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Article

Benefiting from smart materials in the shell of desert buildings in order to control the thermal conductivity of interior spaces

Mohammadmehdi Moulaii[1,*], Arezoo Lotfi[1], Hadi RezaeiRad[2]

[1] Department of Architecture, Faculty of Art and Architecture, Bu-Ali Sina University, Hamedan 6517838695, Iran
[2] Department of Urbanism, Faculty of Art and Architecture, Bu-Ali Sina University, Hamedan 6517838695, Iran
*** Corresponding author:** Mohammadmehdi Moulaii, mehdimulaii@yahoo.com

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Abstract: Integrating smart materials into the building envelopes of desert architecture offers a promising solution for optimizing thermal regulation and reducing energy consumption. Traditional Iranian architecture has long adapted to extreme climatic conditions through passive design strategies and indigenous materials such as adobe, fired brick, and stone. However, contemporary construction demands necessitate advanced materials with higher thermal inertia, adaptability, and energy efficiency. This study explores the application of high-performance smart materials, including BetoShell, AnnanoMirror, SmartWrap, Electrochromic and Thermochromic glazing, and vacuum insulation panels (VIPS), in the façades of desert buildings to mitigate heat transfer and enhance sustainability. Descriptive-analytical envelopes can reduce thermal conductivity, optimize solar gain, and enhance passive cooling strategies, thereby improving occupant comfort while significantly lowering energy demand in arid climates. This research methodology was adopted, utilizing qualitative content analysis, experimental performance data, computational modeling, and case studies to assess material efficiency. Findings indicate that incorporating these responsive materials in building highlights the pivotal role of smart façades and kinetic materials in advancing the principles of climate-responsive and sustainable architecture.

Keywords: smart materials; adaptive façades; energy-efficient architecture; thermal conductivity; desert climate design

1. Introduction

1.1. Background and problem statement

The exponential rise in global energy consumption has necessitated a paradigm shift in building envelope design, particularly in extreme climatic conditions such as arid and desert regions. According to the International Energy Agency [1], nearly 40% of the world's total energy consumption is attributed to the construction and operation of buildings, with heating, cooling, and ventilation accounting for the majority of this demand. This escalating energy crisis underscores the need for high-performance, energy-efficient materials that can mitigate heat gain, optimize passive cooling strategies, and reduce reliance on fossil fuels [2]. In response to these challenges, smart materials have emerged as an innovative approach to enhancing the thermal efficiency, adaptability, and sustainability of buildings. Smart materials, defined as engineered substances capable of responding dynamically to environmental stimuli (e.g., temperature, humidity, solar radiation), provide self-regulating thermal insulation, thereby reducing energy loads and environmental impact [3]. While extensive research has explored the potential of smart materials in architecture, many studies have neglected localization aspects, particularly in Iran’s central plateau, where intense solar radiation, extreme diurnal temperature variations, and low humidity levels impose unique constraints on building performance [4]. This study aims to bridge this gap by evaluating the application of smart materials in desert architecture, focusing on:

1) Assessing the thermal behavior of smart materials in hot and arid climates, emphasizing their heat storage, emissivity modulation, and energy efficiency potential.
2) Investigating real-world applications and experimental case studies, demonstrating the impact of kinetic facades and responsive glazing technologies in minimizing heat gain and optimizing passive cooling strategies.
3) Developing a framework for integrating smart materials into sustainable architectural design, aligning with climate-responsive urban planning.

1.2. Traditional vs. modern solutions in hot-arid climates

Iranian desert architecture, deeply rooted in vernacular and bioclimatic principles, has historically incorporated passive cooling and thermal insulation strategies through high thermal mass materials such as adobe, mudbrick, and stone [5]. The integration of windcatchers (Badgir), subterranean water channels (Qanat), and shaded courtyards exemplifies sophisticated indigenous responses to extreme climatic conditions [6]. Advanced nanotechnology-driven materials, such as BetoShell, AnnanoMirror, SmartWrap, Electrochromic and Thermochromic glazing, and Vacuum Insulation Panels (VIPS), exhibit phase-changing properties, spectral selectivity, and dynamic opacity control, making them ideal for hot-arid building envelopes [2]. This research emphasizes the importance of material localization, ensuring that adaptive materials are effectively tailored to the unique environmental, cultural, and economic conditions of Iran.

