

Green Construction Technologies: A Comprehensive Review of Sustainable Building Materials, Energy-Efficient Design Strategies, and Lifecycle Assessment Frameworks

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ABSTRACT

Green construction technologies have turned out to be a strategic reaction to the global call of low-emission and green infrastructure. This review attempt will give a general overview of the green building concepts that focus on three dimensions that are matters of concern: the sustainable material used in construction, energy-efficient design process, and lifecycle assessment (LCA) approaches. The main task is to digest the existing improvements and discover new possibilities of sustainable building. Due to the direction of the study and the description above, a thematic review methodology is adopted in the definition and screening of peer-reviewed literature, industrial reports, and international standards on low-carbon materials including geopolymers concrete (up to 70% of embodied carbon reduction), recycled aggregates (30-40% resource saving), bamboo (tensile strength equal to mild steel), and phase-change materials (3-5 induction temperature flux capacity). Passive cooling, daylighting (creating natural lighting up to 50 percent more), thermal insulation (preventing energy loss by 2535 percent), and intelligent HVAC systems (lowering operational energy by 2030 percent) count among the design methods that have been critically re-evaluated. Further, the review assesses LCA tools including SimaPro and OpenLCA and discusses their use in measuring embodied energy, carbon footprint and a wider scope of environmental impact within a building life course. The results demonstrate that, although the possibility of green materials and energy-efficient designs is growing, the combination problems, data standardization and economic trade-offs problems are still preventing a full-scale implementation. Lifecycle assessment, albeit promising, needs wider alignment of interested parties and formulation of regionframe works to meet variability in environmental information. In this review, it is concluded that the argument about the multidisciplinary approach through an integration of material innovation, intelligent energy systems and a robust LCA modeling are critical towards the mainstreaming of green construction and realization of measurable outputs of sustainability. The paper provides practical guidance on how engineers, architects and policy makers can proceed in having their built environment work with climate objectives and the regulatory system.

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INTRODUCTION

Construction contributes significantly to environmental degradation all over the world and this is attributed to high use of energy in the industry as well as using highly carbonated products like cement and steel.^[1] With a recent increase in frequency and intensity of the

climate changes and the lack of resources, the modern world urgently needs the transition to environmentally friendly and responsible building operations. Here, green construction technologies have come out as an important solution in overcoming the effects on the environment on building lifecycle. This review seeks to offer an integrative overview of three pillars of green construction

consisting of the following: (i) sustainable construction materials, (ii) energy-efficient structural and system design, and (iii) lifecycle assessment (LCA) studies on measuring environmental performance. Other possibilities include passive solar building design, sophisticated HVAC integrated systems, building materials, including geopolymers, concrete, bamboo and the use of recycled aggregates that can lead the way towards carbon minimisation and energy efficiency and heat retention.

Nevertheless, most of the available studies have a predilection to isolate these areas. There are scanty interdisciplinary works, which comprehensively assess the overall effect of materials novelty, design solutions, and LCA nudges on the sustainability of buildings. In addition, the degree of standardization across regions and the comparative performance measures of LCA tools has not been developed.^[2, 3]

The review will fill these gaps by taking a thematic narrative review approach and integrating the recent developments in materials science, architectural design, and environmental scrutiny. As compared to systematic review, which is conducted according to specific inclusion/exclusion criteria (e.g., PRISMA), and provides more specific and limited vision, in this study, a thematic synthesis of peer-reviewed literature, industrial whitepapers, and international guidelines will be used to provide a broader, and interdisciplinary view. The goal is to develop combined strategies in touch with the global climate goals and sustainable concepts of development besides pinpointing the existing shortages of LCA standardization, cross-sector combining, and scalability of green building solutions.

LITERATURE REVIEW / RELATED WORK

During the past few decades, the green construction technologies received much attention because of the increased environmental and energy challenges. The current body of knowledge can be mostly subdivided into three distinguishable spheres, i.e., sustainable construction materials, energy performance building designs, and the evaluation of environmental performance through lifecycle approach.

Sustainable Materials

Low-carbon materials, especially geopolymer concrete have been widely studied as industrial by-products such as fly ash and ground granulated blast furnace slag (GGBFS) can be used to lower embodied carbon emissions by up to 80% in a geopolymer concrete mix relative to OPC-based concrete.^[1] Some other research deals with the possibilities of using natural materials, including

bamboo, hempcrete and cork that have advantages related to biodegradability, heat performance and renewability.^[2] There are however some challenges to the standardization of the materials and also their mechanical resistance to changes in climate conditions.

