



Comparative Analysis of Smart Material Criteria in Sustainable Architecture: A Systematic Literature Review

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Abstract

The increasing energy consumption and environmental impacts in the building sector demand adaptive and sustainable material innovations. Smart materials offer this potential; however, previous studies remain partial and have not provided integrated criteria for their evaluation and implementation. This study aims to identify the key criteria of smart materials and analyze their contributions to environmental performance and building energy efficiency. The method used is a Systematic Literature Review (SLR). A total of 31 articles were rigorously selected from 598 initial publications through stages of research question formulation, literature search and selection, data extraction, and comparative analysis. The results indicate that the main criteria consist of four aspects: (1) adaptive capability, (2) energy efficiency, (3) life-cycle sustainability, and (4) technological integration. Various smart materials, such as electrochromic, thermochromic, shape memory, hygromorphic, piezoelectric, and self-healing materials, have been proven to improve environmental control, energy efficiency, and building service life. This study produces a more systematic and integrative comparative framework and provides practical guidance for designers in selecting performance-based materials. Further research is recommended to include empirical testing, energy simulations, life cycle assessment (LCA), and applications in tropical climates.

Keywords: energy efficiency, material criteria, smart material, sustainable architecture

Analisis Komparatif Kriteria Smart Material dalam Arsitektur Berkelanjutan: Sebuah Tinjauan Literatur Sistematis

Abstrak

Peningkatan konsumsi energi dan dampak lingkungan pada sektor bangunan menuntut inovasi material yang adaptif dan berkelanjutan. Smart material menawarkan potensi tersebut, namun penelitian sebelumnya masih bersifat parsial dan belum menyediakan kriteria terpadu untuk evaluasi dan penerapannya. Penelitian ini bertujuan mengidentifikasi kriteria utama smart material serta menganalisis kontribusinya terhadap performa lingkungan dan efisiensi energi bangunan. Metode yang digunakan adalah systematic literature review (SLR). Sebanyak 31 artikel dipilih secara ketat dari 598 publikasi awal melalui tahapan perumusan pertanyaan, pencarian dan seleksi literatur, ekstraksi data, serta analisis komparatif. Hasil penelitian menunjukkan bahwa kriteria utama meliputi empat aspek yaitu: (1) kemampuan adaptif, (2) efisiensi energi, (3) keberlanjutan siklus hidup, dan (4) integrasi teknologi. Berbagai smart material seperti electrochromic, thermochromic, shape memory, hygromorphic, piezoelectric, dan self-healing terbukti meningkatkan kontrol lingkungan bangunan, efisiensi energi, dan umur layanan. Penelitian ini menghasilkan kerangka komparatif yang lebih sistematis dan integratif, serta memberikan acuan praktis bagi perancang dalam memilih material berbasis performa. Penelitian lanjutan disarankan mencakup pengujian empiris, simulasi energi, analisis life cycle assessment (LCA), dan penerapan pada iklim tropis.

Kata-kunci: arsitektur berkelanjutan, efisiensi energi, kriteria material, smart material

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Introduction

Global climate change, energy crises, and environmental degradation have become major issues in the development sector. The building and construction sector has a significant contribution to global energy consumption and carbon emissions. According to the Global Status Report for Buildings and Construction by UNEP (Table 1), this sector accounts for approximately 36% of global final energy consumption and 37% of carbon (CO₂) emissions [1].

Table 1. Contribution of the Building Sector to the Environment [1]

No	Environmental aspect	Contribution of the building sector	Description
1	Global Energy Consumption	±34–36% of global final energy consumption	Energy is used for building operations (cooling, heating, lighting)
2	Carbon Emissions (CO ₂)	±37% of total global CO ₂ emissions	Includes emissions from building operations and construction/material processes
3	Greenhouse Gas Emissions (GHG)	±21% of total global emissions	Represents the overall contribution of the building sector to climate change
4	Global Energy Demand	±34% of total energy demand	Shows the sector's dominance in global energy use
5	Embodied Carbon Emissions	±18% of construction sector emissions	Originates from material production such as cement and steel

In addition, the building sector is projected to experience an increase in energy demand of up to 50% by 2050 if no sustainable design interventions are implemented [2]. On the other hand, this sector also consumes approximately 50% of global material resources and generates up to 30% of construction waste, further reinforcing the urgency of transitioning toward more efficient and environmentally friendly construction practices (Table 2).

