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SMART

AND RENEWABLE BUILDING MATERIALS FOR SUSTAINABLE ARCHITECTURE: PROPERTIES, APPLICATIONS, CHALLENGES, FUTURE PERSPECTIVES, SYSTEMATIC REVIEW

MATERIALES INTELIGENTES Y RENOVABLES PARA ARQUITECTURA SOSTENIBLE: REVISIÓN SISTEMÁTICA, PROPIEDADES, APLICACIONES, DESAFÍOS Y PERSPECTIVAS FUTURAS

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ABSTRACT

Rapid urbanization, increasing energy consumption, natural resource depletion, and intensifying climate change impacts have positioned the construction industry as a critical sector for sustainable development. Buildings account for substantial global energy consumption, greenhouse gas emissions, and resource utilization, making advanced building materials with smart functionalities and renewable origins essential for reducing environmental impacts while enhancing performance. Smart materials respond to external stimuli, including temperature, humidity, light, mechanical stress, and electric fields, by modifying their physical or chemical properties in controlled ways. Renewable building materials, derived primarily from renewable resources or bio-based feedstocks, contribute to reducing embodied carbon, energy consumption, and environmental pollution. Integrating smart and renewable materials can improve building durability and service life while reducing energy demand, maintenance costs, and carbon emissions. Their convergence with emerging technologies, including the Internet of Things, Building Information Modeling, Artificial Intelligence, and Digital Twin technology, creates opportunities for intelligent, energy-efficient, and low-carbon buildings. This study employs a systematic literature review to examine recent scientific advances in smart and renewable building materials, analyzing their main categories, functional characteristics, applications, advantages, limitations, and future trends. Findings indicate that self-healing concrete, self-sensing concrete, shape memory alloys, smart glazing systems, phase change materials, engineered wood, bio-based composites, and building-integrated photovoltaic systems can enhance structural performance and support sustainable architecture. However, high initial costs, insufficient implementation standards, technical complexity, limited long-term performance data, and constraints in large-scale manufacturing remain significant barriers to their widespread adoption, highlighting the need for further research, standardization, technological development, and interdisciplinary collaboration.

Keywords:

Smart materials, renewable building materials, sustainable architecture, green buildings, self-healing concrete, smart buildings, advanced construction technologies.

RESUMEN

La rápida urbanización, el aumento del consumo energético, el agotamiento de los recursos naturales y la intensificación de los efectos del cambio climático han posicionado a la industria de la construcción como un sector crítico para el desarrollo sostenible. Los edificios representan una proporción considerable del consumo energético mundial, las emisiones de gases de efecto invernadero y la utilización de recursos, lo que convierte a los materiales de construcción avanzados, con funcionalidades inteligentes y de origen renovable, en elementos esenciales para reducir los impactos ambientales y mejorar simultáneamente el rendimiento. Los materiales inteligentes responden a estímulos externos, como la temperatura, la humedad, la luz, el estrés mecánico y los campos eléctricos, mediante la modificación controlada de sus propiedades físicas o químicas. Los materiales de construcción renovables, derivados principalmente de recursos renovables o materias primas de origen biológico, contribuyen a reducir el carbono incorporado, el consumo energético y la contaminación ambiental. La integración de materiales inteligentes y renovables puede mejorar la durabilidad y la vida útil de los edificios, al tiempo que reduce la demanda energética, los costos de mantenimiento y las emisiones de carbono. Su convergencia con tecnologías emergentes, como el Internet de las Cosas, el Modelado de Información de Construcción, la inteligencia artificial y la tecnología de gemelos digitales, genera oportunidades para desarrollar edificios inteligentes, energéticamente eficientes y con bajas emisiones de carbono. Este estudio emplea una revisión sistemática de la literatura para examinar los avances científicos recientes en materiales de construcción inteligentes y renovables, analizando sus principales categorías, características funcionales, aplicaciones, ventajas, limitaciones y tendencias futuras. Los resultados indican que el hormigón autorreparable, el hormigón autosensible, las aleaciones con memoria de forma, los sistemas de acristalamiento inteligente, los materiales de cambio de fase, la madera de ingeniería, los biocompuestos y los sistemas fotovoltaicos integrados en edificios

pueden mejorar el desempeño estructural y favorecer una arquitectura sostenible. Sin embargo, los elevados costos iniciales, la insuficiencia de normas de implementación, la complejidad técnica, la limitada disponibilidad de datos sobre el desempeño a largo plazo y las restricciones para la fabricación a gran escala continúan siendo obstáculos significativos para su adopción generalizada, lo que evidencia la necesidad de continuar impulsando la investigación, la normalización, el desarrollo tecnológico y la colaboración interdisciplinaria.

