

# *Smart and Energy-Efficient Building Materials: A Comprehensive Review for Sustainable Urban Development and Green Infrastructure*

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**Abstract**— Rapid urbanization and increasing energy consumption have intensified the demand for sustainable construction practices that minimize environmental impacts while enhancing the performance and resilience of built environments. Smart and energy-efficient building materials have emerged as a transformative solution by integrating advanced material science, nanotechnology, phase change materials, self-healing technologies, and intelligent sensing capabilities into modern construction systems. These materials contribute significantly to reducing energy consumption, improving indoor thermal comfort, lowering greenhouse gas emissions, and extending the service life of buildings. This comprehensive review examines the latest developments in smart building materials and evaluates their role in achieving sustainable urban development and green infrastructure. The study explores various categories of innovative materials, including high-performance insulation, energy-harvesting materials, adaptive façades, bio-based composites, recycled construction materials, and smart glazing technologies. Furthermore, the review analyzes their applications in residential, commercial, and public infrastructure projects while discussing their economic, environmental, and social benefits. Challenges such as high initial costs, scalability, material durability, regulatory barriers, and integration with existing construction practices are also critically assessed. Additionally, emerging trends involving artificial intelligence, the Internet of Things, digital twins, and circular economy principles are highlighted as key enablers for the next generation of intelligent buildings. The review concludes that the widespread adoption of smart and energy-efficient building materials can substantially improve resource efficiency, reduce carbon footprints, and support the development of resilient, sustainable, and climate-responsive urban infrastructure, thereby contributing to global sustainable development goals and future smart city initiatives.

**Keywords:** Smart building materials, Energy-efficient construction, Sustainable urban development, Green infrastructure, Intelligent construction technologies, Phase change materials, Self-healing materials, Smart glazing, Sustainable buildings, Circular economy, Smart cities, Low-carbon construction.

## I. INTRODUCTION

The rapid growth of urban populations, increasing industrialization, and the continuous expansion of infrastructure have significantly increased global energy demand and environmental degradation. The building sector is one of the

largest consumers of energy and natural resources, accounting for a substantial share of greenhouse gas emissions throughout the lifecycle of buildings, including material extraction, construction, operation, maintenance, and demolition. Consequently, achieving sustainable urban development requires the adoption of innovative construction materials and technologies that enhance energy efficiency while minimizing environmental impacts [1].

Traditional building materials such as conventional concrete, steel, and fired clay bricks have played a fundamental role in infrastructure development; however, their production processes are associated with high carbon emissions, excessive energy consumption, and depletion of natural resources. Growing concerns regarding climate change, resource scarcity, and environmental sustainability have encouraged researchers, policymakers, and construction industries to explore smart and energy-efficient building materials as viable alternatives for future infrastructure development [2]. These advanced materials are designed not only to improve structural performance but also to optimize energy utilization, enhance occupant comfort, and reduce the overall ecological footprint of buildings.

Smart building materials represent a new generation of construction materials capable of responding dynamically to environmental changes through adaptive physical or chemical properties. These materials include self-healing concrete, phase change materials (PCMs), smart glass, thermochromic coatings, electrochromic windows, shape-memory alloys, nanomaterial-enhanced composites, and energy-harvesting materials. Their ability to regulate heat transfer, repair micro-cracks, harvest renewable energy, and monitor structural health makes them highly suitable for intelligent and sustainable buildings [3]. Unlike conventional materials, smart materials contribute to extending building lifespan while reducing maintenance costs and operational energy requirements.

Energy-efficient building materials have become essential components in the pursuit of net-zero energy buildings and green infrastructure. High-performance insulation materials, reflective roofing systems, aerogels, vacuum insulation panels, bio-based composites, recycled aggregates, and low-carbon cement alternatives significantly reduce heating and cooling loads, thereby lowering energy consumption and carbon emissions. The integration of these materials with digital technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), Building Information Modeling (BIM), and smart sensors enables continuous optimization of building performance and resource utilization throughout the building lifecycle [1], [4].

The concept of green infrastructure extends beyond individual buildings to encompass environmentally responsible urban systems that promote resilience, biodiversity conservation, efficient resource management, and climate adaptation. Smart

and energy-efficient building materials play a crucial role in this transformation by supporting sustainable construction practices, reducing urban heat island effects, improving indoor environmental quality, and facilitating circular economy principles through material recycling and reuse. As cities continue to expand, intelligent construction technologies are expected to become indispensable for developing low-carbon and climate-resilient urban environments [5].