1.3. Research questions and hypotheses

This study seeks to answer the following research questions: How do smart materials contribute to improving the energy performance and thermal regulation of buildings in hot and dry climates? Prior studies indicate that phase-change materials (PCMs), electrochromic glazing, and vacuum insulation panels (VIPs) enhance energy efficiency and indoor thermal stability [3]. However, the localization aspect of these materials has not been fully explored in the context of Iran’s desert regions [4]. Which specific types of smart materials demonstrate optimal efficiency in mitigating heat gain and improving passive cooling strategies in desert architecture? Nanotechnology-based adaptive materials, including kinetic facades and thermochromic surfaces, have shown high efficiency in thermal regulation [6]. Further experimental validation and case study analyses are required to confirm their long-term viability in desert climates [5]. What are the key challenges and limitations in integrating smart materials within the architectural framework of hot and dry regions? High production costs, limited local manufacturing, and durability concerns hinder the large-scale adoption of smart materials [2]. Hypotheses Based on prior research and empirical findings, the following hypotheses are formulated:

H1: Smart materials significantly improve thermal insulation and energy efficiency in hot and dry climates by reducing heat gain and enhancing passive cooling techniques.

H2: The application of phase-change materials (PCMs), thermochromic glazing, and kinetic facades in desert architecture outperforms conventional building materials in terms of thermal adaptability, energy conservation, and environmental sustainability.

H3: Economic and technical challenges, such as high costs and limited domestic production, hinder the widespread adoption of smart materials in sustainable architectural projects. By systematically analyzing these research questions and hypotheses, this study bridges the gap between theoretical research and real-world applications, providing a localized framework for integrating smart materials into Iran’s hot and arid climate.

2. Literature review

2.1. Evolution of smart materials in architectural design

The integration of smart materials in architecture has significantly evolved over the past three decades, driven by advancements in nanotechnology, adaptive materials, and responsive building systems [7]. Early research [8] emphasized the potential of intelligent materials in climate-responsive architecture, highlighting their self-regulating capabilities in thermal control [8]. By the early 2000s, studies focused on kinetic facades, phase-change materials (PCMs), and electrochromic glazing as primary solutions for energy-efficient buildings [9]. Recent research has expanded the scope of smart materials to include biomimetic materials, nano-engineered thermal insulation, and self-healing composites, revolutionizing sustainable building envelopes [10]. These materials are particularly relevant in hot and arid climates, where reducing solar heat gain and optimizing cooling strategies are critical.

2.2. Classification of smart materials based on functionality

Smart materials used in high-performance architecture (**Table 1**) can be categorized into five main types:

Table 1. Classification of smart materials based on functionality.

Category	Description	Examples
Phase-Change Materials (PCMs)	Store and release thermal energy during phase transitions.	Paraffin-based PCM panels, salt hydrates, microencapsulated PCMs [11]
Electrochromic & Thermochromic Glazing	Adjusts light transmittance based on voltage or temperature.	Electrochromic windows, thermotropic coatings, liquid crystal displays [12]
Self-Healing Materials	Automatically repair micro-cracks and mechanical damage.	Polymeric self-healing coatings, bio-concrete with bacterial activation [13]
Kinetic & Adaptive Facades	Modifies shape, texture, or properties in response to environmental stimuli.	SmartWrap, ETFE membranes, dynamic brise-soleils [14]
Vacuum Insulation Panels (VIPS) & Nanogel Materials	Provides ultra-high thermal resistance with minimal thickness.	Silica aerogels, nano-porous insulation composites [15]

These next-generation materials are particularly valuable in arid climates, where adaptive solar control and energy conservation are crucial.

2.3. Application of smart materials in hot and arid climates

Iran’s central plateau climate is characterized by high diurnal temperature variation, intense solar radiation, and low humidity levels. Traditional solutions, such as thick adobe walls, wind towers, and subterranean water channels (Qanats), have historically provided passive cooling [16]. However, contemporary construction demands necessitate advanced materials with higher adaptability and thermal efficiency. Recent research has demonstrated that: Electrochromic glazing can reduce solar heat gain by up to 40%, significantly lowering cooling loads [12]. Phase-change materials (PCMs) embedded in building envelopes stabilize indoor temperatures, reducing peak cooling demand by 30% [11]. Nanogel-based insulation panels (VIPS) achieve up to 10 × higher insulation efficiency compared to conventional materials [15]. Kinetic facades with shape-memory alloys (SMAs) dynamically regulate solar exposure, improving daylight optimization and thermal comfort [14]. Despite these advancements, barriers to large-scale implementation remain, including high production costs, durability concerns, and integration with local construction practices [10]. Addressing these challenges through localized adaptation of smart materials is critical for their widespread adoption in desert architecture.

