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Synergizing Nature-Inspired Adaptive Facades: Harnessing Plant Responses for Elevated Building Performance in Alignment with Saudi Green Initiatives

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Abstract

Saudi Arabia has a large part of the country's power consumption in the building area, mainly operated by cooling demands under extreme climatic conditions, where the summer temperature is more than 45 °C and solar radiation peaks are more than 1200 W/MIC. Facing this challenge, this research examines the translation of biometric principles in the design of adaptive building construction for dry areas. We present a comprehensive, four-phase method structure: removing thermoregulatory and shading strategies from desert vegetation; computer display simulation using EnergyPlus 9.7.0 and CFD (ANSYS Fluent 2022 R2); and the development of an implementation guideline. Our findings achieve three central insights. First, the dynamic factor system, such as the electrochromic glazing tested in our student project, reduced the use of HVAC energy by 30%, while advanced materials, such as the polycarbonate panel, demonstrated notable thermal stability. Secondly, the synergy between cultural knowledge and technical performance proved to be decisive; vernacular-inspired Mushrabias improved generic louver not only in thermal efficiency but also in user acceptance, which increased the 97% approval rate in post-acquisition surveys. Finally, we demonstrate that scalability is economically viable, indicating a seven-year payback period for simulation, phase-transit material (PCM), which aligns with the budgetary realities of public and educational projects. By fusing the plant-induced strategies with rigorous computational modeling and real-world applications, the work provides actionable guidelines for permanent failure design in the warm-dry climate. It underlines that maximizing energy efficiency requires the cohesion of thermodynamic principles with the craft traditions of local architecture, an approach directly aligned with the Saudi Green Initiative and the ambitions of global carbon neutrality goals.

Keywords: biomimetic façades; passive cooling; adaptive building envelopes; vernacular design; arid climates; Saudi Green Initiative; lifecycle cost analysis

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Academic Editor: Antonio Caggiano

Received: 28 April 2025
Revised: 7 September 2025
Accepted: 10 October 2025
Published: 27 October 2025

Citation: Mohamed, A.S.Y.; Binabid, J. Synergizing Nature-Inspired Adaptive Facades: Harnessing Plant Responses for Elevated Building Performance in Alignment with Saudi Green Initiatives. *Buildings* **2025**, *15*, 3878. https://doi.org/10.3390/buildings15213878

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1. Introduction

A unique climate challenge in Saudi Arabia's building area is that the summer temperature is regularly more than 45 °C, while solar radiation occurs from peaks at about 1200 w/m gust, resulting in more than 70% of the country's electricity, mainly for cooling ([1,2]) Traditional static forearms, which dominate current construction exercises, are poorly equipped to deal with these extremes, as they cannot react dynamically to dynamic and

seasonal ups and downs. In response, this study further enhances an adaptive forearm structure that integrates biometric principles with computational modeling and real-world prototypes. Drawing strategies developed in desert flora, such as cacti's shading structures of the geometric and mangrove root systems, show how nature-inspired design can reduce the demand for cooling in dry climates. Initial results from a student-led retrofit in Riyadh (Arch 368: Advanced Surface Tectonics Course at Effat University) showed that glass fiber reinforced concrete (GRC) Masarbia reduced the cooling load by 19%, lowering the ability to reduce the merger with modern performance verification.

The research creates a comparative empirical analysis of retrofit strategies in three contexts: geometric shading in a Riyadh office, a cloth-first retrofit in Jeddah Housing, and a systemic double-skin for a Jeddah commercial building. This classification of approaches shows a spectrum from passive solutions with low technology to technically advanced fake systems. Conclusions suggest that simple passive strategies excel in climate uniqueness and cost-effectiveness, providing high performances as systemic mediation attitudes such as double-skin facades, but at the cost of more complexity, embodied energy, and financial burden. With passive and hybrid solutions, active systems such as building-integrated photovoltaic (BIPV) provide a supplementary capacity. The study confirms that BIPVs can reduce the intensity of energy by 28% [3], while their integration in the biometric adaptive structure has shown even more promise [4]. Nevertheless, empirical cases confirm that technical efficacy alone is inadequate in Saudi Arabia; successful adoption requires cultural and relevant alignment. For example, the Arch 368 project achieved a 97% post-occupancy satisfaction rate by incorporating Islamic geometric motifs into the electrochromic glass facade, resulting in a 30% reduction in HVAC consumption.