Energy-Efficient Building Design

Various models of passive design methodology are there including thermal mass optimization, orientation of structures in buildings, and planning of ventilations to reduce energy demand in minimization levels.^[3] Integrative systems with active energy and photovoltaics, smart HVAC and building energy management systems (BEMS) have also been considered.^[4] With such developments it happens that energy efficient designs are inefficient in terms of material and environmental aspects of sustainability, and merely emphasize the operational performance aspects.

Lifecycle Assessment (LCA)

LCA models, which have been popularly applied to measure the footprint on the environment throughout the life cycle of a building (out of the ground to the ground) include SimaPro, GaBi, and OpenLCA.^[5] These tools have been used in studies to quantify global warming potential (GWP), embodied energy and water footprint of different building materials and designs.^[6] However, data set, definition of boundaries, and regional norm differences still have implications on study cross-comparability and replicability.

Besides, trade-offs of impact categories are common in comparative LCAs, particularly when comparing biogenic materials with industry materials. As an example, bamboo is normally found to have lesser GWP and embodied energy because of the fast renewability and carbon dumping biology. Nevertheless, treatment and preservation processes may cause increase in acidification potential or eutrophication because of the use of chemicals. On the other hand, geopolymer concrete considerably minimizes embodied carbon store up of to 70 percent lesser than Portland cement, however, its manufacture can be associated with increased overall energy use because it utilizes industrial by-products such as fly ash and alkali activators. These trade-offs point to the need of multi-criteria LCA assessment methods which consider more than single-impact metrics in order to achieve more balanced sustainability analysis.

Identified Gaps

There is a lot of individual progress in each of the fields, but there aren't many studies that provide

an integrated approach to sustainable materials and energy efficient designs with an LCA-based evaluation all together. Furthermore, query studies on real world performance validation, cost benefit analysis and policy parallelism towards large scale implementation are low. This review fills these gaps by overlying the findings of the interdisciplinary work and providing a single view on green construction technologies.

SUSTAINABLE BUILDING MATERIALS

Use of material in construction has a significant impact in ascertaining embodied energy of a structure, carbon footprint, and sustainability. Newer inventions have led to the emergence of alternative materials and technologies which secure to minimise the use of resources, boost the energy in buildings, and circularity. This section is grouping sustainable building materials into four broad categories namely: geopolymer binders, recycled aggregates, renewable bio-based materials and smart functional composites.

Geopolymer Concrete and Low-Carbon Binders

Geopolymer concrete technology is becoming an acceptable alternative to conventional Ordinary Portland Cement (OPC) which has much lesser effect on the environment. It is also produced using the alkali activation of alumino-silicate-rich industrial by-products (fly ash, blast furnace slag and metakaolin) instead of the clinker production process. It has already been shown that the embodied carbon of geopolymer concrete can be 70-80 percent lower than the same using OPC based concrete, although they can be similar or better in terms of their engineering and service life qualities.^[1] Besides carbon mitigation, such binders are highly fireproofed and chemically stable, which implies their use in infrastructure located in aggressive environments. In Figure 1, a comparison of the environmental and material impacts of cement produced by the OPC method and geopolymer concrete has been given, including the benefits of geopolymer concrete because of the sustainability of the product.

Recycled Aggregates and Demolition Waste

Utilization of construction and demolition waste (CDW) in new concrete mixes is in line with resource savings and landfill. Reclaimed masonry and recycled concrete aggregates (RCAs) have found their place in both structural and non structural usages, creating closed loop materials. Although RCAs can be weak and absorb water under the influence of mortar attached to it, improvement in the surface treatment method, pre-soaking and hybridization with natural aggregates has