Table 2. Trends in Energy Consumption and Emissions in the Building Sector until 2050 [2]

Year	Energy consumption (%)	CO ₂ emissions (%)
2010	32%	34%
2015	34%	36%
2020	36%	37%
2025*	38% (projections)	38%
2050*	50% (energy-demand projections)	-

Sustainable architecture has become a strategic approach to respond to these conditions through

energy efficiency, resource optimization, and the reduction of environmental impacts throughout the building life cycle [2]. This approach is divided into two main strategies: a low-technological approach (passive strategies and natural materials) and a high-technological approach (integration of technology and adaptive systems).

Within the high-technology approach, smart materials represent one of the most important innovations. These materials are capable of responding dynamically to environmental changes such as temperature, light, and humidity. Several types of smart materials have demonstrated significant performance in improving building efficiency.

Although they have significant potential, the application of smart materials in architectural practice remains limited. Several main constraints include:

1. The absence of structured implementation standards or criteria
2. Limited integration within building design systems
3. Relatively high implementation costs (approximately 10–25% more expensive than conventional materials)
4. Lack of performance-based evaluation guidelines

However, studies indicate that the application of adaptive façade technology can reduce building energy consumption by up to 30% and improve thermal comfort by up to 25% [3].

In addition to improving building performance, smart materials also shift the architectural design paradigm toward a more adaptive and responsive approach. Materials are no longer passive elements, but part of a dynamic system that directly interacts with the environment [4].

Although various studies have discussed the types, characteristics, and applications of smart materials in architecture, existing research remains largely fragmented. Addington and Schodek examined the classification and working mechanisms of smart materials, but did not formulate application criteria for design [5, 6]. Loonen et al. focused on the performance of climate adaptive building shells in improving energy efficiency [3], while Fox and Kemp discussed the integration of smart materials within interactive architectural systems [4]. Other studies have also explored specific material performances, such as electrochromic windows for energy efficiency and visual comfort [7], as well as shape memory-based materials and adaptive actuators for dynamic façades [8–10]. In addition, research on adaptive material systems highlights the potential integration of sensors

and actuators in enhancing building responsiveness [11, 12].

However, these studies have not yet integrated technical, functional, and environmental aspects into a single comprehensive evaluation framework. The absence of such criteria synthesis results in suboptimal application of smart materials in design practice and makes comparative assessment difficult. Therefore, a study is needed to formulate systematic and measurable implementation criteria as a basis for decision-making in sustainable architectural design.

Based on this condition, this study has two research questions:

1. What are the main criteria for the application of smart materials in sustainable buildings?
2. How can the integration of smart materials improve environmental performance and building energy efficiency?

Accordingly, this study aims to identify the characteristics of smart materials and develop a comprehensive set of application criteria, serving as both a conceptual and practical foundation for sustainable architectural design.

Methods

This study employs a Systematic Literature Review (SLR) method with a systematic and stepwise literature selection process (Fig. 1). The article search was conducted through various academic databases using keywords related to smart materials and sustainable architecture. The selection process included the stages of identification, duplicate removal, title and abstract screening, full-text review, and eligibility assessment based on inclusion and exclusion criteria. The final stage is the included studies, namely articles deemed relevant and used in the research analysis.

Data Collection Methods

The data sources used in this study are secondary data obtained from various scientific databases, namely Google Scholar, Scopus, ScienceDirect, SpringerLink, MDPI, Garuda/SINTA, and Crossref with a publication year range from 2001 to 2024.

Based on the table, each database provided different search results depending on the keywords used. The main keywords applied include *smart material architecture*, *smart materials in architecture*, as well as specific material types such as thermochromic, photochromic, electrochromic, shape memory alloy, hygromorphic, piezoelectric, and self-healing materials, along with sustainable architecture.

