable construction practices is no longer a niche aspiration but a mainstream imperative, driven by the convergence of climate regulation, investor pressure, occupier demand, and the growing economic competitiveness of low-carbon alternatives. The materials reviewed in this article — bamboo, cross-laminated timber, hempcrete, recycled metals, low-carbon concrete, aerogel insulation, green roofing, and BIPV — collectively demonstrate that the construction sector has access to a comprehensive palette of green alternatives for every structural and envelope application.

The environmental case for green building materials is robust and well-evidenced across life cycle dimensions. Embodied carbon savings of 30 to 80 percent are demonstrated for the principal alternatives to conventional materials. Operational energy savings of 25 to 90 percent are achievable through the integration of passive design strategies with high-performance building envelopes. Water use reductions of 30 to 50 percent are routinely achieved in certified green buildings. Cumulatively, these gains represent a transformative reduction in the construction sector's contribution to climate change, resource depletion, and environmental degradation.

The economic case is equally compelling when evaluated on whole-life cost terms. Upfront premiums of 2 to 10 percent are recovered within 3 to 10 years through operational savings, while green certification delivers measurable increases in rental income, asset value, and market liquidity. The principal barriers to adoption — skills gaps, supply chain immaturity, regulatory inertia, and first-cost bias among clients — are real but addressable through policy intervention, industry investment, and professional education.

The built environment of 2050 will be shaped by decisions made in design offices and construction sites over the next decade. If those decisions embrace the green building materials and sustainable construction strategies reviewed in this article, the construction sector can make a decisive contribution to a livable, resource-efficient, and climate-stable world. The technical knowledge, commercial products, and policy frameworks necessary for this transition are available. What remains is the collective will to deploy them at

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e-ISSN : 3139-065X

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Vol. 01, Issue 5, May 2026, pp : 1-6

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