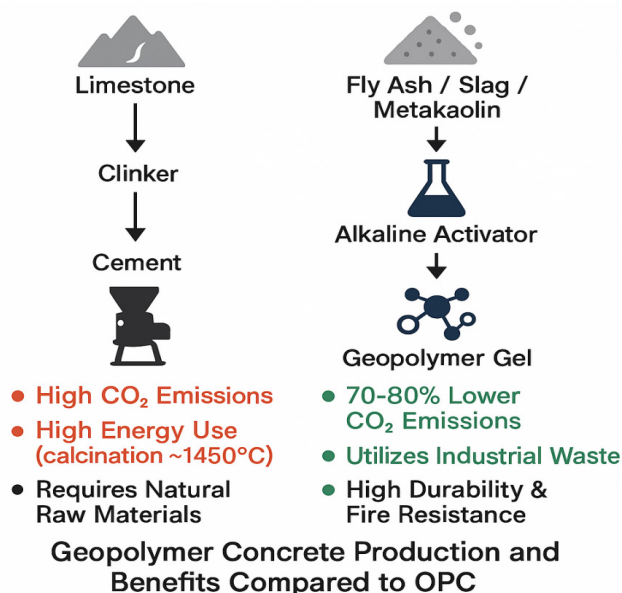


Fig. 1: Comparative Overview of OPC-Based Cement vs. Geopolymer Concrete: Raw Materials, Process Pathways, and Environmental Impacts

bettered the performance.^[2] In the areas where there is a high level of urban redevelopment, adoption is on the increase helped by green certification system on the environment.

In Figure 2, the recycling process of CDW in a closed-loop can be described by the following steps of improving sustainability in concrete production, that is, collection, processing, treatment and reintegration of CDW.

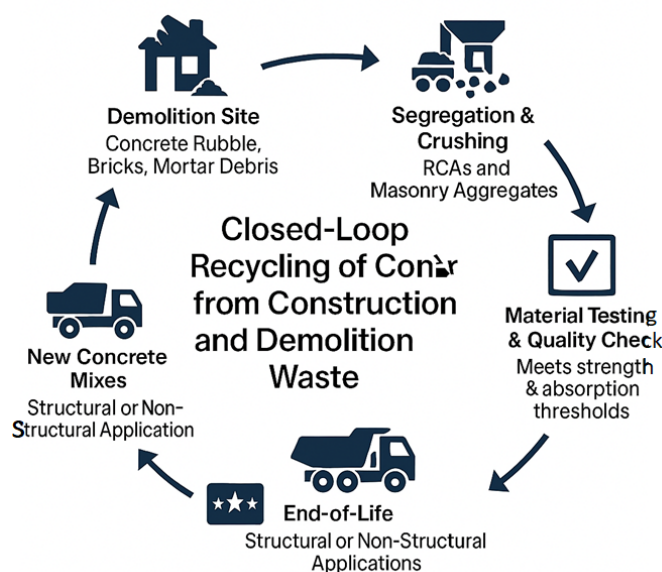


Fig. 2: Closed-Loop Recycling Process of Construction and Demolition Waste (CDW) for Sustainable Concrete Production

Table 1: Comparative Properties of Selected Sustainable Building Materials

Material	Density (kg/m ³)	Thermal Conductivity (W/m·K)	Compressive Strength (MPa)	CO ₂ Savings	Notes
RCAs	2300-2500	1.4-1.8	20-30 (with treatment)	~30-50% compared to virgin concrete	Requires moisture conditioning; higher porosity
Bamboo	600-800	0.12-0.15	Up to 80 (parallel to fiber)	Up to 60% compared to steel	High tensile strength; renewable; treatment required
Hempcrete	300-500	0.06-0.12	1-3	~80% compared to conventional concrete	Excellent insulation; used for non-load-bearing walls
PCMs (e.g., paraffin)	800-900	0.2-0.4	-	Indirect energy savings via HVAC	Stabilizes indoor temp by 3-5 °C; embedded in wallboards

Renewable Natural Materials

Low embodied-energy, locally available ecologically-friendly materials like cork, bamboo, straw bale, hempcrete and rammed earth, benefit in respect of low embodied-energy and carbon sequestration. Bamboo (especially) is becoming known because of its extreme strength to weight ratio, short growth cycle and possibilities of prefabrication in mobile homes.^[3] The material that is created by a composition of hemp shiv and lime hempcrete has great insulating and humidity control qualities and is appropriate to use in temperate and humid climates. The challenge affecting these materials however is international standards and longevity testing as well as fire safety marking certification.