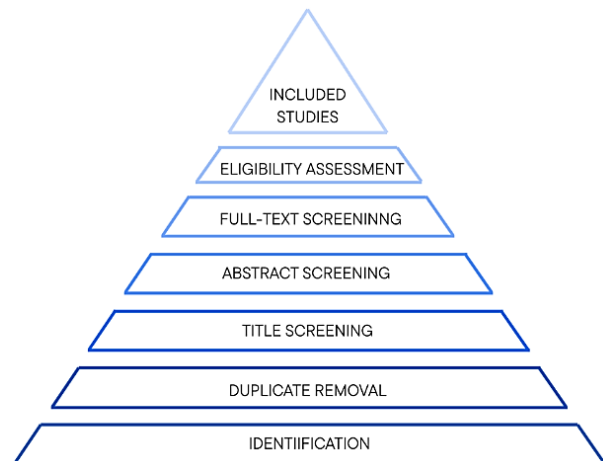


Figure 1. Diagram of Systematic Literature Review (SLR) Stages (Authors own work)

Data Analysis Methods

The data analysis technique in Table 3 was conducted using a Systematic Literature Review (SLR) approach. The process began with an initial identification stage through searches using various keywords related to smart materials in architecture, resulting in a total of 598 articles as the initial dataset. This was followed by a title screening stage to filter out articles that were not relevant to the research topic, reducing the number to 106 articles. The next stage was initial selection, which involved reviewing abstracts and preliminary content to ensure alignment with the research focus, resulting in 58 selected articles. In the final stage, an in-depth analysis was conducted through a full-text review, considering quality, relevance, and scientific contribution, resulting in 31 articles used as the basis for the study analysis. This process demonstrates a systematic and rigorous filtering procedure to ensure that the selected literature aligns with the research objectives.

Table 3. Literature search matrix of smart materials (Authors own work)

Database	Keyword	Initial results	After title screening	Initial selection	Final selection
Google Scholar, Scopus, ScienceDirect	smart material architecture	72	12	6	4
Google Scholar, Garuda/Sinta	<i>material cerdas arsitektur</i>	26	7	4	2
Scopus, ScienceDirect, Google Scholar	thermochromic material	44	8	4	1
Scopus, Google Scholar	photochromic material	38	6	3	1
Scopus, ScienceDirect, Google Scholar	electrochromic material	46	9	5	2
Scopus, SpringerLink, ScienceDirect	shape memory alloy	68	15	9	5
Scopus, SpringerLink, Google Scholar	hygromorphic material	54	12	7	4
Scopus, ScienceDirect, MDPI	piezoelectric material	58	11	6	3
Scopus, ScienceDirect, MDPI	self-healing material	60	11	6	3
Google Scholar, Garuda/Sinta	<i>material cerdas arsitektur</i>	18	4	2	1
Google Scholar, Scopus, Crossref	sustainable architecture	70	7	4	2
Google Scholar, Garuda/Sinta	<i>arsitektur berkelanjutan</i>	44	4	2	3
Total		598	106	58	31

Results and Discussion

Smart materials are materials that have the ability to respond to external stimuli such as temperature, light, pressure, humidity, or electric and magnetic fields by reversibly and adaptively changing their physical or chemical properties [5]. Smart materials are equipped with sensors that detect changes in stimuli, transmit signals to a control unit, and then respond accordingly to ensure the material system operates optimally.

In this context, the term “smart” does not imply human-like intelligence, but rather refers to the material’s ability to sense and respond to environmental changes automatically and repeatedly (self-actuating) [6]. Thus, smart materials enable buildings to adapt automatically to changing environmental conditions and become an important component in strategies for achieving sustainable architecture [13].

Classification and Working Principles of Smart Materials

Smart materials are classified based on the type of external stimulus that triggers their physical or chemical changes [11]. In general, there are three main systems: passive, active, and hybrid. Passive systems respond directly to environmental changes without additional control, active systems involve integrated sensors and actuators, while hybrid systems combine both approaches to achieve more complex and adaptive responses. The main principle of smart materials lies in their ability to sense stimuli (sensing), respond to stimuli (actuating), and return to

their original state (recovering) in a reversible manner [12]. This capability makes them ideal for application in building elements that require high flexibility toward environmental changes, such as façades, roofs, and natural ventilation systems.

Based on the study by M. Addington and further supported by research conducted by J. Yoon in Architectural Science Review, smart materials can be classified into eight main types. These types are distinguished by their response mechanisms to external stimuli such as temperature, light, pressure, humidity, electric fields, and magnetic fields [6, 8].