Recent advancements in material science and nanotechnology have accelerated the development of multifunctional construction materials capable of simultaneously providing structural strength, thermal regulation, energy generation, and environmental sensing. Examples include photovoltaic building-integrated materials that generate electricity, self-cleaning surfaces utilizing photocatalytic nanoparticles, and self-healing concrete incorporating bacteria or microcapsules that automatically repair cracks. These innovations reduce lifecycle costs while improving durability and sustainability, making them attractive for modern infrastructure projects [3].

Despite their significant advantages, several challenges hinder the widespread implementation of smart and energy-efficient building materials. High manufacturing costs, limited standardization, scalability issues, lack of skilled professionals, uncertainty regarding long-term durability, and regulatory barriers continue to restrict their adoption in many developing and developed economies. Furthermore, integrating these advanced materials with existing construction practices requires multidisciplinary collaboration among architects, engineers, material scientists, policymakers, and technology developers [1], [4].

Given these opportunities and challenges, a comprehensive review of smart and energy-efficient building materials is essential for understanding their current state of development, technological advancements, practical applications, and future research directions. This review aims to synthesize recent progress in intelligent construction materials, evaluate their contributions toward sustainable urban development and green infrastructure, analyze emerging trends involving AI-enabled building systems and circular economy strategies, and identify existing research gaps. The findings are expected to provide valuable insights for researchers, industry professionals, and policymakers working toward the realization of sustainable, energy-efficient, and resilient cities.

## II. LITERATURE SURVEY

The growing emphasis on sustainable urbanization has significantly increased research on smart and energy-efficient building materials that can minimize environmental impacts while enhancing building performance. Recent studies have shifted from focusing solely on structural strength toward multifunctional materials capable of energy conservation, self-adaptation, and intelligent monitoring. The literature demonstrates that integrating advanced materials with digital technologies is essential for achieving low-carbon and resilient urban infrastructure [6].

One major research direction involves the development of smart materials that respond dynamically to external environmental stimuli such as temperature, humidity, mechanical stress, and solar radiation. Smart materials including phase change materials (PCMs), electrochromic glass, thermochromic coatings, piezoelectric materials, and shape-memory alloys have

been extensively investigated for their ability to regulate indoor thermal conditions and reduce energy consumption. These materials improve occupant comfort while lowering dependence on mechanical heating and cooling systems, thereby enhancing overall building sustainability [7].

Recent reviews have highlighted the role of energy-harvesting materials in transforming buildings into active energy producers rather than passive energy consumers. Building-integrated photovoltaics, thermoelectric materials, triboelectric nanogenerators, and smart roofing systems are capable of converting solar, thermal, or mechanical energy into electricity. Such technologies contribute significantly toward the realization of net-zero energy buildings and renewable urban infrastructure while reducing greenhouse gas emissions [7].

Researchers have also emphasized the importance of high-performance insulation materials for improving building energy efficiency. Aerogels, vacuum insulation panels, nano-insulation materials, and advanced polymer composites exhibit extremely low thermal conductivity, thereby minimizing heat transfer through building envelopes. These innovations reduce heating and cooling loads and consequently lower operational energy costs throughout the building lifecycle [8]. Compared with conventional insulation materials, advanced insulation systems provide superior thermal performance while occupying less space, making them particularly suitable for densely populated urban environments.

Another significant area of investigation is self-healing construction materials, particularly self-healing concrete. Microbial techniques, encapsulated healing agents, and mineral-based repair mechanisms enable concrete to autonomously repair micro-cracks before structural deterioration occurs. Such materials increase durability, reduce maintenance requirements, and extend service life, thereby decreasing lifecycle costs and resource consumption associated with repair and reconstruction activities [9]. The literature indicates that self-healing technologies can substantially improve the sustainability of long-term infrastructure systems.

The application of nanotechnology in construction materials has emerged as another promising research field. Nanomaterials such as nano-silica, carbon nanotubes, graphene oxide, titanium dioxide nanoparticles, and nano-clays improve mechanical strength, durability, corrosion resistance, and photocatalytic properties of construction materials. Photocatalytic coatings containing titanium dioxide additionally provide self-cleaning capabilities and contribute to air purification by decomposing atmospheric pollutants under sunlight exposure [10]. These multifunctional characteristics enhance both structural performance and environmental sustainability.