Palabras clave:

Materiales inteligentes, materiales de construcción renovables, arquitectura sostenible, edificios verdes, hormigón autorreparable, edificios inteligentes, tecnologías avanzadas de construcción.

INTRODUCCIÓN

The construction industry is one of the world's largest consumers of energy and natural resources and is responsible for a substantial share of construction waste generation and greenhouse gas emissions. Rapid urbanization, population growth, the depletion of natural resources, and the intensifying impacts of climate change have highlighted the urgent need to reconsider conventional approaches to building design, construction, and operation. In this context, sustainable architecture has emerged as one of the most important scientific and practical approaches in the field of building engineering, aiming to minimize environmental impacts, improve energy efficiency, enhance occupants' quality of life, and preserve natural resources for future generations.

One of the fundamental pillars of sustainable architecture is the selection of appropriate building materials. Although conventional construction materials have played a significant role in the expansion of urban infrastructure over recent decades, the production of many of these materials requires high energy consumption, extensive extraction of natural resources, and considerable carbon dioxide (CO₂) emissions. Consequently, increasing research efforts have been directed toward developing a new generation of building materials that not only satisfy structural and engineering requirements but also provide intelligent functionality, environmental compatibility, and sustainable life-cycle performance.

Smart building materials are defined as materials capable of responding to environmental stimuli such as temperature, humidity, mechanical stress, light, or electric fields by adaptively altering their physical, chemical, or mechanical properties. These materials contribute to enhanced structural durability while enabling structural health monitoring, reducing energy consumption, improving

operational safety, and increasing occupants' thermal comfort. Representative examples include self-healing concrete, self-sensing concrete, shape memory alloys (SMAs), piezoelectric materials, smart coatings, and electrochromic glazing systems.

In contrast, renewable building materials are primarily manufactured from renewable natural resources or bio-based feedstocks. Owing to their lower production energy requirements, recyclability, carbon sequestration potential, and reduced environmental footprint, these materials have gained increasing importance within the construction sector. Engineered timber, particularly Cross-Laminated Timber (CLT), bamboo, natural fiber-reinforced composites, bio-based insulation materials, and biomass-derived construction products are among the most prominent examples. These materials play a crucial role in reducing the embodied carbon of buildings while supporting the transition toward low-carbon construction practices.

Recent advances in digital technologies have expanded the concept of smart buildings beyond conventional automation and equipment control toward the development of multifunctional, self-regulating, and intelligent material systems. The integration of advanced construction materials with emerging technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), Building Information Modeling (BIM), and Digital Twin technology enables the design of buildings capable not only of optimizing energy consumption but also of continuously monitoring structural conditions, predicting potential failures, facilitating predictive maintenance, and extending the service life of building assets.

Moreover, the integration of smart and renewable materials represents a promising pathway toward achieving high-performance and sustainable buildings. By combining adaptive functionality with environmentally responsible material selection, these innovative systems can simultaneously improve energy efficiency, structural resilience, occupant comfort, and environmental sustainability. As global sustainability policies become increasingly stringent, these materials are expected to play a pivotal role in meeting international carbon neutrality targets and advancing resilient urban development.

Accordingly, the present study aims to provide a comprehensive and systematic review of recent advances in smart and renewable building materials. It examines their classifications, functional characteristics, applications, environmental and technical benefits, implementation challenges, and future research directions. Furthermore, the study explores how the integration of these materials with digital construction technologies contributes to the realization of next-generation intelligent, energy-efficient, and low-carbon buildings.

MATERIALS AND METHODS

This study was conducted through a systematic literature review with a descriptive and analytical approach aimed at identifying, organizing, and synthesizing recent scientific knowledge on smart and renewable building materials and their contribution to sustainable architecture. The review focused on the properties, functional characteristics, technological applications, environmental benefits, implementation challenges, and future development perspectives of these materials.

The literature search covered publications primarily issued between 2018 and 2025. Earlier studies were considered when they provided relevant theoretical foundations, conceptual definitions, or background information necessary to understand the evolution of the technologies examined. The search was conducted using Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley Online Library, IEEE Xplore, and Google Scholar. Specialized academic books and technical publications were also considered when directly related to the objectives of the review.

The search strategy combined terms associated with the principal dimensions of the study, including smart building materials, renewable building materials, sustainable construction materials, sustainable architecture, self-healing concrete, self-sensing concrete, smart glass, phase change materials, shape memory alloys, nanomaterials, engineered wood, cross-laminated timber, bamboo, bio-based composites, adaptive building envelopes, building-integrated photovoltaics, and intelligent buildings. These concepts were combined during the search process to identify publications addressing the relationship between advanced material technologies, building performance, energy efficiency, environmental sustainability, and emerging construction systems.