Each type of smart material has sensory and actuation characteristics that enable it to detect environmental changes and respond automatically without the need for additional mechanical systems [6]. Meanwhile, [8] emphasizes the importance of developing thermo-responsive and lightweight materials, particularly for applications in building skins or adaptive building envelopes. In general, the eight types of smart materials most widely used and developed in the context of architecture include:

1. Thermochromic material

Thermochromic material works by changing color or transparency in response to temperature changes, thereby controlling the transmission of light and heat into a space [14]. This thermal response occurs through a reversible change in molecular structure.

Thermochromic materials change color or transparency as a response to temperature through

reversible molecular transformations. These materials have been developed in solid-state forms for smart window applications, such as octadecyl acrylate polymers, which exhibit thermotropic transitions at approximately 24.5–39°C, enabling controlled light transmission. In addition, cholesteric liquid crystal-based coatings have also been developed, offering stable and repeatable color changes when heated [15].

Thermochromic products are generally available in laminated glass form with dimensions of 1200 × 2400 mm or 1500 × 3000 mm and a thickness of 5–10 mm, as well as in film form with roll widths of 1.2–1.5 meters. In Indonesia, these products are not yet produced locally and still rely on imports from China, Korea, and Japan, available in the form of glass, film, and façade coatings. Their availability remains limited and they are mostly used in commercial building projects.

Real-world application: The Denver Federal Center in the United States became a real-world test site for the installation of chromogenic glass, including thermochromic glass, in a 2013 pilot project. The goal was to reduce HVAC and lighting energy consumption by 10–20% and cut peak electricity demand by 20–30% (Fig. 2).



Figure 2. Exterior view of the west façade showing the locations of three types of windows. Low-e windows were installed in 2005. [16]

2. Photochromic Material

Photochromic material is a type of adaptive material that changes color or transparency level when exposed to light, usually ultraviolet light or direct sunlight. This change occurs through molecular isomerization or structural rearrangement in the pigment or film, which then alters optical properties such as light transmission and reflection [17].

In architectural applications, photochromic material is used as a coating or film on glass windows and façades, and it can also be applied to transparent panels such as transparent wood. This material allows glass to automatically adjust its light and heat transmission

without sensors or external control. In office buildings, its use can reduce transparency when solar intensity is high and increase it again when light levels drop, thereby improving occupants' visual comfort [18].

Photochromic products are generally available in standard architectural glass sizes, such as sheets of approximately 1200 × 2400 mm or 1500 × 3000 mm, as well as in roll film form with widths of 1.2–1.5 m. Laboratory studies have also shown photochromic glass prototypes measuring 60 × 48 cm² that can transition between tinted and transparent states [17].

Real-world application: Research [17] developed a photochromic window panel based on Fe-doped WO₃, tested on a model house to simulate its adaptive ability to regulate solar heat and light transmission automatically in response to temperature changes (Fig. 3).

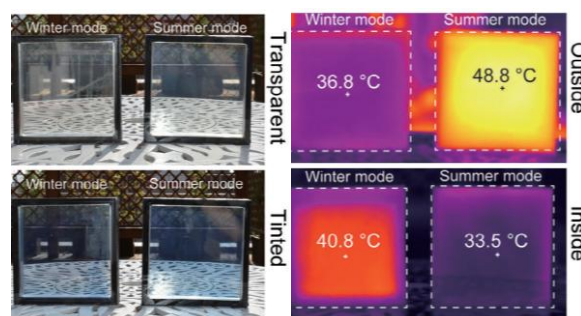


Figure 3. Transparent state and tinted state [19]

3. Electrochromic Material

Electrochromic material is a smart material that can change color or transparency level when a small electric voltage is applied. This change occurs through ion movement, for example lithium ions, between electrode layers, allowing the glass to switch from transparent (clear) to dark (tinted) [7].

Electrochromic material is used as dynamic glazing (smart windows) in the form of laminated glass with an EC layer between two transparent glass panes. This system can also be integrated with light sensors or building automation to adjust the level of tint according to outdoor conditions, thereby controlling solar heat gain, glare, and indoor lighting [7].

Commercial electrochromic glazing is generally produced as insulating glass units (IGUs) with panel sizes up to approximately 1500 × 3000 mm. Glass thickness ranges from 4–10 mm, with total IGU thickness varying depending on the double- or triple-glazing configuration. Products are available in various forms and can be integrated into curtain wall systems

or windows, with performance specifications such as VLT, SHGC, and U-value that differ by manufacturer.

Real-world application: SwissTech Convention Center, Switzerland. This project uses SageGlass electrochromic glazing, which can adjust transparency according to light intensity and reduce lighting energy use by up to 40% (Fig. 4).