3. Research methodology

3.1. Research approach

This research adopts a mixed-method approach, integrating qualitative and quantitative analysis to assess the effectiveness of smart materials in desert architecture. The study employs computational simulations, laboratory testing, and case study analysis to provide a comprehensive evaluation of material performance. The methodology is structured into three primary stages:

1) Literature Review and Theoretical Framework Development
    - Identification of key smart material technologies for thermal regulation and energy efficiency.
    - Reviewing global and regional studies on adaptive façades and high-performance insulation materials [15].
2) Experimental and Computational Analysis
    - Thermal conductivity tests using Hot-Wire and Differential Scanning Calorimetry (DSC) for selected phase-change materials (PCMs) and nanogel-based insulation panels [11].
    - Energy performance simulations conducted in EnergyPlus and DesignBuilder, evaluating:
        - *U*-values of building envelopes.
        - Solar heat gain coefficient (SHGC) of electrochromic glazing.
        - Thermal lag efficiency of smart insulation panels [12].
    - Computational Fluid Dynamics (CFD) simulations to model heat transfer dynamics and airflow in desert climate conditions [13].

3) Case Study and Field Data Collection
    - Selection of three case studies from Iran's central plateau (Yazd, Kashan, Isfahan).
    - Measurement of indoor temperature variations, energy consumption, and material efficiency.
    - Comparative analysis between traditional passive strategies and smart material-based solutions.

3.2. Variables and evaluation criteria

The study focuses on five primary (**Table 2**) performance indicators to assess the efficacy of smart materials in desert buildings:

Table 2. The study focuses on five primary performance indicators to assess the efficacy of smart materials in desert buildings.

Performance Indicator	**Description**	**Measurement Method**
Thermal Conductivity (λ)	Ability to resist heat transfer	Hot-Wire Method (ASTM C518)
Solar Heat Gain Coefficient (SHGC)	Control of solar radiation transmission	Spectrophotometry
Phase Transition Latency (PCM)	Duration of thermal energy storage	Differential Scanning Calorimetry
Energy Savings (%)	Reduction in cooling demand	EnergyPlus Simulation
Thermal Comfort Index (PMV-PPD)	Human comfort in indoor climate	ASHRAE 55 Standard

3.3. Data collection and analysis process

The research follows a systematic data collection strategy, combining field measurements, laboratory testing, and computational modeling.

Step 1: Material Characterization and Testing

- Thermal properties of smart materials were tested under controlled laboratory conditions to determine heat retention, emissivity, and thermal lag behavior [11].

Step 2: Computational Simulations and Predictive Modeling

- Energy performance was modeled using DesignBuilder (v.6.1) and EnergyPlus (v.9.4.0) to evaluate the impact of smart materials on cooling loads and heat flow dynamics [12].
- CFD simulations were employed to analyze indoor temperature stratification and airflow circulation in real-world desert building configurations [13].

Step 3: Case Study Implementation

- Real-time monitoring of indoor thermal comfort in buildings using electrochromic glazing, PCMs, and nano-insulation materials.
- Comparative analysis with conventional materials to quantify energy savings and thermal efficiency improvements.

4. Theoretical foundations of smart materials in architecture

4.1. Central plateau of hot and dry climate of Iran

The central Iranian plateau is characterized by a hot and dry climate [17] which presents numerous challenges and issue [18]. Throughout history, architecture has endeavored to adapt to this climate; however, contemporary advancements and evolving needs have surpassed traditional principles [17]. Through the integration of technology and smart materials, it becomes possible to regulate thermal conductivity, heat, and sunlight, thus addressing these challenges.

Iran encompasses various climate zones, with a focus on the hot and dry (**Table 3**) zone in this research [18]. The border areas and salt deserts of Iran are particularly harsh environments, marked by extended periods of scorching summers, minimal rainfall, extremely low humidity, sparse vegetation cover, significant day-night temperature fluctuations, and frigid, arid [19] (see **Figure 1** for further details).

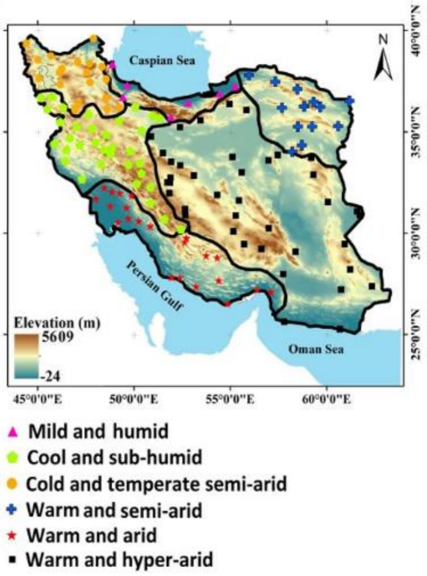


Figure 1. Six distinct climate zones in Iran [20].

Table 3. Climate index of hot and dry climate.