The selection process was conducted through successive stages of identification, screening, eligibility assessment, and final inclusion. Initially, potentially relevant publications were identified from the selected information sources. Titles and abstracts were subsequently examined to eliminate records that were unrelated to the research objective. The remaining publications were assessed according to their relevance, methodological quality, technical contribution, and correspondence with the thematic scope of the review.

Studies were included when they addressed smart, renewable, bio-based, recycled, or advanced building materials; examined structural, mechanical, thermal, energy, environmental, or functional properties; described applications relevant to architecture, buildings, or civil engineering; and provided sufficient scientific or technical information to contribute to the analytical objectives of the review. Priority was given to peer-reviewed journal articles

and academic publications directly related to sustainable construction and advanced material technologies.

Publications were excluded when their content was unrelated to the built environment, when they presented insufficient methodological or technical information, when their contribution was substantially duplicated by another selected publication, or when they did not provide evidence relevant to the properties, applications, sustainability performance, limitations, or technological development of the materials under investigation.

Following the selection process, information from the eligible studies was extracted and organized into thematic categories. These categories included smart material type, renewable or bio-based material type, functional properties, structural performance, thermal behavior, energy efficiency, environmental benefits, architectural and engineering applications, durability, economic considerations, technological integration, implementation barriers, and future research directions. This organization enabled comparison among different material technologies and facilitated identification of recurring patterns and emerging areas of research.

The analytical synthesis was qualitative and comparative. Rather than statistically combining the results of individual studies, the evidence was interpreted according to common technological and sustainability dimensions. Particular attention was given to self-healing and self-sensing concrete, smart glazing, phase change materials, shape memory alloys, nanotechnology-based materials, engineered timber, bamboo, bio-based composites, recycled materials, and building-integrated energy technologies. Their respective advantages and limitations were examined in relation to structural performance, energy demand, durability, environmental impact, resource efficiency, and applicability within sustainable architecture.

Finally, the evidence was synthesized into four interconnected analytical dimensions: technological performance, environmental sustainability, architectural and construction applications, and implementation challenges and future perspectives. This framework provided the basis for the development section and allowed the reviewed evidence to be interpreted in relation to the transition toward intelligent, adaptive, low-carbon, and resource-efficient built environments.

RESULTS AND DISCUSSION

By synthesizing evidence from diverse scientific sources, this research provides a comprehensive overview of the current state of knowledge regarding smart and renewable building materials and highlights their role in supporting sustainable construction, low-carbon building design, and intelligent building systems. The findings also identify existing research gaps and propose future directions for

the development and large-scale implementation of these innovative materials within the construction industry.

The evolution of the construction industry over the past decade has extended beyond the development of materials with superior mechanical properties toward the creation of materials capable of sensing, processing, and responding to their surrounding environment. These materials, commonly referred to as smart building materials, constitute one of the fundamental technological pillars of next-generation intelligent buildings. Their defining characteristic is the ability to dynamically respond to external stimuli, including variations in temperature, humidity, mechanical stress, vibration, light intensity, electric fields, and chemical conditions, through controlled modifications of their physical, chemical, or mechanical properties (Martínez Ángeles et al., 2026).

Unlike conventional construction materials, which generally exhibit passive and static behavior throughout their service life, smart materials continuously adapt their performance to changing environmental conditions. This adaptive behavior contributes to enhanced structural durability, improved energy efficiency, optimized indoor environmental quality, and increased occupant comfort. Recent research indicates that the development and integration of smart materials will play a pivotal role in achieving sustainable, resilient, and low-carbon buildings in the coming decades.

The functionality of smart building materials is generally based on four fundamental principles:

- Sensing: Detecting environmental or structural changes such as crack formation, temperature fluctuations, moisture variation, or mechanical deformation.
- Processing: Interpreting and analyzing information collected from internal or external stimuli.
- Actuation (Response): Adjusting material properties or behavior in response to environmental changes.
- Self-Recovery (Self-Healing): Restoring part or all of the original functionality with minimal or no human intervention.

The integration of sensing, processing, actuation, and self-recovery capabilities transforms smart materials from passive components into active systems that can improve structural safety, extend service life, reduce maintenance costs, and support predictive maintenance. These characteristics make them increasingly relevant to intelligent infrastructure and sustainable construction.