Smart and Functional Materials

The future sustainable building involves the use of the materials that are functional and fitted in such a way that they react to the stimulus in their environment. Examples of phase-change materials (PCMs) include the ability to store and release latent heat, evening out swings in temperature indoors as well as pushing down energy requirements of the HVAC system. ULTRA-LOW Thermal conductivity aerogels are applicable to thermal insulate of space-constrained retrofits. Natural fibers combined as natural fiber reinforcement of bio-based composites in the form of flax, jute or kenaf is also showing the potential as a low-impact alternative in respect to synthetic interior finishes and insulation.^[4] Use of such smart materials in building envelopes has huge potential in energy efficiency, although the costs, scalability and durability throughout the building lifecycle are still to be examined. The functional role and paths of integration of smart and intelligent materials as sustainable building elements are compactly summarized in figure 3 and they

are shown to contribute to adaptive and energy efficient building envelopes.

Functional Roles of Smart Building Materials in Sustainable Construction

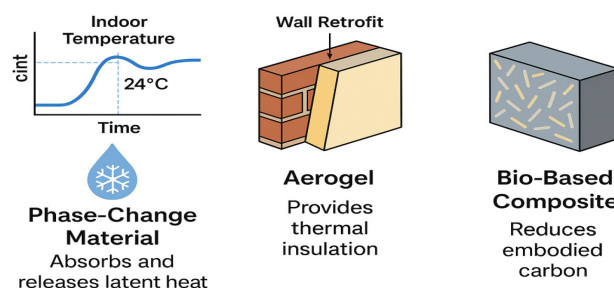


Fig. 3: Smart and Functional Materials in Sustainable Construction: Functional Roles and Integration into Building Envelopes

ENERGY-EFFICIENT DESIGN STRATEGIES

The design of energy efficient buildings is a backbone of green construction and it will directly affect the energy demand of operation of the building, thermal comfort and can affect its future sustainability. Energy performance optimization must allow active renewable energy technology and smart buildings along with a synergetic combination of all capabilities of passive architecture. Figure 4 provides a comparative analysis of the categories of such energy-efficient design solutions in sustainable constructions representing the role of each of the operated components such as passive, active, and smart systems in the energy optimization or the general sustainability performance of the structure in question and helping reach the net-zero energy goal. Each of the categories and their influence to the goals is explained in this section.

Passive Design Elements

The passive design approach is meant to reduce the use of mechanical structure of a building by using natural environmental conditions. There are essentials such as:

- Building orientation: Orientation to maximize sun-gain in colder climates, or minimize solar-gain in warmer climates, has a key impact on indoor thermal performance.
- Natural ventilation: effective passive cooling can take place largely due to cross-ventilation, stack effect, and operable windows, especially in temperate and tropical regions.
- Thermal mass: high-thermal inertia materials (e.g. concrete, rammed earth) act as a heat sink during the day and a heat source at night allowing building interior temperatures to stabilize.
- Daylighting: Optimal window, skylight and light placements eliminate the use of artificial lighting and enhances the well-being of occupants.

Such passive methods have the potential of saving up to 40 percent of energy on heating, ventilation and cooling (HVAC) especially when implemented in the initial design stages.^[1]

Active Energy Systems

Active energy systems are more energy efficient since they rely on mechanical and renewable types of technology to optimize energy at real time. Some of the main items are:

- Building-Integrated Photovoltaics (BIPV): On-site renewable electricity can be supplied without having to dock aside with aesthetics through integrating photovoltaics into the buildings facade or roofs.
- Geothermal Heat Pumps: Ground-source systems are used to heat and cool (space) with an energy efficient method, by using a stable temperate of the earth in the sub-surface.
- Smart HVAC Systems HVAC systems are smart systems with variable refrigerant flow (VRF), demand-controlled ventilation (DCV), and zonal temperature controls with minimal energy consumption.

These technologies, when together, can cut the primary energy required in a building by more than 60 percent and thus are essential in net-zero buildings (NZEBS) [2].

Smart Building Technologies

Smart system integration does not only provide an efficiency level with existing operations but also allows

achieving predictive maintenance, flaw detection, and real-time dashboard on energy consumption, making it to reduce carbon footprint and cost of the operations.^[3] Nonetheless, the application of smart technologies based on the use of the IoT has its significant constraints, as well. There is also an issue of data security and privacy because building automation systems tend to move sensitive occupant and operational data through the networked systems, making them vulnerable to cyberattacks and unauthorized and illegal access of data. Moreover, the anticipated energy savings can be reduced by lifecycle costs such as sensor calibration, computer software, data storage systems and ultimate technological obsolescence unless considered in earliest phases of design. The challenges stipulate the demand of full-scope cost-benefit analysis, advanced cybersecurity measures, and data governance policies to support the sustainability and credibility of smart building technologies in the long term.