This study contributes to the discourse of scholars in three important ways:

a. It provides the empirical verification of retrofit strategies, which are spread in passive, fabric-first, and systemic mediation approaches.
b. It addresses the research difference on the adaptive foretelling performance in a dry climate, where strong data remains limited [5].
c. It develops the implementation guidelines formed with Saudi Vision 2030 and the Saudi Green initiative, including the life cycle cost analysis that displays economic viability, including the low payback period of seven years for phase-change-on-conversion material (PCM).

Those who follow integrated functioning with detailed performance results from sectional EnergyPlus simulation, computational fluid dynamics (CFD), and physical prototypes, with detailed performance results from laboratory experiments and empirical retrofit cases. Collectively, research indicates that the permanent failure design in extreme climates is successful when thermodynamic rigidity reconciles with cultural knowledge, providing evidence-based routes towards energy-skilled and reference-sensitive architecture.

1.1. Problem Statement

The Saudi construction area stands in a decisive moment, where rapid urbanization and severe climate pressure coincide with the demand for increasing energy. With the buildings responsible for more than 70% of the state's power consumption [2], dependence on traditional, static forearm systems has faced three interacting challenges:

- Energy disability: Traditional envelope lacks accountability for solar extremes, resulting in extreme dependence on mechanical cooling [1].
- Thermal instability: Indoor conditions lead to an optimal comfort range by 3 °C, which reduces living welfare.
- Cultural disconnection: Imported failure typology often ignores oral traditions, causing inconsistency between architectural forms and regional identity.

Saudi Green Initiatives and Vision 2030 clearly call for solutions that overcome these challenges. The empirical analysis of three retrofit case studies shows that biometric adaptive facades can offer this integration. By imitating desert flora–which have developed strategies to regulate heat, light, and moisture for more than a millennium ([6–8])—facades are able to create dynamic systems from a static barrier by performing the following:

- Reducing the cooling load by 19–35% through shedding and ventilative strategies;
- Maintaining thermal comfort within 1 °C of optimal categories;
- Protecting cultural authenticity through vernacular design elements;
- Ensuring economic viability through a 7-year of life cycle.

From the course ARCH 368, this considered proposal is evidence of the Riyadh Retrofit Project and a comprehensive comparative framework. Passive GRC Mashrabias achieved a 19% cooling decrease with an approval of 97%, while systemic arbitration strategies revealed the capacity for multi-peak performance at a high cost. Collectively, these conclusions highlight that biometric adaptive fronts can bridge technical performance and cultural resonance, keeping them in position as an important tool for a flexible, low-carbon-made environment in Saudi Arabia.

1.2. Research Objectives

The basis for the creation of the challenges to be identified in the problem and the basis for comparative case is empirical evidence; this research establishes four major objectives:

a. **Quantify Performance Improvements**: Strictly measure the energy and comfort of biometric adaptive forearms under Saudi Arabia's extreme climatic conditions. Specific goals include the following:
   - Cooling load reductions of 25–35%, as is estimated in simulation studies and supported by a 19% reduction in the Riyadh student retrofit;
   - Stabilization of indoor thermal conditions within the 24–26 °C comfort range, reducing diurnal temperatures within 1 °C;
   - Distal optimization via angularly induced geometry that maintains a useful daylight illumination (UDI) of 100–2000 Lux.

b. **Evaluate System Interactions:** Assess the integrated effect of biometric fail strategies on the performance of construction in many dimensions, including the following:
   - Trends of annual energy consumption and seasonal variability;
   - Peak heat gains/loss dynamics, especially during important summer conditions;
   - Indoor environmental quality targeting CO and levels below 1000 ppm and particulate concentrations (PM2.5) below 12 μg/m ing, ensuring health and well-being.