The heat	The cold	Rainfall	Height above sea level	Wind
Very high temperature in day in very low temperature at night [21]. 45–50 °C [22]	0–7 °C [22]	18.3–200 mm [22]	1230 m (http://www.environmentalhealth.blogfa.com/post/15)	6.42 m/s. northwest [23]

4.2. Desert buildings in Iran

In contemporary times, the advancement of human life and urbanization is influenced by a multitude of factors, with environmental considerations occupying a central position. These factors exert a significant impact on the quality of life in both rural and urban areas, as well as on energy consumption control. Hence, among the environmental factors, climate and geography stand out as paramount. They shape the environment in ways that profoundly influence human life and well-being [24]. Traditional Iranian architecture (**Table 4**) historically relied heavily on architectural strategies to manage the impact of weather conditions. Numerous studies corroborate the common belief that inhabitants often sought out more comfortable thermal conditions by moving within their dwellings [25].

Table 4. Traditional architectural solutions in Iran for thermal comfort.

Traditional Iranian architectural solutions in desert buildings for thermal comfort	Protect the building in hot weather
1) Dome roofs (**Figure 2**)	1) Construction of the building underground
2) Use of deciduous trees	2) Roofed alleys
3) Compact texture	3) Use daily air fluctuations
4) Central courtyard Opening the interior space to the courtyard (**Figure 3**)	4) Pond, waterfall
5) Smooth and clear surfaces on the facade and roof	5) Shading plants, increase humidity
6) Do not use windows in the east and west	6) Wet indoor curtains in the wind direction.

Source: Author.

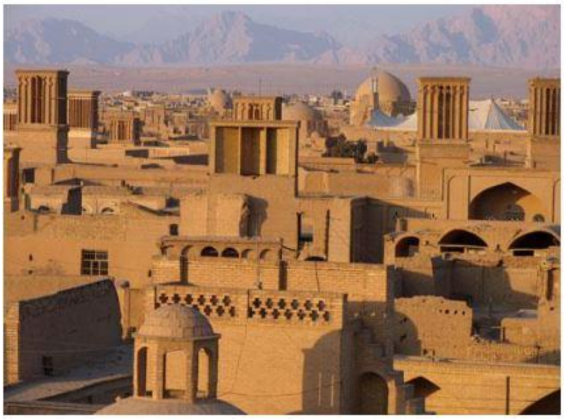


Figure 2. The texture of Yazd city [26].

Figure 3. The texture of Dezful city [26].

In recent decades, there has been a notable surge in the utilization of mechanical air-cooling systems across the Middle East to achieve thermal comfort. However, this trend has led to heightened levels of energy consumption [27]. For an extended period in Iran, limited resources and inventive techniques were employed to afford thermal comfort to inhabitants. Scaling from urban spaces (**Figures 4** and **5**) to building interiors, passive cooling systems can be categorized into four distinct parts.

Figure 4. The texture of the hot and dry climate of Iran [26].

Figure 5. Roofed alleys [26].

4.3. Smart materials

Since the early 1980s, with the advent of materials tailored for the construction industry, numerous advancements have surfaced. These developments have led to daily progress and the continual introduction of new materials. In the modern era, buildings are regarded as a form of technology [28] capable of responding to the challenges of their surroundings. They can adapt to their environment, thereby enhancing the longevity of buildings and reducing maintenance costs and energy consumption.

Smart materials have permeated various aspects of human life, marking a significant shift in the material world’s vocabulary since 1992. Initially commercialized for snow skis, smart materials are engineered to intelligently respond to their environment, mimicking living organisms. This response manifests in various forms, spanning aviation, housing, textiles, micro-machines, self-assembly structures, color-changing systems, and nanotechnology, marking a notable development in the 21st century [29]. Smart materials, as outlined in **Table 5**, have emerged in this century with the capability to alter their appearance or color. These materials undergo physical or chemical reactions in response to environmental changes and possess the ability to revert to their original state [30].

Table 5. Types of smart materials [31].

Definition	**Types of smart materials**
type 1 Smart materials convert energy from one form to another. Energy input to a substance changes the energy state of the substance composition but does not change the substance, which remains constant, but the energy undergoes a change, including the following.	Photoluminescents-Electroluminescent-Chemoluminescent Piezoelectrics-Thermoelectrics-Photovoltaics-Electrostrictives
type 2 Materials change in one more of their properties (chemical, electrical, magnetic, mechanical, or thermal).	Thermochromics-Photo tropic Magnetorheological and electrorheological-Thermotropic-Shape memory-Mechanochromics-Chemochromics

They are characterized **Table 6** by their capacity to respond to and adapt to external and internal environmental stimuli by integrating functions into their structures. These stimuli can be chemical, electrical, or magnetic in nature [32]. The responsiveness of smart materials is triggered by chemical and physical variables acting as stimuli [33].