Renewable building materials are derived from renewable natural resources or bio-based feedstocks and generally have lower environmental impacts than conventional materials. Their lower embodied energy, recyclability, reduced greenhouse gas emissions, and carbon sequestration potential support the transition toward a circular construction

economy. Key examples include Cross-Laminated Timber (CLT), bamboo, hemp, flax fibers, bio-based composites, cork, cellulose insulation, and materials incorporating agricultural or industrial by-products. Many also provide favorable mechanical, thermal, and acoustic performance.

Replacing conventional materials with renewable alternatives can reduce embodied carbon and energy consumption associated with production and transportation. Bio-based materials can also provide long-term carbon storage, contributing to climate change mitigation and carbon neutrality objectives.

Within sustainable architecture, material selection considers not only structural performance but also energy consumption, durability, recyclability, embodied carbon, life-cycle costs, indoor environmental quality, and environmental compatibility. Smart materials contribute to these objectives through their capacity to adapt to changing conditions. Electrochromic glazing regulates solar transmittance to reduce heating and cooling loads, while Phase Change Materials (PCMs) absorb, store, and release latent heat to regulate indoor temperatures and reduce HVAC energy demand.

Similarly, self-healing concrete repairs microcracks through biological, chemical, or encapsulated mechanisms, extending structural service life and reducing maintenance and resource consumption. Combining these adaptive technologies with renewable materials can further improve energy efficiency, environmental performance, and resilience, supporting the development of high-performance buildings capable of responding to future climatic challenges.

Recent scientific advances show a transition from single-function construction materials toward multifunctional systems capable of combining structural, environmental, and technological functions. Next-generation smart materials can integrate sensing, self-healing, energy storage, pollutant removal, carbon reduction, structural health monitoring, and data communication. Smart concrete exemplifies this evolution by incorporating conductive nanomaterials, carbon-based additives, embedded sensors, or bio-inspired healing agents to detect cracks, monitor structural integrity, autonomously repair damage, and potentially store electrical energy. These capabilities can improve infrastructure resilience while reducing inspection and maintenance requirements (Nilimaa, 2023).

More broadly, smart building materials have emerged from advances in materials engineering, nanotechnology, biotechnology, and digital technologies. Unlike conventional materials, they can detect internal or environmental changes and respond adaptively, supporting the development of sustainable, intelligent, and self-regulating buildings.

Self-healing concrete is particularly relevant because microcracking caused by mechanical loading, thermal fluctuations, shrinkage, and environmental exposure can facilitate the penetration of water, chloride ions, and aggressive chemicals, accelerating reinforcement corrosion and reducing structural service life. Self-healing technologies address this problem through autonomous crack repair without direct human intervention (Amran et al., 2022).

Three main mechanisms are used. Autogenous healing relies on continued hydration of unreacted cement particles and calcium carbonate precipitation within small cracks. Biological healing uses microorganisms, particularly calcium carbonate-producing bacteria such as *Bacillus* spp., which become activated when water enters cracks and precipitate calcium carbonate to seal them. Capsule-based systems embed microscopic capsules containing polymers, epoxy resins, or mineral adhesives that rupture during crack propagation and release healing agents into the damaged area (Ferrara et al., 2018).

These mechanisms can reduce concrete permeability, improve durability, extend structural service life, and decrease maintenance and repair costs. Consequently, self-healing concrete represents an important technology for resilient and sustainable infrastructure development (Wong et al., 2024).

Self-sensing concrete represents another important category of smart construction materials. Unlike conventional concrete, it possesses the capability to detect internal structural changes—including stress, strain, crack initiation, and damage—without requiring externally installed sensors.

This functionality is typically achieved by incorporating electrically conductive materials into the concrete matrix, such as:

- Carbon nanotubes (CNTs)
- Graphene and graphene-based nanomaterials
- Carbon fibers
- Steel fibers

The inclusion of conductive fillers creates electrically responsive networks within the concrete. Mechanical deformation alters the electrical resistivity of these networks through the piezoresistive effect, allowing the material itself to function as a distributed structural sensor capable of continuously monitoring structural health.

Applications of self-sensing concrete include bridges, tunnels, high-rise buildings, dams, and transportation infrastructure, where continuous structural health monitoring is essential. Its integration with the Internet of Things (IoT), wireless sensor networks, and Artificial Intelligence (AI) enables predictive maintenance, reduces

inspection costs, and improves infrastructure reliability (Ramachandran et al., 2022).

Smart glass provides an adaptive alternative to conventional glazing by dynamically regulating solar radiation and visible light transmission, thereby influencing daylight, solar heat gain, visual comfort, and building energy performance. Electrochromic glass modifies its optical transmittance through a low electrical voltage, darkening under intense solar radiation and becoming more transparent under moderate conditions. Thermochromic glass responds automatically to temperature variations by adjusting solar energy transmission, while photochromic glass changes its optical properties according to sunlight intensity. These technologies can reduce HVAC energy consumption, improve occupant comfort, and enhance the performance of low-energy and net-zero buildings (Zhang et al., 2026).