Figure 4. SwissTech Convention Center [20]

4. Shape Memory Alloy (SMA) and Shape Memory Polymer (SMP)

Shape Memory Material, including Shape Memory Alloy (SMA) and Shape Memory Polymer (SMP), is a smart material capable of changing shape reversibly in response to temperature. This capability makes it important for adaptive façades and energy-efficient structures in sustainable architecture [9]. This material can return to its original shape after deformation caused by heat or electric current, making it potentially applicable to kinetic façades, adaptive ventilation, and flexible structures [10].

Shape Memory Alloy (SMA) is a metal alloy that exhibits the Shape Memory Effect (SME), meaning it can return to its original shape after deformation when heated, as well as super elasticity (SE), meaning it can withstand large strains without permanent deformation [21]. In practice, Shape Memory Alloy (SMA) functions as an actuator in shading and natural ventilation systems that can open or close automatically in response to temperature changes, helping optimize daylight, airflow, and energy efficiency in sustainable adaptive façades [21].

Shape Memory Polymer (SMP) is a smart polymer that can be programmed to return to its original shape when triggered by stimuli such as heat, light, or a magnetic field. Its advantages lie in its light weight, low cost, high deformability, and ease of adjusting transition temperature, making it ideal for building envelopes [22]. In practice, Shape Memory Polymer (SMP), especially in foam or composite form, is used as an adaptive building envelope capable of

automatically adjusting porosity, thereby supporting passive thermal control and building energy efficiency [23].

Real-world application: Air Flow-er (Alabama, USA) (Fig. 5). This system is a self-powered ventilation system that mimics the behavior of a flower to regulate airflow and temperature without electricity. Its mechanism consists of “petals” that open as temperature rises, inspired by the thermonastic response of crocus flowers. The system uses Nitinol (Ni-Ti) alloy as an actuator to open and close façade panels automatically according to temperature changes [24].

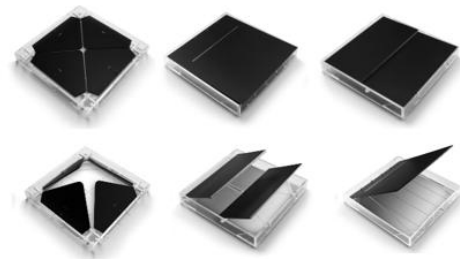


Figure 5. Air Flow(er) - Different prototype versions, closed at low and open at high temperatures [24]

The Harvest Screens (USA). The Harvest Screens apply SMA as an automatic passive ventilation system to adjust indoor temperature (Fig. 6).



Figure 6. Mechanical components of Shape Memory Alloys - The Harvest Screens [25]

5. Hygromorphic material

Hygromorphic material is a category of smart material that shows significant changes in shape, volume, or mechanical properties in response to changes in air humidity or water content [3]. This material is hygroscopic, meaning it can absorb and release water vapor from the surrounding environment. In sustainable architecture, hygromorphic material functions as a passive, energy-independent strategy for regulating a building's microclimate. Its response to humidity occurs through shape change or natural

bending caused by differences in expansion between material layers [26].

Hygromorphic materials are generally layered composites (bi-layer or multi-layer) with different hygroscopic expansion coefficients in each layer. Changes in humidity cause the more hygroscopic layer to expand more [27], resulting in bending or shape change. This mechanism works entirely using environmental energy without actuators, sensors, or control systems, making it highly energy efficient [28].

The two main types of hygromorphic material most widely used in architecture are, first, wood composites. These composites are specifically designed to maximize the natural shrinkage and expansion of wood in response to humidity changes. Examples include two-layer wooden panels that bend in one direction when wet and return to their original form when dry [29]. Second, bacterial spores. A newer and more experimental type, this material takes advantage of the hygroscopic properties of certain bacterial spores, which show dramatic volume changes under different humidity conditions [30].

Real-world application: Hygroskin Pavilion (Stuttgart, ICD/ITKE). This project uses hygromorphic wood panels that open when the air is dry and close when it is humid, functioning as a passive ventilation system (Fig. 7).