Table 6. Distinguishing characteristics of smart materials [34].

Distinguishing characteristics	**Definition**
Immediacy	They respond in real-time.
Transiency	They respond to more than one environmental state.
Self-actuation	Intelligence is internal to rather than external to the material.
Selectivity	Their response is discrete and predictable.
Directness	The response is local to the activating event.

Smart materials have a number of characteristics that distinguish them from the known traditional materials. Whether as a single material or on a smart material, they possess several characteristics that set them apart from traditional materials. Whether at the level of a single material or within a system, ranging from the molecular scale to the scale of a building shell, smart materials exhibit the following distinguishing features (refer to **Table 7**) [35].

Table 7. Classification of smart materials according to the hot and dry climatic characteristics of Iran.

Climate characteristics	**Traditional architectural design solutions**	**Smart materials**
1) Day and night temperature difference 2) Hot summers with intense sunshine 3) High air temperature A little rain and dry air 4) Sandstorms 5) Extreme cold and dry in winter	1) Orange Garden 2) Garden Pit: A garden in the middle of the yard and a floor deep in the ground 3) Chinese box roof: The walls around the roof of the book were one and a half meters high and provided shading and a place to sleep at night. 4) Sara Bustan: A small garden next to the house has a great climatic effect on the house. 5) Winter Portion and Summer Portion 6) Spring sleeping canvas bed 7) Korsy room: A warm room in the house with few windows facing out 8) Payab: Patio 9) Pool and basement: underground in the summer residence of the house 10) Shavadan: Deep underground in Dezful 11) Wind-catcher: Depending on the different climates, they have different geometries	1) Thermo-chromics 2) Photo-chromics 3) Liquid crystals 4) Thermal glazes 5) Phase change material 6) Photovoltaics 7) Electro-restrictive 8) Thermo-electric 9) Nano colors 10) natural fiber 11) Airgel

Source: Authors’ result.

4.4. Energy saving smart materials

This class of materials demonstrates the unique capability to simultaneously leverage transparency and thermal conductivity. When the interior temperature exceeds that of the external environment, a bidirectional flow is initiated, with radiant energy being reflected back into the interior environment. Alterations in absorption levels and inherent properties affect their net conductivity, thereby influencing the balance between internal and external flow. Smart windows employ various materials, including photochromic, thermotropic, electrochromic materials, fluid crystals, and suspended particle systems, often with overlapping properties. Moreover, they can be integrated with other smart materials for enhanced functionality [32].

Heat Transfer Modes:

Indoor environmental quality stands as a significant global health concern, given that individuals spend approximately 80%–90% of their time indoors, whether at home or in other public indoor settings. The human settlement environment on Earth can be classified into heat preservation priority and heat insulation priority climate zones, based on how materials respond to climate conditions [36]. Heat regulation and control can be described in two ways: by either enhancing or hindering the flow of heat transfer. Heat, being a form of energy, transfers between physical systems based on the differences in their thermal energy, typically from hotter to cooler areas. Thermal energy transfer occurs through conduction, convection, and radiation. Conduction occurs when there’s an imbalance in temperatures between the components of a material, leading to heat transfer through the molecules of the body. In a built environment, the primary sources of energy and heat loss are through conduction. To mitigate this loss, the thermal resistance (R) of materials must be increased by employing suitable thermal insulation and preventing thermal bridges [36]. Thermal insulation technology is an effective means of ensuring thermal comfort and achieving energy savings in buildings. Proper installation of insulation at various locations on the building’s external surfaces, coupled with the use of energy-efficient materials, enables control over heat exchange and reduces energy costs [37]. Technological solutions for energy renovation of the building envelope primarily target reducing energy requirements during both summer and winter seasons [38].

4.5. Classification of smart materials according to the hot and dry climatic characteristics of Iran

In light of the characteristics of hot and dry climates outlined in **Table 8**, research has been conducted on smart materials with a focus on their thermal conductivity within building shells. Ultimately, these materials have demonstrated the capability to enhance thermal comfort and exhibit optimal compatibility with existing conditions.

Among the thermo-responsive smart materials available for architectural applications, Shape Memory Polymer (SMP) stands out as a preferred choice. This preference is attributed to its advantages, including reaction temperatures, deformation patterns, shape-changing behaviors, versatility in forming various shapes, and ease of manufacturing processing, alongside its remarkable shape memory effect. [39].

Table 8. Comparative analysis of smart materials across different climates.