Phase Change Materials (PCMs) provide another approach to building thermal energy management by absorbing, storing, and releasing latent heat during reversible phase transitions, typically between solid and liquid states. As temperatures rise, they absorb excess thermal energy during melting, limiting indoor temperature increases. When temperatures decrease, they release the stored heat during solidification, helping stabilize indoor temperatures and improve thermal comfort.

Major building applications include:

- Thermal energy storage walls.
- Smart roofing systems.
- Insulated wall and ceiling panels.
- Passive indoor temperature regulation systems.

The incorporation of PCMs into concrete, gypsum boards, mortars, and insulation materials has been shown to reduce indoor temperature fluctuations, decrease heating and cooling energy demand, and improve thermal comfort. Recent studies indicate that PCM-enhanced building envelopes contribute substantially to energy-efficient building design (Zhou et al., 2012).

Shape Memory Alloys (SMAs) are advanced smart materials capable of recovering their original shape after significant deformation through a reversible solid-state phase transformation between martensite and austenite phases.

Among various SMA systems, nickel-titanium (NiTi) alloys are the most extensively employed in civil engineering because of their exceptional superelasticity, corrosion resistance, fatigue performance, and energy dissipation capacity.

Typical structural applications include:

- Seismic vibration control devices.

- Beam-to-column connection systems.
- Structural reinforcement elements.
- Self-centering structural systems.

Unlike conventional steel components, which may experience permanent deformation after major earthquakes, Shape Memory Alloy (SMA)-based systems can recover much of their original geometry after seismic loading, improving post-earthquake resilience while reducing repair costs and structural downtime. Their integration with intelligent monitoring systems can also support adaptive structures capable of damage detection and functional recovery following extreme loading events (Janke et al., 2005).

Advances in nanotechnology have expanded the capabilities of high-performance construction materials. Titanium dioxide (TiO₂) nanoparticles provide photocatalytic and self-cleaning properties and can contribute to pollutant reduction and façade durability. Carbon nanotubes offer high electrical conductivity and mechanical strength, making them suitable for conductive and self-sensing concrete, while graphene combines mechanical, thermal, and electrical properties that can improve the durability and multifunctionality of cementitious composites. Despite these advantages, nanomaterials present challenges related to production costs, nanoparticle release, occupational safety, and the lack of comprehensive engineering standards (Hassan et al., 2025).

Bio-inspired smart materials constitute another emerging direction in sustainable construction by reproducing natural processes such as self-healing, adaptation, self-regulation, and environmental responsiveness. Bio-inspired cementitious systems use microorganisms, biomineralization, or naturally derived compounds to repair damage autonomously. Similarly, wood, plant fibers, and porous bio-based composites can regulate indoor humidity through their hygroscopic properties, contributing to thermal comfort and healthier indoor environments.

Mycelium-based materials represent an innovative circular solution. Produced by cultivating fungal mycelium on agricultural waste substrates, they combine low density, thermal insulation, biodegradability, low embodied energy, and renewable production pathways. These characteristics make them promising for insulation, interior applications, and other non-load-bearing building components. More broadly, bio-inspired materials reflect a transition from resource-intensive construction toward regenerative and circular material systems.

The convergence of material science, nanotechnology, artificial intelligence, and digital construction is further enabling intelligent materials to interact with Building Information Modeling (BIM), the Internet of Things (IoT), Digital Twin platforms, and Artificial Intelligence (AI)-based

monitoring systems. This integration supports continuous monitoring, predictive maintenance, and operational optimization, positioning multifunctional smart materials as important components of resilient, low-carbon, and intelligent built environments.

Renewable and bio-based building materials can reduce the environmental impacts of construction while supporting the transition from linear resource consumption toward a circular economy based on reuse, recycling, and resource recovery. Their sustainability should be assessed throughout the entire life cycle, including raw material extraction, manufacturing, transportation, construction, maintenance, recycling, and end-of-life management. Compared with conventional alternatives, these materials can provide lower embodied energy, reduced greenhouse gas emissions, carbon sequestration, and greater compatibility with natural resource cycles.

Engineered wood, particularly Cross-Laminated Timber (CLT), represents one of the most important structural applications of renewable materials. CLT consists of multiple layers of lumber arranged orthogonally and bonded with structural adhesives, providing high stiffness, strength, dimensional stability, and relatively low structural weight. Its prefabricated nature can reduce construction time and waste, while lower manufacturing energy requirements and long-term carbon storage contribute to reductions in embodied carbon compared with conventional reinforced concrete and structural steel systems.