Researchers have increasingly focused on bio-based and recycled construction materials as alternatives to conventional resource-intensive materials. Bamboo composites, hempcrete, recycled aggregates, fly ash, slag cement, rice husk ash, and recycled plastic composites have demonstrated considerable potential for reducing embodied carbon while promoting circular economy principles. The use of industrial by-products and agricultural waste in construction not only conserves natural resources but also reduces landfill waste and manufacturing emissions [11]. Consequently, sustainable material selection has become a critical component of green building certification systems worldwide.

The integration of Artificial Intelligence (AI), Building Information Modeling (BIM), and the Internet of Things (IoT) with smart building materials has further expanded the scope of intelligent construction. AI-based predictive models optimize energy consumption, while IoT-enabled sensors continuously monitor structural health, indoor environmental quality, and material performance. BIM facilitates lifecycle management by enabling digital simulation, energy analysis, and efficient decision-making during design and construction stages. Studies indicate that combining digital technologies with advanced materials significantly enhances building efficiency and operational sustainability [8], [12].

Several investigations have examined smart façades and adaptive building envelopes capable of automatically regulating heat gain, daylight penetration, and ventilation. Electrochromic glazing systems, dynamic shading devices, and responsive façade materials reduce cooling loads while maintaining visual comfort. Simulation-based studies suggest that smart façade technologies can decrease building cooling energy demand by more than 30–50% under appropriate climatic conditions, demonstrating their potential for sustainable urban architecture [13].

Another emerging research trend concerns green infrastructure and climate resilience. Smart and energy-efficient materials contribute to mitigating urban heat island effects through reflective surfaces, cool roofs, permeable pavements, and vegetated building systems. These solutions improve stormwater management, reduce ambient temperatures, and enhance ecological sustainability within urban environments. Researchers argue that integrating intelligent materials into city planning supports resilient infrastructure capable of adapting to climate change and extreme weather events [14].

Despite considerable technological advancements, the literature identifies several challenges limiting widespread adoption of smart building materials. High initial investment costs, manufacturing complexity, limited standardization, uncertainty regarding long-term durability, and insufficient regulatory frameworks remain major obstacles. Furthermore, developing countries often face additional barriers related to technical expertise, economic feasibility, and lack of supportive policies [15]. Future research therefore emphasizes scalable manufacturing methods, lifecycle assessment, cost optimization, and standardized performance evaluation.

Overall, the existing literature demonstrates that smart and energy-efficient building materials represent a transformative approach toward sustainable urban development and green infrastructure. The convergence of advanced material science, renewable energy technologies, digital intelligence, and circular economy principles is expected to redefine future construction practices. Nevertheless, further interdisciplinary research is required to bridge the gap between laboratory innovations and large-scale commercial implementation while ensuring affordability, durability, and environmental sustainability [6], [12], [15].

**TABLE 1: LITERATURE REVIEW TABLE FOR PREVIOUS YEAR RESEARCH PAPER COMPARISON**

S. No.	Research Paper	Methodology	Major Findings
1	Itanola (2024), <i>The Impact of</i>	Scientometric and systematic review of	BIM and AI significantly improve

	<i>Digital Technologies on Energy-Efficient Buildings</i>	literature published between 2010 and 2023.	energy-efficient building design, optimize resource utilization, and reduce lifecycle energy consumption.
2	Umoh et al. (2024), <i>AI and IoT in Smart Green Building Technologies</i>	Comprehensive literature review and qualitative analysis.	Integration of AI and IoT enhances building automation, energy management, and sustainability while improving occupant comfort.
3	Ejidike (2023), <i>Benefits of Adopting Smart Building Technologies</i>	Systematic review of smart building technology adoption.	Smart technologies increase energy efficiency, safety, productivity, and operational cost savings but face implementation barriers.
4	Bhattacharjee and Roy (2024), <i>Smart Materials for Sustainable Energy</i>	Review of responsive materials and renewable energy applications.	Smart materials such as photovoltaics, thermoelectric materials, and piezoelectric systems contribute to sustainable energy generation and conservation.
5	Chen et al. (2025), <i>Research on Sustainable Building Development</i>	Bibliometric and qualitative review of 418 publications.	Sustainable materials and intelligent technologies collectively improve building performance and reduce environmental impacts.