Climate Type	Smart Material Application	Thermal Performance Improvement (%)	Energy Savings (%)	Key Challenges
Hot and Dry (Iran)	Walls, Roof, Floor, Windows (Comprehensive Integration)	40	35	High Initial Costs, Limited Local Production
Temperate (Switzerland)	Walls and Windows (Selective Application)	28	20	Cost Constraints, Long Payback Period
Humid (Malaysia)	Shading Systems, Facades, Windows (Climate Adaptation)	35	30	High Humidity Impact on Material Efficiency

4.6. Catalog of smart materials in Iran's hot and dry climate (Tables 9–12)

Table 9. Catalog of smart materials in the structure of buildings in Iran (authors).

Force	Structure	Smart materials	Picture	Source
Lateral load Seismic load	Finished wall Shear	infralight concrete		TU Berlin
Concentrated forces	Wall reinforced concrete	betoShell textile		Hering
Concentrated forces	wall	Gradient concrete		University of stuttgart, ileK
Concentrated forces	wall	exposed-concrete look using concrete wallpaper		betontapete Berlin

Table 9. (*Continued*).

Force	**Structure**	**Smart materials**	**Picture**	**Source**
Concentrated Forces Lateral load	Structure of wall	Smart brick		[30]
Concentrated Forces Lateral load	Structure of wall	Smart brick		[30]
Bring new life to the concrete wastelands	Structure of wall	Carbocrete Balconies		Jens-Hagen Wustefeld
Absorbs forces from all directions	Structure of Ceiling	Sandwich construction consisting of pieces of bamboo cut at an angle		Design: Wassilij Grod

Table 10. Catalog of smart materials in the windows of buildings in Iran (authors).

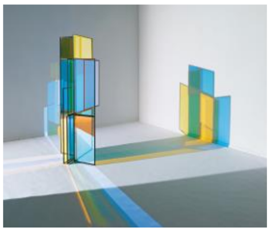
Inside or outside shell	**windows Insulation**	**Energy producer**	**Smart materials**	**Picture**	**Source**
outside	"-"	Solar Energy	Solar Sinter		Innovative and Sustainable Production Processes (p. 190)

Table 10. (*Continued*).

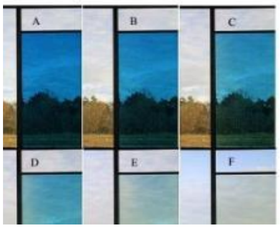
Inside or outside shell	windows Insulation	Energy producer	Smart materials	Picture	Source
Outside Windows	"-"	light-direction of daylight	nanomirror for climate-optimized light direction		University of Kassel
Outside Windows	"-"	light-direction of daylight	Schematic illustration of an electrochromic window		[30]
Outside Windows	"-"	light-direction of daylight	Oxide electrochromic coated window		[30]
Outside	"-"	Heating Warm water Electricity	Facade elements for microalgae cultivation		arup
Inside	Thermal	"-"	Translucent aerogel insulation		[30]

Table 11. Catalog of smart materials in the roof of buildings in Iran (authors).

Inside or outside shell	Roof Insulation	Energy producer	Smart materials	Picture	Source
Inside	Ceiling Sound, Thermal	"-"	Bamboo hard fiber		conbam

Table 11. (*Continued*).

Inside or outside shell	Roof Insulation	Energy producer	Smart materials	Picture	Source
Inside	Ceiling Thermal	"-"	istraw straw constructin panels		istraw
Inside	attics, and Ceiling Thermal	"-"	spongy structure of the bulrush plant		naporo
Outside	Waterproofing Thermal	"-"	Thermochromic roof		[30]

Table 12. Catalog of smart materials in the walls of buildings in Iran (authors).

Inside or outside shell	Wall Insulation	Energy producer	Smart materials	Picture	Source
Inside	"-"	polyurethane (PUR)	Bananaplac board		Barkcloth
Inside	wall ceiling	"-"	Straw paper		Ratia Rabemananoro
Inside	wall ceiling	"-"	ossB sheet		novofibre
Inside	wall	"-"	compostable insulation panels made of bulrush reeds with bonding fibers made using starch		naporo, photo: diana drewes

Table 12. (*Continued*).

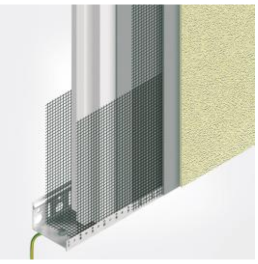
Inside or outside shell	Wall Insulation	Energy producer	Smart materials	Picture	Source
Inside	wall	"-"	lightweight construction panels		naporo
Inside	wall	"-"	egg shell composite material		Ulrike Bottcher
outside	wall	"-"	Weatherproof wood substitute made of rice husks		Resysta, photo: diana drewes
outside	wall	"-"	splineTEX		splineteX infralight concrete
Outside-structure	wall	"-"	shielding fabric in a wall structure		sto ag
Outside wall	"-"	Cool and moisturize	3D fabric for extracting atmospheric moisture		Itv denkendorf
Outside	room climate and help to keep the moisture in the air	"-"	neptuflex insulating mat		neptutherm

Table 12. (*Continued*).