c. **Optimize Hybrid Systems:** Develop and validate hybrid solutions connecting passive biometric strategies with active renewable technologies. Major objectives include the following:
   - Integrating a 20–30% renewable energy contribution through BIPV into adaptive fronts;
   - Search for synergistic operations between passive thermal regulation and active energy production;
   - Ensuring cultural and aesthetic suitability displayed by the Arc 368 Project, where electrochromic glazing was integrated with Islamic geometric patterns and received 30% HVAC savings and 97% user satisfaction.

d. **Develop Implementation Framework**: To adopt a biometric failure in Saudi Arabia, a practical, scalable, and evidence-based roadmap is structured around the following:

- Alignment with Saudi Vision 2030 and Saudi Green Initiative stability benchmarks;
- Life-related cost analysis, which demonstrates economic viability, with the target of 7 years with a payback period (as is indicated by the PCM simulation);
- Scalability in both new constructions and retrofits, informed by comparative case study insights;
- Integration of rustic design principles with advanced materials, strengthening cultural authenticity by achieving a high performance.

These purposes will be carried forward through a multi-phase method that integrates computational modeling (EnergyPlus/CFD), laboratory-based tests, and empirical verification. Arch 368 serves as an initial proof of the students' retrofit concept, reflecting the ability of biomimetic design to provide average energy savings and strong user acceptance.

1.3. Research Hypothesis

This study envisages that the biometric adaptive forearm designed to simulate plant reactions to environmental stimuli will provide an average improvement in both energy performance and thermal comfort under the extreme climatic conditions of Saudi Arabia. Taking inspiration from desert vegetation-like cactus-inspired cinematography, it is expected to act as a dynamic, responsible envelope rather than a stable obstacle.

In particular, it will be envisaged that the biometric adaptive forearm will

- Improve energy efficiency by reducing the cooling load by 25–35% through passive strategies that optimize shading and natural ventilation.
- Increase thermal comfort by stabilizing indoor temperatures within the range of 24–26 °C (ASHRAE standard 55) [9], reducing dependence on energy-intensive HVAC systems.
- Optimize the daylight, as useful daylight of 100–2000 lux achieves the light of daylight (UDI), which ensures visual comfort, reducing glow and additional solar heat gains.

In addition, when the building is integrated with photovoltaics (BIPVs), an adaptive front is expected, contributing 20–30% of the total building energy demand through renewable generation:

- The overall building flexibility will be improved by reducing dependence on traditional cooling systems;
- The stability of the Saudi Green initiative displays economic viability with a life cycle of 7–10 years, in line with the benchmark. This hypothesis is preliminarily supported by empirical evidence.

Retrofit, a student project from the ARCH 368 course, demonstrated a 19% decrease in the cooling load through GRC Mushrabia, obtaining a 97% satisfaction, and accepted both technical performance and cultural echoes of biometric design in its behavior.

2. Research Methodology

This study employs a multi-phase research design that bridges theoretical examination, computational analysis, and empirical verification. The approach to ensure both scientific hardness and practical prevention in Saudi Arabia's extreme climate context was deliberately structured.

2.1. Phase One: Biomimetic Strategy Synthesis

The first phase included a biological translation process, which removes adaptive strategies from desert vegetation and systematically maps them to the principles of design. For example:

- Cactus morphology informed the development of self-sharing geometry, reducing direct solar risk while maintaining the reach of daylight.
- Mangrove root structures inspired the ventilative system capable of modifying airflows and reducing indoor heat accumulation.

This phase provided an ideological basis for converting plant adaptation logic into an architectural prototype.

2.2. Phase Two: Computational Modeling

In the second phase, these biomimetic concepts were subject to quantitative analysis:

- Energy plus for dynamic thermal simulation enabled the evaluation of cooling load cuts under peak summer conditions.
- To assess computational fluid dynamics (CFD), thermal comfort, and indoor air quality improvements, airflow and ventilation modeling was used.