Life Cycle Assessment studies indicate that replacing conventional structural systems with engineered timber can reduce greenhouse gas emissions throughout the building life cycle. However, broader implementation of CLT depends on addressing fire performance, moisture exposure, biological degradation, building code requirements, and sustainable forest management. Advances in fire engineering, preservation technologies, standardization, and responsible forestry are therefore essential for its large-scale adoption.

Bamboo is an attractive renewable construction material because of its rapid growth, high strength-to-weight ratio, carbon sequestration capacity, flexibility, and seismic resistance. Advances in manufacturing have expanded its traditional use toward engineered bamboo panels, laminated beams, flooring, interior finishes, and fiber-reinforced composites. Engineered bamboo can replace higher-carbon materials in selected structural and non-structural applications, although its long-term performance depends on adequate protection against moisture, fungal degradation, ultraviolet exposure, and insects. Preservation technologies and standardized manufacturing methods are therefore essential for broader implementation.

Bio-based composites combine natural fibers, including flax, hemp, jute, coconut, wood, and recycled agricultural

fibers, with bio-derived or polymeric binders. Their applications include building panels, thermal and acoustic insulation, interior finishes, and other architectural components. These materials can reduce dependence on petroleum-derived products, manufacturing energy consumption, and greenhouse gas emissions while providing favorable thermal and moisture-regulating properties. However, moisture sensitivity, biological degradation, variability in mechanical properties, long-term durability, and limited standardization remain important barriers to their widespread use (Amaechi et al., 2026).

Agricultural residues, industrial by-products, demolition debris, and municipal waste can be transformed into construction resources, including concrete incorporating fly ash, silica fume, or rice husk ash, as well as recycled plastics, glass, and metal aggregates (Lekhya & Kumar, 2024). Their incorporation into construction reduces land-fill disposal, consumption of virgin resources, manufacturing energy demand, and greenhouse gas emissions while supporting circular economy and Zero Waste Building principles. Although many recycled materials can provide satisfactory mechanical, thermal, and durability performance, variability in waste composition, quality control, standardization, and long-term behavior continue to constrain large-scale implementation.

Overall, renewable and recycled materials provide an important pathway toward carbon-neutral buildings, resource-efficient infrastructure, and sustainable urban development. Their environmental benefits can be further enhanced when combined with smart materials capable of adapting building performance to changing environmental conditions.

Smart materials contribute particularly to reducing operational energy demand associated with heating, cooling, ventilation, and lighting. Smart glazing dynamically regulates light and solar heat transmission, reducing unwanted solar gains while improving daylight utilization. Phase Change Materials (PCMs) absorb and store excess thermal energy at elevated temperatures and release it as temperatures decrease, reducing indoor temperature fluctuations and peak energy demand. Thermally responsive coatings, high-reflectance surfaces, and radiative cooling materials can further reduce thermal loads. Combined with passive strategies such as appropriate building orientation, natural ventilation, and daylighting, these technologies support the development of nearly zero-energy and net-zero-energy buildings (Nasr et al., 2023).

Net-Zero Energy Buildings (NZEBs) minimize annual energy consumption through high-performance design and balance remaining demand with renewable energy generated on-site or nearby. Smart and renewable materials contribute to this objective through high-performance

envelopes, thermal energy storage, adaptive solar control, and renewable energy generation. Bio-based insulation, smart glazing, adaptive façades, and high-performance coatings improve thermal performance, while PCMs increase thermal inertia by storing and releasing heat according to environmental conditions.

Building-Integrated Photovoltaic (BIPV) systems extend this approach by incorporating photovoltaic modules directly into roofs, façades, skylights, and curtain walls. These systems allow building-envelope components to perform conventional architectural functions while simultaneously generating renewable energy. The combined use of adaptive envelopes, thermal storage, renewable materials, and energy-generating components can therefore reduce operational energy demand and carbon emissions, supporting the transition toward carbon-neutral built environments.

Adaptive building envelopes represent an evolution from static protective barriers toward dynamic systems capable of responding to changing environmental conditions. Technologies such as dynamic solar shading, intelligent daylight controls, electrochromic and thermochromic glazing, responsive coatings, and materials with variable thermal transmittance can modify building-envelope performance according to climatic conditions. Often inspired by biological systems, these technologies can reduce energy consumption while improving daylight availability, thermal and visual comfort, and overall building performance (Schwartz & Lagerwall, 2022).