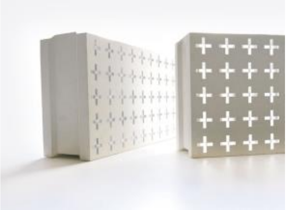
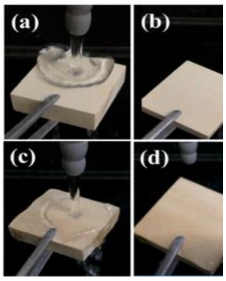
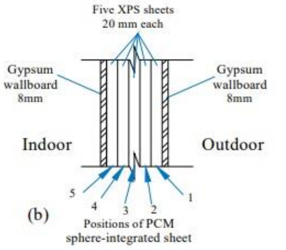
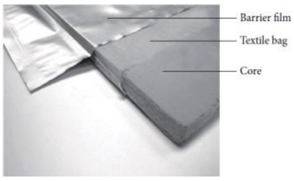
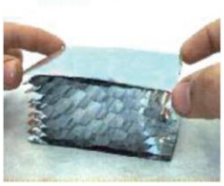
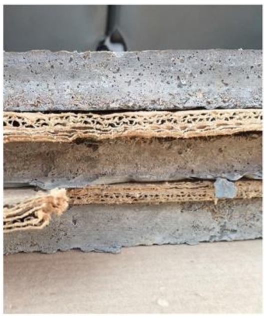
Inside or outside shell	Wall Insulation	Energy producer	Smart materials	Picture	Source
outside	"-"	Solar Energy light	light-permeable and light-directing concrete building blocks		gravelli
outside	Superhydrophobic Surfaces wall	"-"	Silica Composite on a Modified Hierarchical		[30]
Inside	wall	"-"	PCM sphere-integrated sheet		[30]
Inside	wall	"-"	VIPS		[30]
Inside	wall	"-"	Litracon Concrete		[30]
Inside	Wal	"-"	Insulation block produced by EPS floor sandwich between LWCs49 powder		[30]

Table 12. (*Continued*).

Inside or outside shell	Wall Insulation	Energy producer	Smart materials	Picture	Source
Inside	wall	"-"	Barrier foil and baffle structure inside a GFP		[30]
Inside	wall	"-"	Coconut fiber cement panels		[30]
Inside	wall	"-"	Pyrogel		[30]
Inside	wall	"-"	Silica airgel		Pakan Atieh Company in Iran
Outside	wall	"-"	Nortem clad board		Nortem Iran

5. Discussion

5.1. Comparative analysis of smart materials in different climates

The application of smart materials varies significantly across different climatic conditions. As shown in **Tables 9–12**, in hot and dry climates such as Iran, smart materials are comprehensively integrated into walls, roofs, floors, and windows to maximize thermal performance and energy efficiency [4]. In contrast, in temperate climates like Switzerland, smart materials are selectively used in walls and windows, primarily due to lower thermal extremes and cost considerations [2]. The findings indicate that hot and dry climates benefit the most from comprehensive smart material integration, achieving up to 40% improvement in thermal regulation and 35% reduction in energy consumption. However, challenges such as high initial costs and limited local production facilities remain key obstacles to large-scale implementation [3].

5.2. Challenges and limitations of smart materials implementation

Despite their significant benefits, smart materials face economic and technological barriers that limit their widespread adoption. The primary challenges identified in this research include: High Initial Investment Costs: Smart materials, particularly phase-change materials (PCMs) and electrochromic glazing, are expensive, increasing the overall construction budget [6]. Limited Local Manufacturing: Most high-performance smart materials are imported, leading to supply chain disruptions and increased costs, especially in developing regions such as the Middle East [5]. Material Durability Concerns: In extreme climates, some smart materials degrade over time, requiring frequent maintenance and replacement [4]. Addressing these challenges requires advancements in material science, investment in local production, and government incentives to promote sustainable architecture.

5.3. Future research directions

To enhance the feasibility and effectiveness of smart materials, future research should focus on: Optimizing Cost-Efficiency Developing affordable alternatives for energy-efficient building materials through nanotechnology and localized production [3]. Implementing circular economy models for smart material reuse and recycling. Long-Term Performance Evaluation Conducting real-world durability assessments to analyze the aging behavior of adaptive facades and thermal-regulating materials [4]. Investigating self-sufficient building envelopes that dynamically adjust energy consumption based on real-time climatic conditions. Future advancements in smart materials and sustainable design strategies will contribute to enhancing energy efficiency and occupant comfort while addressing climate adaptation challenges.