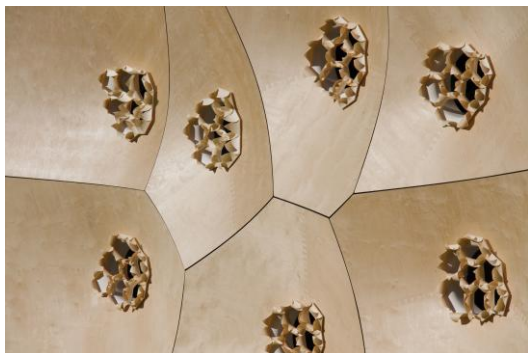


Figure 7. Meteorosensitive pavilion; ICD Universität Stuttgart, Germany [31]

Biohybrid Facade Project (MIT Media Lab). This project develops hygromorphic microbial materials to regulate air circulation automatically (Fig. 8). Hygromorphic materials can be applied in tropical façade systems to reduce HVAC loads and improve natural ventilation in line with bioclimatic architecture principles [32].

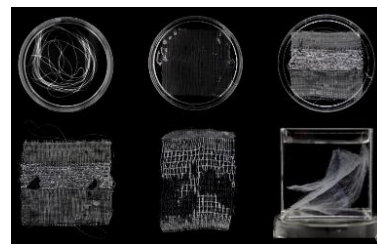


Figure 8. Components of the Biohybrid Façade Project [33]

6. Piezoelectric material

Piezoelectric material is a smart material capable of generating electrical charge when subjected to mechanical pressure and, conversely, changing shape when exposed to an electric field, a phenomenon known as the piezoelectric effect. Materials such as PZT (lead zirconate titanate) and PVDF (polyvinylidene fluoride) are widely used because of their sensitivity, stability, and ability to operate without an external power source. In smart buildings, this material functions to respond to user activity while also harvesting small amounts of previously wasted energy [34].

One of the main applications of piezoelectric material is the energy harvesting floor, where modules are installed beneath the floor to capture the pressure of footsteps and generate around 2–4 joules of energy that can be used for lighting or low-power sensors [35]. These modules are generally in the form of approximately 50 × 50 cm tiles. In addition, piezoelectric material is also used in structural health monitoring (SHM) through PZT sensors that can detect cracks, stiffness changes, and corrosion in building structures in real time [36].

Another application is found in responsive façades and interiors, where piezoelectric material is used as an actuator to produce small but precise movements. Piezo actuators in the form of piezo stacks with diameters of 3–20 mm or PVDF films with thicknesses of 20–100 µm can move façade panels or shading devices that respond to light, wind, and automation commands [37]. This technology supports adaptive façades that improve thermal comfort and energy efficiency. In addition, its ability to generate energy and detect structural conditions makes piezoelectric material highly relevant to sustainable architecture.

Real-world application: Shibuya Station (Tokyo). This station uses piezoelectric flooring to generate electricity from passenger footsteps (Fig. 9).



Figure 9. Mechanism of Electricity Generation Using Piezoelectric Elements in Flooring (Energy Harvesting Floor) [38]

PaveGen Project (London). This project develops piezoelectric tiles that generate energy for street lighting (Fig. 10).

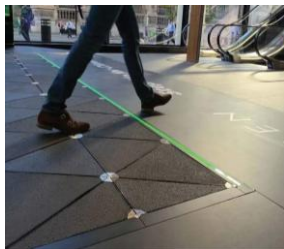


Figure 10. Implementation of Modular Kinetic Energy Harvesting Paving Blocks (Example of an Electromechanical System) [38]

The use of this material is relevant for high-traffic public areas and supports the concept of smart energy management [32], through the sustainable use of self-healing material.

7. Self-healing material

Self-healing material is a material capable of repairing damage, especially microcracks, automatically without human intervention. Its mechanism can occur naturally through autogenous healing in concrete, or through engineered systems using microcapsules containing healing agents that become active when cracks appear. This concept is inspired by biological processes and has the potential to increase structural lifespan and reduce long-term maintenance costs [39].

In construction, self-healing material is most widely applied in structural concrete, especially in areas that are difficult to access or prone to cracking such as floor slabs, retaining walls, basements, and columns. Healing systems may take the form of bacterial capsules (1–3 mm), polymer microcapsules (10–500 μm), or microcapillary networks (0.5–3 mm) that release healing agents when cracking occurs. Their size is designed not to compromise the concrete's compressive strength while remaining responsive to cracks, with selection adjusted to the type of structure and crack characteristics [39].