The effectiveness of smart materials is further enhanced through their integration with digital technologies. Building Information Modeling (BIM) provides a digital representation of buildings throughout their life cycle and enables material-performance data to support simulations of structural behavior, energy consumption, durability, and maintenance requirements. Embedded sensors connected through the Internet of Things (IoT) can continuously monitor temperature, humidity, mechanical stress, structural damage, and energy consumption, transmitting this information to building management systems for real-time optimization (Ghaffarianhoseini et al., 2017).

Artificial Intelligence (AI) can analyze these data to identify patterns, predict structural deterioration, optimize energy consumption, and support predictive maintenance. Combined with BIM, IoT, and Digital Twin technologies, this integration contributes to the development of self-aware buildings capable of assessing their condition, learning from operational data, and adapting their performance over time.

Practical applications already include Cross-Laminated Timber (CLT) in high-rise buildings, intelligent façades and responsive glazing in commercial buildings, self-healing and self-sensing concrete in bridges and tunnels, and

bio-based or recycled materials in low-carbon construction. These applications demonstrate the transition from passive buildings toward adaptive and environmentally responsive systems that integrate natural materials, advanced technologies, and intelligent management.

Despite these advances, widespread implementation remains constrained by technical, economic, regulatory, and organizational barriers. Smart materials such as self-healing concrete, electrochromic glazing, nanomaterial-enhanced composites, and bio-based products often require advanced manufacturing processes, specialized equipment, and strict quality control, resulting in higher initial costs. Although Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA) can demonstrate long-term benefits through reduced maintenance, lower energy consumption, and extended service life, initial investment remains a significant barrier, particularly in cost-sensitive markets.

The absence of comprehensive international standards represents another limitation. Unlike conventional concrete and structural steel, many emerging materials lack harmonized procedures for design, testing, certification, durability assessment, and field implementation. This is particularly relevant to self-healing concrete, bio-based composites, adaptive façade systems, and multifunctional nanomaterials. Internationally recognized standards and performance-based guidelines are therefore necessary to increase confidence among engineers, architects, contractors, regulatory authorities, and investors.

Long-term durability also requires further investigation because laboratory performance does not necessarily reproduce real service conditions. Temperature fluctuations, humidity, ultraviolet radiation, freeze-thaw cycles, pollution, mechanical fatigue, and cyclic loading can affect material performance. Bamboo and natural-fiber composites, for example, require protection against moisture, biological degradation, insects, and fungi, while some nanomaterials may undergo physicochemical changes over time. Field validation, accelerated aging tests, long-term monitoring, and durability assessments are therefore essential.

Environmental impacts must also be considered throughout the complete material life cycle. Some nanomaterials require energy-intensive manufacturing or critical raw materials, while complex composites can present recycling difficulties and potential risks associated with nanoparticle release. Sustainability assessments should therefore consider embodied carbon, energy consumption, resource depletion, recyclability, toxicity, and end-of-life recovery alongside operational performance.

Finally, limited technical knowledge and industrial acceptance continue to restrict implementation. Greater professional training, specialized education, pilot projects,

technology transfer, documented case studies, and collaboration among academia, industry, government, and regulatory institutions are required to facilitate adoption. Addressing these economic, technical, environmental, and institutional barriers will be essential for moving smart and renewable materials from experimental applications toward large-scale implementation in sustainable construction.

One of the main directions in advanced materials research is the transition from single-function to multifunctional systems. Future building materials may simultaneously carry structural loads, generate renewable energy, repair damage, monitor structural health, regulate indoor temperatures, and improve environmental quality. Combining these functions can reduce the number of building components, simplify construction, improve resource efficiency, and lower life-cycle costs.

Artificial Intelligence (AI) is increasingly transforming the discovery, optimization, and design of advanced construction materials. Machine learning algorithms can analyze large datasets of chemical compositions, microstructures, and experimental results to predict materials with targeted mechanical, thermal, electrical, and environmental properties. Compared with conventional trial-and-error methods, AI-driven design can accelerate research, reduce experimental costs, improve prediction accuracy, optimize manufacturing processes, predict long-term performance, and support real-time quality control.

Living and self-adaptive materials represent another emerging research frontier. By incorporating biological systems such as bacteria, fungi, algae, or genetically engineered cells, these materials can provide functions including self-regeneration, autonomous healing, carbon sequestration, pollutant removal, and adaptation to environmental changes. They could transform buildings from static structures into biologically active systems capable of continuous adaptation. Although many of these technologies remain experimental, advances in synthetic biology, biomaterials engineering, and biofabrication may accelerate their application in sustainable construction.