The simulation tested several scenarios—geometry, glazing properties, and double-skin cavities—for the comparative evaluation of design strategies before dynamics–hypothesis–physical implementation.

2.3. Phase Three: Empirical Validation

The third stage focused on real-world testing and empirical analysis that moves beyond theoretical simulation. This included a double approach to controlled laboratory experiments and field-based verification through academic retrofit projects, providing important data on real-world performance, construction, and user acceptance. A Live Retrofit Project was a Live Retrofit Project as part of the Senior Elective Course ARCH 368 in Spring 2022, a foundation stone of this empirical verification: Architecture and Design, Advanced Surface Tectonics at Efat University. The attention of the course paid to "Materials and Methods in Attaching" provides an ideal platform to translate biometric theory into a tangible application. Under faculty supervision, students designed, coined, and monitored the performance of a retrofit solution for a campus facility in Riyadh. The project employed glass fiber reinforced concrete (GRC), which was to create a contemporary Mashrabia screen inspired by the self-shading principles of desert vegetation. The ARCH 368 project served as an important live case study, where the established GRC Mashrabias achieved a 19% decrease in cooling demand while maintaining 97% user satisfaction in post-authorized surveys.

To refer to these findings within a comprehensive structure, three additional retrofit case studies were assessed–a Riyadh office (geometric shading), a Jeddah residential building (fabric-first), and a Jeddah Commercial Building (Double-Skin Aggar)—via an Axial Analysis. Each case was strictly evaluated against its specific climate drivers, technical specifications, theoretical performance matrix, and verification methods, creating a structured empirical structure for the region.

This comparative approach revealed a practical classification of adaptive forearm solutions for dry climates, including low-technically inactive measures to high-technical systemic mediation strategies. This effectively highlighted the underlying strength of each approach—such as climate specificity and cultural resonance—while the risk of overshading the autonomy of the daylight and the risk of reducing significant capital costs also highlighted their limitations.

2.4. Phase Four: Implementation Framework

The final stage integrated insight by biological synthesis, simulation output, and empirical verification to develop a practical implementation structure. This structure includes the following:

- Performance benchmarks for inactive and hybrid fail systems in a dry climate;
- Parameters for life cycle cost analysis and phase-transit materials (PCMs) within 7 years;
- Cultural–technical guidelines demonstrating how vernacular geometrics (e.g., Mushbia) can be paired with advanced materials (e.g., electrochromic glass, polycarbonate panel) and how it can be added;
- Scalability Pathway, Saudi Green Initiative, and Vision 2030 were formed for both new construction and retrofit applications.

3. Literature Review

3.1. Nature-Inspired Design and Adaptive Facades in Architecture

Nature-inspired design has emerged as a central paradigm in contemporary architectural discourse, especially for its ability to increase energy efficiency and environmental flexibility. Adaptive facades—defined as envelopes capable of dynamically reacting to external conditions such as temperature, solar radiation, air speed, and humidity—represent a major application of this paradigm [5]. These systems rapidly integrate sensors, actuators, and AI-powered algorithms, allowing real-time adjustments that improve energy and living comfort [1,10].

Biomimetic approaches, in particular, have gained prominence by portraying similarities between envelopes and the creation of biological systems. By imitating the thermoregulatory mechanism of plants and animals, the adaptive forearm acts not only as a protective layer but also as an active mediator of heat, light, and airflow [6,11]. For example, Cacti display the ability to translate self-shading geometric or mangrove root ventilation patterns to translate ecological strategies into architectural solutions.

In addition, the integration of building-integrated photovoltaics (BIPVs) within adaptive facades has expanded the role of building envelopes from passive regulators to active energy producers [12]. Recent studies reported a decrease of up to 28% in the manufacture of energy intensity when BIPVs are employed in combination with responsible failure systems [3]. Parallel to this, kinetic design strategies—such as the louver or morning panel rotation—create a balance between thermal safety, day adaptation, and aesthetic expression [10] by enabling additional adaptability capable of physically re-configuring in response to climatic stimuli.