In practice, self-healing material is effective for infrastructure such as bridges, tunnels, and public facilities. This technology can close cracks up to approximately 0.8 mm without additional maintenance. In buildings, its use can extend structural lifespan, reduce basement leakage, and improve façade resistance to weathering. Overall, self-healing concrete has the potential to increase service life by 30–50%, thereby supporting sustainable architecture and smart infrastructure [40].

Real-world application: Self-Healing Concrete (Netherlands). This material uses *Bacillus pseudofirmus* bacteria, which produce calcium carbonate to seal cracks in concrete (Fig. 11).



Figure 11. Characterization of the Self-Healing Mechanism in Bacteria-Assisted Concrete (Bio-mineralization). [41]

Microencapsulated Asphalt in Fenghai Road (China). This material repairs itself when temperatures rise, extending road lifespan by up to two times (Fig. 12).



Figure 12 Illustration of the Self-Healing Mechanism in Asphalt Using Microcapsules [42]

The results of this study show that smart materials are not merely an innovation in responsive materials, but also an architectural strategy that drives a shift from passive systems toward environmentally adaptive systems. In sustainable architecture, their main value lies in their ability to respond to temperature, light, humidity, and pressure in order to reduce dependence on mechanical systems. However, not all smart materials can be widely applied because of differences in technological maturity, the need for supporting systems, and the context of use. Therefore, smart materials should be understood as part of a contextual design strategy, not as a single solution.

The classification results show differences in the readiness level of smart materials, ranging from those that are close to commercial use to those that are still in the research stage. Electrochromic material is relatively ready for application because it is already used in smart glass, while thermochromic, photochromic, hygromorphic, and self-healing materials still face limitations in production, stability, and performance consistency. This confirms that the success of smart materials is determined not only by their responsiveness, but also by their technological readiness. From an architectural perspective, these materials are most relevant when applied to elements that interact directly with climate, such as façades, windows, roofs, ventilation systems, and building envelopes.

In the context of sustainability, the assessment of smart materials cannot rely solely on operational energy efficiency. It must also consider the material life cycle, initial cost, ease of maintenance, and the environmental footprint of the production and distribution process. Many smart materials can indeed reduce cooling loads, lighting demand, or building maintenance, but some of them require additional control technologies that actually increase system complexity. Therefore, the application of smart materials must consider system simplicity, user readiness, and suitability to local climate and resources. In this way, the main contribution of smart materials to sustainable architecture lies not only in technological aspects, but also in the appropriate selection of materials, building performance efficiency, and their relevance to the broader design context.

Based on the classification in Table 4, smart materials exhibit variations in their stimuli, responses, levels of

technological readiness, and application elements. Thermochromic, photochromic, and electrochromic materials all function to control light and heat on façades, windows, and roofs; however, they differ in their response mechanisms and levels of technological maturity, with electrochromic materials being the most precise and commercially ready. Shape memory materials (SMA/SMP) and hygromorphic systems play a role in adaptive responses through changes in form for ventilation; SMA/SMP are more active in nature, whereas hygromorphic systems are more passive, relying on natural humidity. Meanwhile, piezoelectric and self-healing materials focus on floors and structural components for energy harvesting, monitoring, and improving the durability and service life of buildings. These differences indicate that each material has a specific contribution, and therefore, its selection must be aligned with the function, context, and performance objectives of the building.

In general, smart materials cannot be regarded as equivalent due to differences in their functions, technological readiness, and contributions to sustainability. Electrochromic materials and shape memory materials (SMA/SMP) excel in controlling building performance (light, heat, and ventilation); however, electrochromic systems depend on electrical energy, while SMA/SMP still face challenges related to cost and complexity. Thermochromic, photochromic, and hygromorphic materials are more prominent as passive, energy-efficient strategies, with hygromorphic systems being the most aligned with sustainability principles as they utilize natural humidity without requiring additional systems; nevertheless, passive responses tend to be less precise and are highly dependent on climatic conditions. This indicates that sustainability is not solely determined by low energy consumption, but also by the suitability of materials to the environmental context and the functional requirements of the building (Table 5).