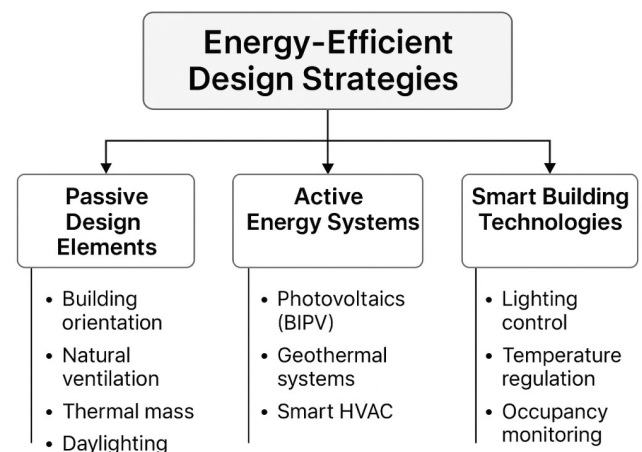


Fig. 4: Energy-Efficient Design Strategies in Sustainable Buildings

LIFECYCLE ASSESSMENT (LCA) IN GREEN CONSTRUCTION

Lifecycle Assessment (LCA) is a quantitative and systemic approach that is applied in the assessment of the environmental impact of an entire life cycle of a building, a product or a process which is measured starting with extraction of raw materials up to disposal or recycling of this product. Within the framework of green construction LCA offers a powerful tool in terms of acquiring a picture of the embodied and operational environmental loads of materials, systems, and construction processes. It is also useful in making evidence-based decisions that can further reduce an eco-footprint of a building and make it sustainable enough to endorse the requirements

of sustainability rating tools like the LEED, BREEAM, and Green Star. In Figure 5 is shown the standardized LCA approach of green building describing the stages of the sequential process of a typical LCA, i.e. goal and scope definition, inventory analysis, impact assessment and interpretation throughout the life cycle of the construction work.

LCA Methodologies

The LCA is a common pattern with an established approach that is used according to ISO 14040 and ISO 14044, which includes four major steps:

1. Goal and Scope Definition: Describes goal, boundaries of the system (cradle-to-gate, cradle-to-grave), and the functional unit (e.g. per m² of building site).
2. Life Cycle Inventory (LCI): Measures energy and flow of materials (inputs / outputs) of all stages of life cycle.
3. Life Cycle Impact Assessment (LCIA): Converts inventory analysis into the categories of environmental impacts: carbon emission, acidification, eutrophication, etc.
4. Interpretation: Determines hotspots and trade-offs to aid in the process of decision making by facilitating environmental optimization.

In the construction of buildings with a green construction technique, methodology is exercised at all the stages of building life, namely, at the stage of material production, transportation, building, working, maintenance, and the end-of-life (EOL) destruction or recycling.^[1]

LCA Tools and Databases

A number of LCA-specific tools and databases are facilitating LCA in the building industry:

- SimaPro: a general purpose LCA program, with full modeling and impact analysis capability, popular in academia and industry.
- Athena Impact Estimator: Specifically designed to the North American building construction methods, centers on materials and full building LCA.
- OpenLCA: An open-source tool that has the capability to work with several databases (e.g. ecoinvent, GaBi).
- Tally^{#194}: Revit plugin that allows real-time BIM-linked LCA modeling inside an architecture application.

These instruments are based on life cycle in-depth inventories (LCIs) obtained in such databases as Ecoinvent, GaBi and USLCI, and include emission factors, energy consumption patterns, material flow information that are absolutely necessary in proper analysis.^[2]

Performance Metrics and Impact Categories

Results of LCA are normally expressed in quantified form of impacts into various dimensions. Some indicators are:

- Global Warming Potential (GWP): Measured in kg CO₂-equivalent GWP is an indicator of the overall carbon footprint of the building.
- Cumulative Energy Demand (CED): Signifies the amount of primary energy consumed throughout the life cycle of the building, including non-renewable and renewable sources as dissociated.
- Water Footprint: quantifies the amount of freshwater used in the process of extracting and processing materials as well as the construction process.
- Ozone Depletion Potential (ODP), Acidification Potential (AP), as well as Photochemical Ozone Creation Potential (POCP) are usually determined based on the scope of the project.