These developments highlight a comprehensive disciplinary change towards adaptive, ecological, unwavering, and technical mediation systems, underlining their ability as the foundational stone of sustainable architecture in dry regions.

3.2. Biomimicry and Responsive Façades

Biomimicry—the systematic transfer of strategies from biological organisms to human design—provides a theoretical and practical structure for the next generation adapted forearm [13,14]. While early applications focus on symbolic copying, contemporary research leads to functional simulation, where the fronts serve as dynamic, self-regulation systems rather than static obstacles.

Plant-inspired approaches reflect this change. For example, modeling has been done after the Stomatal Regulation in leaves or cactus-induced ribbing, which achieves a decrease in solar heat gains while maintaining airflow and daylight penetration [15,16]. Similarly, mangrove-condensed geometry indicates designs that optimize natural ventilation in high-humidity contexts, reducing dependence on mechanical systems. Emerging technologies carry forward these ideas through 4D parametric systems, where the programmable materials change their appearance in response to environmental inputs, staining the boundary between materiality and mechanisms [6].

An equally important trajectory module is contained in the development of modular adaptive systems, which facilitate retrofitting in diverse building types. By enabling incremental upgrades rather than bulk reconstruction, modular biomimetic flexibility, scalability, and economic viability [5] are enhanced. This direction is particularly important in contexts such as Saudi Arabia, where mass retrofitting will be required to align the existing building stock with Vision 2030 stability goals.

3.3. Precedent Case Studies in Biomimetic Façades

Table 1 Summarizes three impressive case studies that portray the global application of biometric design principles in the front:

Table 1. Biomimetic façade case studies.

Case Study	Location	Key Innovation	Performance Data	Source
Eastgate Centre	Harare, Zimbabwe	Termite mound-inspired passive ventilation	35% cooling energy savings	[17]
BIQ House	Hamburg, Germany	Algae-powered bio-reactive façade	50% renewable energy coverage	[18]
King Abdullah Petroleum Studies and Research Center (KAPSARC)	Riyadh, Saudi Arabia	Solar-responsive stone-like panels (“stone leaves”)	28% lower energy use intensity	[19]

These examples demonstrate the various parameters and strategies of biometric fakes, from ventilation-powered systems (Eastgate) to bio-reactive energy-producer skins (BIQ house) and culturally adapted solar north facades (Kapsarc). Collectively, they confirm the dual capacity of biomimicry to distribute both average energy performance benefits and reference-sensitive architectural identity.

3.4. Performance of Adaptive Facades: Energy Efficiency, Thermal Comfort, and Sustainability

The adaptive forefather for improvement in construction performance under various climate pressures has emerged as one of the most important architectural innovations. Unlike static envelopes, these systems dynamically regulate heat, light, and airflow, often integrating smart materials, kinetic components, or bio-inspired mechanisms. Their performance is usually evaluated through three interconnected dimensions: energy efficiency, thermal comfort, and stability integration. Adekunye & Oke, 2022 [12] and Magri et al., 2021 [20], showed that adaptive envelopes equipped with embedded sensing and activation systems can reduce the demand for annual cooling energy by 30%, while the dials maintain operative temperatures within 24–26 °C despite fluctuations. Similarly, Moghaddam et al., 2022 [21] reported that the vertical greenery system applied to mid-growing residential blocks in a hot climate reduces indoor air temperatures from 2–4 °C, which reduces the cooling load by 15–20% [22]. These conclusions confirm that relatively low technical object adaptation can also increase thermal comfort by reducing energy dependence.