6	El-Khiary (2021), <i>Simulation Analysis for Evaluating Smart Material of Energy-Efficient Building Envelopes</i>	Simulation using DesignBuilder and EnergyPlus software.	Smart façade materials can reduce building cooling energy demand by more than 50% under suitable climatic conditions.
7	Review on Phase Change Materials (PCM) for Buildings	Experimental studies and thermal performance evaluation.	PCMs regulate indoor temperatures by storing and releasing latent heat, thereby reducing HVAC energy consumption.
8	Research on Self-Healing Concrete Technology	Laboratory investigations using microbial and capsule-based healing techniques.	Self-healing concrete repairs micro-cracks automatically, increasing durability and lowering maintenance costs.
9	Study on Smart Glazing Technologies	Experimental evaluation of electrochromic and thermochromic glass systems.	Smart windows regulate solar radiation and daylight, improving thermal comfort while reducing cooling loads.
10	Research on Nanomaterials in Construction	Material characterization and mechanical testing.	Nano-silica, graphene oxide, and titanium dioxide nanoparticles improve strength, durability, and self-cleaning properties of construction materials.
11	Study on High-Performance Thermal	Comparative thermal conductivity analysis of advanced	Aerogels and vacuum insulation panels significantly

	Insulation Materials	insulation systems.	reduce heat transfer and operational energy consumption.
12	Research on Bio-Based Building Materials	Experimental evaluation of hempcrete, bamboo composites, and agricultural fiber products.	Bio-based materials reduce embodied carbon emissions while providing good thermal insulation and sustainability benefits.
13	Study on Building-Integrated Photovoltaics (BIPV)	Performance assessment of photovoltaic façade and roofing systems.	BIPV enables buildings to generate renewable electricity while serving as structural components, improving energy independence.
14	Research on IoT-Based Structural Health Monitoring	Sensor-based monitoring and predictive analytics.	Smart sensors enable continuous monitoring of structural conditions, facilitating predictive maintenance and extending infrastructure lifespan.
15	Review on Smart and Sustainable Urban Infrastructure	Integrated review of smart materials, AI, IoT, and green construction technologies.	Combining intelligent materials with digital technologies supports resilient, low-carbon, energy-efficient, and sustainable urban development.

**III. SUSTAINABLE URBAN DEVELOPMENT AND GREEN INFRASTRUCTURE**

**A. Sustainable Urban Development**

Sustainable urban development refers to the process of planning, designing, and managing cities in a manner that meets present societal needs without compromising the ability of future

generations to meet their own needs. It aims to achieve a balanced integration of economic growth, environmental protection, and social well-being while ensuring efficient utilization of natural resources. Rapid urbanization has increased the demand for housing, transportation, energy, and public infrastructure, leading to excessive resource consumption, greenhouse gas emissions, and environmental degradation. Therefore, sustainable urban development has become a fundamental strategy for creating resilient, inclusive, and low-carbon cities.

One of the primary objectives of sustainable urban development is to reduce the environmental footprint of urban areas through energy-efficient buildings, renewable energy integration, sustainable transportation systems, and responsible land-use planning. Modern urban planning encourages mixed-use development, compact city design, public transportation networks, and pedestrian-friendly infrastructure to minimize dependence on fossil fuels and reduce traffic congestion. Additionally, digital technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), Geographic Information Systems (GIS), and Building Information Modeling (BIM) enable data-driven decision-making for optimizing urban resource management and improving infrastructure performance. The construction sector plays a significant role in sustainable urban development because buildings account for a substantial proportion of global energy consumption and carbon emissions. The adoption of smart and energy-efficient building materials—including high-performance insulation materials, phase change materials, self-healing concrete, recycled aggregates, and smart glazing systems—helps reduce operational energy demand while improving occupant comfort and structural durability. Furthermore, incorporating circular economy principles through material recycling and waste minimization contributes to long-term environmental sustainability. Sustainable urban development therefore requires interdisciplinary collaboration among engineers, architects, planners, policymakers, and environmental scientists to develop cities that are economically viable, environmentally responsible, and socially equitable.

## B. Green Infrastructure

Green infrastructure is a strategically planned network of natural and semi-natural areas that delivers multiple ecosystem services while enhancing biodiversity and improving environmental quality. Unlike conventional "gray infrastructure," which primarily focuses on engineered systems such as roads and drainage networks, green infrastructure integrates natural elements into urban environments to provide ecological, economic, and social benefits. Examples include urban forests, green roofs, green walls, parks, wetlands, rain gardens, bioswales, permeable pavements, and restored waterways. These systems improve stormwater management, air quality, climate resilience, and public health while creating more livable cities.

Green infrastructure plays a crucial role in mitigating the urban heat island effect by increasing vegetation cover and reducing heat absorption from impervious surfaces. Trees and vegetation provide shading and evapotranspiration, lowering ambient temperatures and decreasing the energy required for building cooling. Green roofs and walls improve thermal insulation, extend roof lifespan, absorb pollutants, and enhance urban biodiversity. Similarly, permeable pavements and bioswales

facilitate groundwater recharge and reduce surface runoff, thereby minimizing flood risks during extreme rainfall events.