Multidirectional indicators enable that material selection options, design options and retrofit plans can be evaluated comparatively, with several climatic and legislative scenarios.^[3]

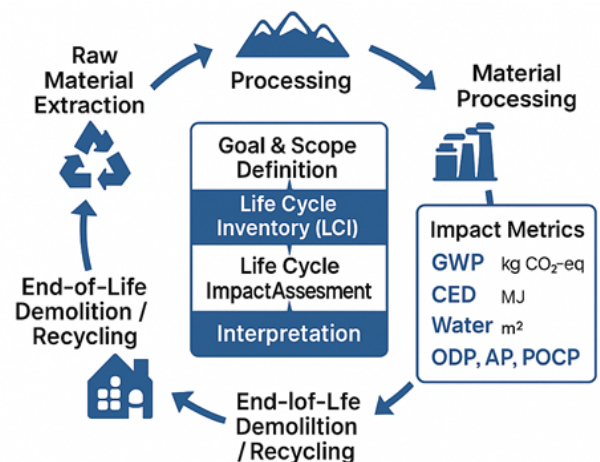


Figure 5: Lifecycle Assessment Framework for Green Buildings

CHALLENGES AND RESEARCH GAPS

Compared to the promising progress made in terms of green construction technologies, there are still a

number of barriers and unsolved questions that prevent the diffusion of green technologies and their successful performance demonstration. These gaps either cut across the domain of standardization, data availability, system integration, as well as socioeconomic factors. Resolving these challenges and gaining a further in-depth comprehension of them is critical to achieving the scale of sustainable practices worldwide in a fair manner.

Lack of Standardized Lifecycle Assessment (LCA) Frameworks

Even though LCA is a generally recognized process to measure environmental effects, the general feedback is that one does not exist to make a universal processing model that includes regional differences whereby buildings are done, climatic conditions, and energy mixes. Software such as SimaPro and OpenLCA are based on other databases (e.g. ecoinvent, GaBi), which might not represent local data of developing countries or tropical climates. Interestingly, LCA data invariances in system boundaries, functional units and impact categories undermine the consistency of the output results in a study to another study and even the global benchmarking.

Integration Complexity of Smart Systems

There are immense challenges on deployment of smart technologies such as smart HVAC systems with IoT, building lighting automation, and building energy management systems (BEMS) in legacy buildings, and existing urban infrastructure. The capability of these technologies to work together and expand is restricted by compatibility problems, the shortage of experienced resources, and cybersecurity weaknesses. Not only that, multi-vendor systems are expensive and technically difficult to integrate due to the lack of harmonized communication protocol and standards in different platforms.

Limited Long-Term Performance Data on Emerging Materials

Although materials, including geopolymer binders, bio-based composites, and phase-change materials, display promising laboratory-level performance, long-term data in field settings has not confirmed the materials sustainability to a wide range of environmental conditions. There is still a concern on the degeneration of the material, sensitivity to moisture, fire and the kind of compatibility under real life circumstances. The lack of performance monitoring tools and unified accelerated aging procedures also limit the procedure of material certification and code acceptance even more.

Socioeconomic and Policy Barriers to Adoption

Economic feasibility, regulatory-related requirements as well as awareness are significant threats to the adoption of green construction technologies. In less wealthy parts of the world, or in the case of lower-income and middle-income parts, it is a deterrence due to higher costs of sustainable material and smart technology acquisition, although in many cases, lifecycle savings are relatively advantageous. Also, equitable implementation is hindered by the lack of green financing opportunities and an insufficient policy framework, as well as provision of capacity-building programs. In the absence of inclusive structures and facilitating administration, Green shift to sustainable construction continues to be skewed towards regions.

To enable the development of strategic decisions and purposeful interventions, the table below provides the synthesis of the key barriers presented in this section as well as the suggested mitigation strategies:

FUTURE DIRECTIONS

To achieve a low-carbon, resource consistent and resiliency-based built environment, innovation at the nexus of material science, digital engineering and

Table 2: Summary of Challenges and Mitigation Strategies in Green Construction

Challenge	Description	Proposed Mitigation Strategy
Lack of Standardized LCA Frameworks	Inconsistent system boundaries, regional databases, and impact categories	Develop region-specific LCA templates and harmonized global benchmarking metrics
Smart System Integration Complexity	Limited interoperability, high retrofitting costs, cybersecurity risks	Establish open-source protocols and promote cross-platform compatibility standards
Insufficient Long-Term Data on Emerging Materials	Lack of durability validation under field conditions	Implement field monitoring, accelerated aging tests, and real-world pilot projects
Socioeconomic and Policy Barriers	High initial costs, lack of incentives, and limited stakeholder awareness	Provide green subsidies, capacity-building programs, and enforce supportive policies

environmental policy are required. With increasingly ambitious sustainability objectives being set within frameworks (like the UN Sustainable Development Goals (SDGs) or the European Green Deal), and in nationally-established net-zero commitments, the following future directions will dominate the next generation of green construction technologies.