Biometric examples also highlight the ability to translate natural systems into scalable architectural applications. The Eastgate Center in Harre is inspired by the termite mound ventilation, which works with about 35% less cooling energy demand compared to comparable office buildings [23,24]. The BIQ house in Hamburg is characterized by the characteristic of an algae-operated bio reactive factor, which is also more than 50% of the building’s energy, and also works as a dynamic shading device [25]. Within the Saudi context, the Capsark Complex in Riyadh integrates the crystalline solar north panels,

inspired by the desert rock structures, which acquire a decrease of 45% in the intensity (EUI) of energy use (EUI) compared to the ASHRAE baseline [19,26].

Analytical Insight–Energy Efficiency: In these cases (Table 2), the adaptive forearm continues to display a 20–50% decrease in the demand for energy compared to traditional facades. However, the climate drivers are different: the Eastgate dial depends on temperature swings, the BIQ house capitalizes on the biomass generation in the medium climate, and the kapsarc reacts directly to the high solar radiation of the Gulf.

Table 2. Comparative performance of adaptive façade case studies.

Case Study	Location/Climate	Adaptive Strategy	Measured Performance	Reference
Eastgate Centre	Harare, Zimbabwe (semi-arid)	Termite mound-inspired passive ventilation + thermal mass	~35% lower cooling energy than comparable offices	[24]
BIQ House	Hamburg, Germany (temperate maritime)	Algae-powered bio-reactive façade (heat + biomass)	50% of energy demand met through façade-integrated bio-reactors	[25]
KAPSARC	Riyadh, Saudi Arabia (hot-arid)	Solar-responsive crystalline panels + passive design	45% reduction in EUI; 5000 MWh/year PV output; and LEED Platinum	[19]

Thermal Comfort: Passive biometric mechanisms—such as termite-induced ventilation or vegetative-based shedding- in indoor conditions—are effective in moderating conditions with the continuous, measured comfort range of the ASHRAE standard 55 [9].

Stability Integration: Beyond operating efficiency, these systems increase environmental stability. The BIQ House displayed renewable energy harvesting as part of the performance of the facade, while KAPSARC culturally combines inactive cooling, attaining both environmental and socio-cultural stability.

Research Gap and Contribution

Although these examples confirm the capacity of the adaptive forearm, there is still limited empirical evidence for the warm-minded climate, where solar radiation peaks at 1200 w/m, and it is insufficient to support the solar radiation peaks and nocturnal cooling east-type ventilation strategies. In addition, many high-performance BIQ bio-reactors face challenges in their scalability in areas such as Saudi Arabia, carrying highly embodied carbon and complex maintenance requirements.

Our study builds upon these lessons by

- Translating desert vegetative strategies (e.g., cactus rib shedding, mangrove-like ventilation) in facade prototypes.
- Validating performance under Saudi climatic conditions through EnergyPlus, CFD, and field-based retrofit interventions.
- Empirically showing that a GRC Mashrabia Retrofit in Riyadh reduced the cooling load by 19%, gaining 97% user satisfaction, reducing the difference between technical rigidity and cultural authenticity.

This locates our bio-reactor as not only an energy-saving device, but also a culturally resonant, reference-specific design strategy that directly aligns with the Saudi Green Initiative and Vision 2030.

4. Design Principles of Nature-Inspired Adaptive Facades

4.1. Overview of Key Design Principles: Biomimicry and Biophilic Design

The theoretical foundations of a nature–individual adaptive forearm lie in two complementary paradigms: biomimicry and biophilic design.

Biomimicry exceeds a metaphor borrowing from nature; it is a rigid design function that translates biological strategies into architectural solutions. As Butt (2022) [14] is classically defined, biomimicry involves simulating nature's models, systems, and processes to solve human challenges. In the created environment, this approach has produced innovations such as the exemplary cactus-motivated self-shaking geometry by the Eastgate Center in Zimbabwe [27] to the terrace-inspired inactive ventilation system in the Term. The strength of biomimicry lies in its ability to change complex ecological adaptation as kinetic morphology [28], self-regulation, and resource cycling into practical design strategies that reduce cooling loads, adapt to daylight, and reduce physical waste [29].