The integration of smart materials, renewable energy technologies, Artificial Intelligence (AI), the Internet of Things (IoT), Building Information Modeling (BIM), Digital Twin technology, and advanced automation is also enabling the development of self-sufficient and intelligent buildings. These systems can generate renewable energy, autonomously manage consumption, monitor structural and environmental conditions, predict deterioration, support predictive maintenance, adapt to climatic conditions and occupant needs, and interact with smart grids and urban infrastructure.

As these technologies converge, buildings are expected to evolve from passive resource consumers into adaptive

cyber-physical systems capable of learning from operational data and continuously optimizing their performance. Future research should therefore prioritize integrated material systems that combine structural performance, energy efficiency, environmental sustainability, resilience, and occupant well-being. This evolution will require interdisciplinary collaboration among architecture, civil engineering, materials science, computer science, environmental research, and policymaking, with advanced materials, artificial intelligence, biotechnology, and digital construction technologies shaping the next generation of sustainable built environments.

CONCLUSIONS

The rapid advancement of material technologies has introduced a new paradigm in architecture and construction, transforming building materials from passive structural components into active, adaptive, and environmentally responsive systems. Smart and renewable materials offer significant potential to address excessive energy consumption, greenhouse gas emissions, natural resource depletion, maintenance demands, and the need for greater structural durability and resilience.

Smart materials, including self-healing and self-sensing concrete, smart glazing, Phase Change Materials (PCMs), shape memory alloys (SMAs), and nanotechnology-based coatings, provide capabilities such as autonomous adaptation, structural health monitoring, thermal energy management, and damage recovery. These functions can reduce maintenance requirements, extend structural service life, improve energy efficiency, and enhance the economic and environmental performance of buildings. Renewable and bio-based alternatives, including engineered timber, bamboo, natural-fiber composites, and recycled materials, can further reduce embodied carbon and dependence on non-renewable resources while promoting carbon sequestration, recyclability, and circular economy principles.

Despite these benefits, widespread adoption remains constrained by high initial costs, insufficient standardization, uncertainties regarding long-term durability, technological complexity, manufacturing requirements, and limited technical and industrial acceptance. Overcoming these barriers requires coordinated research and development, appropriate regulatory frameworks, professional training, industrial collaboration, standardized performance evaluation, and large-scale demonstration projects.

Future progress will increasingly depend on integrating advanced materials with Artificial Intelligence (AI), the Internet of Things (IoT), Building Information Modeling (BIM), Digital Twin systems, and biotechnology. This convergence can support buildings capable of generating energy, intelligently managing consumption, monitoring

their own condition, predicting maintenance needs, adapting to environmental changes, and recovering from damage. Smart and renewable materials therefore represent not merely alternatives to conventional products but essential components of the transition toward regenerative, adaptive, resilient, and carbon-neutral built environments.

Future research should prioritize multifunctional materials that integrate structural, energy, environmental, and adaptive capabilities while examining their long-term performance under diverse climatic conditions. Particular attention should be given to extreme temperatures, humidity, freeze-thaw cycles, environmental pollutants, and other factors affecting durability and reliability. Artificial Intelligence (AI) and machine learning can support the discovery, prediction, design, and optimization of new material compositions with improved mechanical, thermal, and environmental properties.

Research should also advance cost-effective manufacturing methods for renewable and bio-based materials and conduct comprehensive Life Cycle Assessments (LCA) covering raw material extraction, production, transportation, use, maintenance, recycling, and end-of-life management. International standards and performance evaluation frameworks are needed to assess the reliability, durability, safety, and environmental impacts of emerging smart materials and facilitate their large-scale implementation.

Further investigation should address the integration of smart materials with building energy management systems, smart grids, digital twins, and smart city infrastructure to improve energy efficiency, resource management, real-time monitoring, and predictive maintenance. Bio-inspired and living materials also warrant greater attention, particularly through advances in biotechnology, synthetic biology, and biomaterial engineering that could enable adaptive and self-regenerating construction systems.

Ultimately, research should move beyond improving isolated material properties toward integrated systems that combine intelligence, sustainability, resilience, and compatibility with digital construction technologies. Interdisciplinary collaboration among materials science, architecture, civil engineering, computer science, environmental research, industry, and policymaking will be essential for developing the next generation of adaptive, low-carbon, and regenerative built environments.

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Conflicts of Interest:

The authors declare no conflicts of interest.

Author Contributions:

Mohammad Javad Ghorbani, Dariush Sattarzadeh: Conceptualization, data curation, formal analysis, investigation, methodology, supervision, validation, visualization, original draft writing, and writing, review, and editing.

Ethical statement:

The study was based on the analysis of documentary sources and publicly available data, and therefore did not involve the direct participation of human subjects. No personally identifiable information was handled.