From an environmental perspective, green infrastructure supports ecosystem services such as carbon sequestration, water purification, habitat conservation, and soil protection. It also contributes to climate change adaptation by increasing the resilience of urban systems against floods, droughts, and heat waves. Socially, accessible green spaces promote physical activity, mental well-being, recreation, and community interaction, thereby improving overall quality of life. Economically, investments in green infrastructure can reduce long-term infrastructure maintenance costs, increase property values, and create employment opportunities in sustainable development sectors.

The integration of smart and energy-efficient building materials with green infrastructure provides a comprehensive approach to sustainable urban development. Intelligent façades, photovoltaic building materials, advanced insulation systems, and sensor-enabled monitoring technologies can operate alongside green roofs, urban forests, and permeable landscapes to optimize energy efficiency and environmental performance. Future smart cities are expected to combine digital technologies with nature-based solutions to create resilient, low-carbon, and resource-efficient urban environments capable of addressing the challenges of rapid urbanization and climate change. Recent research indicates that coordinated planning of green and built infrastructure can enhance ecosystem services while reducing resource consumption and greenhouse gas emissions, making it a key strategy for sustainable urban development.

## IV. CONCLUSION

The rapid pace of urbanization and the increasing demand for energy-efficient infrastructure have highlighted the necessity of adopting innovative construction materials that support environmental sustainability and long-term economic development. This review demonstrates that smart and energy-efficient building materials represent a transformative advancement in modern construction by integrating material science, digital technologies, and sustainable engineering principles. Unlike conventional building materials, these advanced materials possess adaptive, multifunctional, and intelligent characteristics that significantly improve building performance while reducing energy consumption and environmental impacts.

The review reveals that technologies such as phase change materials, self-healing concrete, smart glazing systems, nanomaterial-enhanced composites, high-performance insulation materials, and bio-based construction materials contribute substantially to improving thermal efficiency, structural durability, indoor environmental quality, and lifecycle sustainability. Furthermore, the integration of renewable energy technologies, including building-integrated photovoltaics and energy-harvesting materials, enables buildings to function as active energy producers, supporting the transition toward net-zero and carbon-neutral infrastructure.

The study also highlights the growing importance of digital technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), Building Information Modeling (BIM), digital twins, and smart sensor networks in maximizing the effectiveness of intelligent building materials. These technologies facilitate real-time monitoring, predictive maintenance, optimized energy management, and data-driven

decision-making, thereby enhancing the operational efficiency and resilience of modern buildings and urban infrastructure.

Green infrastructure and sustainable urban development are closely interconnected with the adoption of smart construction materials. The incorporation of green roofs, permeable pavements, recycled materials, adaptive façades, and environmentally friendly building components contributes to reducing greenhouse gas emissions, mitigating urban heat island effects, improving stormwater management, conserving natural resources, and enhancing biodiversity. Consequently, the combination of intelligent materials and nature-based solutions provides a comprehensive framework for developing resilient and climate-responsive cities.

Despite these significant advancements, several challenges continue to limit widespread implementation. High initial investment costs, manufacturing complexity, lack of standardized performance evaluation methods, limited long-term durability data, regulatory constraints, and insufficient technical expertise remain major barriers to commercialization and large-scale adoption. Additionally, disparities in technological accessibility between developed and developing countries present further obstacles to achieving global sustainability goals.

Future research should focus on developing cost-effective and scalable manufacturing processes, multifunctional hybrid materials, recyclable and biodegradable construction products, and standardized testing protocols for smart building materials. Greater emphasis should also be placed on integrating AI-driven optimization algorithms, digital twin technologies, advanced nanomaterials, and circular economy strategies to improve the entire lifecycle performance of buildings. Interdisciplinary collaboration among material scientists, civil engineers, architects, environmental researchers, policymakers, and industry stakeholders will be essential for accelerating innovation and practical implementation.

In conclusion, smart and energy-efficient building materials have the potential to redefine the future of sustainable construction by creating intelligent, resilient, low-carbon, and resource-efficient built environments. Their successful integration into urban planning and green infrastructure development will not only enhance energy efficiency and environmental protection but also improve social well-being and economic sustainability. As global efforts toward achieving the Sustainable Development Goals (SDGs) and carbon neutrality continue to intensify, these advanced materials are expected to play a pivotal role in shaping the next generation of smart cities and sustainable urban ecosystems.

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