Table 4. Types of Smart Materials Based on Stimulus and Application Fields in Buildings (Authors own work)

No	Type of smart material	Primary stimulus	Material response	Usage status	Application elements				
					Facade	Window	Roof	Slab	Structure
1	Thermochromic	Temperature	Color/transparency change	Research stage – commercial	√	√	√	-	-
2	Photochromic	Light (UV)	Color/transparency change	Research stage – commercial	√	√	√	-	-
3	Electrochromic	Electricity	Transparency control through voltage	Commercial	√	√	√	-	-
4	Piezoelectric	Mechanical pressure	Generates electrical energy	Semi-commercial	-	-	-	√	√
5	Shape Memory Alloy / Polymer	Temperature / electricity	Shape changes, automatic opening-closing	Research stage – commercial	√	-	√	-	√
6	Hygromorphic Material	Air humidity	Natural bending / opening-closing	Research stage	√	-	√	-	-
7	Self-healing Material	Mechanical damage	Automatically closes cracks	Research stage – commercial	-	-	-	-	√

Table 5. Critical Comparative Analysis of Materials (Authors own work)

No	Type of smart material	Main strength	Limitation	Sustainability value	Critical analysis
1	Thermochromic	Responds to temperature, helping to control light and heat passively	Performance is highly dependent on environmental temperature and material stability	Fairly good for reducing operational energy consumption	Relevant for façades and windows, but its effectiveness is not always stable across different climates
2	Photochromic	Adjusts transparency in response to light/UV	Response is more specific and not always precise for thermal control	Good for visual comfort and glare reduction	More suitable for lighting control rather than a comprehensive energy solution
3	Electrochromic	Provides the most measurable transparency control and is relatively commercially ready	Depends on electricity, sensors, and control systems	High in terms of operational energy efficiency	The most ready-to-use option, but its sustainability must be evaluated alongside the energy demand of supporting systems
4	SMA/SMP	Adaptive shape response for façades, shading, and ventilation	Cost, complexity, and application readiness remain challenges	Good for adaptability and reducing operational energy use	Performatively promising, but requires careful selection to avoid overburdening building systems
5	Hygromorphic	Highly passive, operates using humidity without electricity	Response is influenced by environmental conditions and requires highly precise material selection	Most aligned with passive energy efficiency	Closest to low-energy architecture principles, but requires strong contextual design
6	Piezoelectric	Enables energy harvesting and structural monitoring	More specific function, not intended for primary climate control	Good for micro-energy efficiency and smart management	Strong sustainability value in utilizing wasted energy and monitoring structures, rather than in passive façade applications
7	Self-healing	Extends the lifespan of structures and reduces maintenance requirements	Extends the lifespan of structures and reduces maintenance requirements	Extends the lifespan of structures and reduces maintenance requirements	Extends the lifespan of structures and reduces maintenance requirements

Piezoelectric and self-healing materials have distinct roles, as they focus more on resource efficiency and extending the lifespan of buildings rather than climate control. Piezoelectric materials are used for energy harvesting and structural monitoring, while self-healing materials help extend service life and reduce maintenance needs as well as construction waste. Although their applications are more specific, both contribute significantly to prolonging the building life cycle and reducing the material footprint.

Conclusion

This study shows that the main criteria for applying smart materials in sustainable buildings include (1) the material's adaptive capability to environmental stimuli (temperature, light, humidity, and pressure), (2) its contribution to operational energy efficiency, (3) material sustainability in terms of life cycle, durability, and environmental impact, and (4) its ability to integrate with building systems, whether passively, actively, or in hybrid forms. These criteria emphasize that the selection of smart materials must be carried

out comprehensively and contextually, not only based on technological innovation but also on suitability to climate, function, and building performance objectives.

The integration of smart materials has been proven to enhance environmental performance and energy efficiency through responsive and adaptive mechanisms. Materials such as electrochromic, thermochromic, and photochromic function to control light and heat, while SMA/SMP and hygromorphic systems support adaptive façades and ventilation. Meanwhile, piezoelectric materials contribute to micro-energy harvesting, and self-healing materials improve the structural service life. Overall, this integration enables buildings to transform into more efficient, adaptive, and sustainable systems.

Theoretically, this study produces a more systematic and integrative comparative framework for smart material criteria, while practically providing guidance for designers in selecting appropriate, performance-

based materials. Future research should focus on empirical testing, energy performance simulations, life cycle assessment (LCA) analysis, as well as the exploration of applications in tropical climates and integration with intelligent building systems to ensure more applicable and measurable implementation.

AI Use Declaration

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