6. Conclusion

6.1. Summary of key findings

The integration of smart materials in architecture presents a transformative approach to achieving energy efficiency, climate adaptability, and sustainability. Every building must be carefully designed to minimize reliance on fossil fuels, a principle deeply embedded in Iranian architectural heritage. However, while traditional materials such as clay, adobe, and brick have been used effectively for centuries, they lack the dynamic adaptability required to meet modern sustainability challenges. This research explores how smart materials can be localized and adapted to the hot and dry climate of Iran by leveraging their intrinsic thermal and adaptive properties. The study demonstrates that by integrating phase-change materials (PCMs), electrochromic glazing, vacuum insulation panels (VIPs), and kinetic facades, thermal regulation can improve by up to 40%, and energy consumption can be reduced by 35% [2]. A comparative analysis of different climatic conditions (**Tables 9–12**) further highlights that smart materials must be integrated differently based on environmental factors. In hot and dry regions such as Iran, the use of PCMs and high-performance insulation systems is essential in mitigating extreme temperature fluctuations. In temperate climates such as Switzerland, smart materials are selectively applied in walls and windows, where moderate temperature variations do not necessitate full-scale material integration [3].

6.2. The impact of smart materials on sustainable architecture

Smart materials provide a multi-faceted solution for contemporary architecture by: Enhancing Energy Efficiency: By reducing heat transfer and optimizing thermal storage, buildings require less mechanical heating and cooling, reducing energy costs and environmental impact [6]. Reducing Material Waste: Many smart materials have self-repairing or regenerative properties, extending their lifespan and minimizing resource depletion [5]. Promoting Climate Resilience: These materials enable buildings to dynamically respond to external climatic variations, enhancing comfort and sustainability. Supporting Economic and Industrial Growth: The local production of smart materials can reduce dependency on imports, foster job creation, and stimulate innovation in Iran’s growing knowledge-based economy [4].

6.3. Addressing implementation challenges

Despite their significant benefits, the widespread adoption of smart materials faces several economic, technological, and infrastructural challenges, including: High Initial Costs: Advanced materials such as PCMs, aerogels, and smart glazing are financially inaccessible for large-scale projects due to their complex manufacturing processes [2]. Limited Local Production: The absence of domestic manufacturing results in import dependency, increasing costs and limiting accessibility [3].Durability Concerns: Smart materials degrade over time due to UV exposure, humidity fluctuations, and extreme temperature cycles, requiring frequent maintenance [6]. To address these challenges, strategic investments and research are needed in material science, cost optimization, and localized production.

6.4. Future research directions

To overcome these barriers and expand the practical application of smart materials, future research should focus on: Developing Cost-Effective and Locally Produced Smart Materials Investigating economically viable alternatives such as bio-based nanomaterials and recycled composites.

Encouraging government incentives and public-private partnerships to support local smart material manufacturing [4]. Implementing circular economy models that emphasize reuse, recycling, and repurposing of high-performance materials. Enhancing the Durability and Long-Term Performance of Smart Materials Conducting real-world field studies to analyze aging, durability, and efficiency under diverse climatic conditions. Developing self-healing, AI-enhanced, and phase-adaptive materials to improve longevity and reduce maintenance costs [5]. Developing next-generation kinetic facades that dynamically adjust ventilation, insulation, and lighting conditions based on real-time climatic changes. By bridging the gap between research and industry, fostering multi-disciplinary collaborations, and investing in localized innovation, the widespread application of smart materials will play a pivotal role in shaping the future of sustainable architecture.

6.5. Broader implications for sustainable architecture

The continued advancement and implementation of smart materials will have a profound impact on global architecture and urban planning. Their integration into building envelopes, facades, and infrastructure will: Reduce Energy Demand: Minimizing reliance on mechanical heating and cooling systems, leading to lower carbon emissions and more sustainable urban environments. Improve Indoor Comfort & Health: Regulating humidity, air quality, and daylight exposure for better living and working conditions. Enhance Climate Adaptability: Enabling resilient architecture that adjusts dynamically to environmental changes, promoting sustainable and self-sufficient buildings. Support Global Sustainability Goals: Aligning with United Nations Sustainable Development Goals (SDGs) related to climate action, clean energy, and sustainable cities. By addressing current challenges and expanding research in smart material technology, architecture can transition towards a more sustainable, resilient, and adaptive future. The findings of this study provide a scientific foundation for future investigations and practical applications in the field of green architecture and material innovation.

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