Development of AI-Assisted LCA Tools for Real-Time Performance Modeling

However, although robust, the traditional Lifecycle Assessment (LCA) methods used are too time-consuming, static, and can be only manual. Artificial Intelligence (AI) integration, especially machine-learning and knowledge-based systems can transform LCA and make it possible to perform modeling of the performance in real time and predictive analytics and benchmarking of the materials on an automated basis. Actual environmental impact profiles could be dynamically changed via LCA platforms enhanced by AI in the case of changes in projects, site-specific variables, and sensor reports by smart infrastructure. Such swap would have a considerable benefit of enhancing the speed and accuracy of decision making throughout design and retrofitting processes.

Mainstreaming Biocomposite and Carbon-Negative Materials

Construction activities in the future will feel the benefit of popularization of biogenic and carbon-negative materials (hempcrete, mycelium-based insulation, biochar-infused concrete, algae-derived binders). The materials do not only bind atmospheric CO₂ in creating the materials but can also present lightweight, biodegradable and energy-efficient alternatives to building materials based on petrochemicals. Research Horizons to speed the uptake in the market should concentrate on increasing the volume of fabrication processes; on increasing fire and water resistance and, setting international requirements of performance standards.

Policy-Driven Incentives for Zero-Energy and Circular Construction

Systemic sustainability will only be achieved in case of strong policy systems that favor the economic feasibility and social acceptance of the green technologies. Future research areas are:

- Green tax credits and carbon pricing that give incentives to low-emission buildings
- The Building codes that are needed on LCA-based buildings
- Circular economy requires rematerialization and recuperation

- Green finance at subsidized interest rate to low-income housing schemes

Ecosystems that use incentives play an essential role in transforming construction norms to net-zero energy in construction buildings (NZEBS) and closed-loop material cycles.

Creation of Global Material Passports and Digital Twins for Infrastructure Sustainability

The coming of material passports as computerized datasets including comprehensive details about the composition, lifecycle impact, reuse potential and circularity score of a material will change the manner in which sourcing, handling and reuse of materials is carried out. Combined with building information modeling (BIM) and digital twin technologies these tools make possible:

- Traceability of end-to-end materials
- Infrastructure predictive maintenance

Planning and material recovery operations on a data-drive basis

The particular advantage of digital twins is that they enable real-time physical performance monitoring of the building, which enables the adaptive operations and more intelligent resource deployment during the building lifecycle.

CONCLUSION

The green construction technologies are a revolutionary solution to the decarbonization of the built environment and its climate resilience. The state-of-the-art was reviewed on the basis of 3 key pillars which are; sustainable material innovation, energy-efficient design strategy, and lifecycle assessment (LCA) frameworks. In the combination, all these methods have been found to show considerable degrees of being able to decrease the amount of embodied and operational carbon emissions, improve the energy performance, and increase the practical life of any building. The example of geopolymer concrete, recycled aggregates, bio-based composites, and smart materials show a change in resource flow owing to a linear-circular relationship. At the same time, the merger of passive approaches and active measures has revealed that with the help of smart building technologies, it is possible to strive to achieve the net-zero energy levels in both climatic and socioeconomic environments. Other tools of lifecycle assessment and metrics have also facilitated making decisions based on data quantification of environmental trade-offs over a building as a unit over the building life span.

Even after these improvements, other issues still exist in standardization, long-term material validation, and inclusive policy implementation. Responses to them should be taken by the further research which should be interdisciplinary and involve the use of civil engineering, environmental studies, digital technologies and economics. Also, the regulatory requirements, the system of incentives, and education would be critical in the stimulation of practices which are green.

To sum it all up, green construction has evolved to a working reality, leaving it no longer a dream. Its mainstreaming will be crucial to reach net-zero emission, UN Sustainable Development Goals (SDGs), and urban climate adaptation and is therefore the key to sustainable infrastructure of future generations.

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