Recent advances in functions and performance expand biomimicry beyond where adaptive forearms act as dynamic systems that are able to modify their properties in response to environmental stimuli. For example, the mangrove-inspired ventilation logic has been adapted to the double-skin facade prototype that exploits the stack effect airflow for passive cooling [28,30]. Similarly, the ingredient-based biomimetic-like size mixes and hygroscopic composite-active systems require at least external energy input [31] to the forefather to operate as a self-active system. These examples suggest that biomimicry not only carries forward energy performance but also provides culturally resonant, resource-skilled routes for sustainable architecture in areas such as Saudi Arabia.

Biophilic design, in parallel, emphasizes human dimensions by integrating natural elements in the environment created to enhance health, welfare, and cognitive performance [24]. While biomimicry focuses on how buildings act like ecosystems, biophilia emphasizes how people interact with nature within those ecosystems. Major principles include natural lighting, vegetation, water features, and fractal geometrics [32], which collectively reduce stress, improve productivity, and promote strong emotional connections between the living and the location [33]. In healthcare architecture, biophilic interventions such as indoor greenery and daylight optimization have been linked to rapid recovery rates and better employee satisfaction [34].

From an urban perspective, biophilic design extends to biophilic urbanism, where green infrastructure—planters, vertical gardens, and ecological corridors—and urban heat islands originally interact with city fabrics to reduce the effects and promote social harmony [32]. In the Saudi context, such strategies resonate with traditional courtyards and oasis settlements, where shadows, vegetation, and water historically define thermal comfort and communal life. Thus, biophilic theory not only provides environmental and health benefits but also strengthens cultural continuity within an adaptive design.

Collectively, biomimicry and biophilic design establish the conceptual foundation for adaptive façades that are responsive, resource-efficient, and human-centered. While biomimicry delivers technological and ecological intelligence—translating evolutionary resilience into material and structural strategies—biophilia ensures that these innovations foster psychological well-being and cultural acceptance. Together, they redefine façade design as a holistic practice that balances thermodynamic rigor, human experience, and ecological harmony, aligning directly with the sustainability imperatives of the Saudi Green Initiative and Vision 2030.

4.2. Implementation of Adaptive Facade Principles for Advanced Architectural Design

The translation of biomimicry and biophilic principles in adaptive forward technologies represents one of the most promising borders in architectural innovation. By imitating

natural processes [35], these systems not only improve energy performance but also promote a healthy, more culturally resonant environment.

Biomimetic strategies: Adaptive forearms can be engineered to repeat the dynamic behavior of plants, which regulate continuous heat, light, and airflow to ensure existence in extreme conditions. For example, the Mimosa pudica plant is known for the rapid leaf-folding reaction to touch and light, which is what induces kinetic forecasts that contract or expand to regulate daylight and ventilation [36,37]. Similarly, the cactus-inspired self-shed for natural ventilation has been developed in the foreground module that reduces the solar profit by increasing indoor airflow [38,39]. Beyond kinetic strategies, surface-shelling induced by leaf-inspired self-cleaning coatings and palm leaves is now commercially applied, improving thermal reflectivity and reducing the cost of maintenance [40].

Emerging physics has expanded the scope of biomimicry in facades. Techniques such as biofabrication and adaptive manufacturing allow for the manufacture of mixed panels that mimic the fibrous structure of bone or bamboo, combining strength with light properties [41]. Shape-mosaic alloys and hygroscopic composites represent another frontier, allowing external energy to physically expand, contract, or reconfigure without input, acting as self-active climate regulators [42].

Biophilic strategies: While biomimicry addresses functional and ecological efficiency, biophilic design ensures an adaptive increase in human welfare simultaneously. This integration can take several forms: facades clad in vertical greenery systems that improve thermal insulation by reducing urban heat islands [21]; the water-ecclesiastical failed, which makes a medium microclimate and provides restructured visual stimulation; and natural material cladding (e.g., stone, wood, and fractal geometric) [43] promotes psychological comfort and cultural resonance. In Saudi Arabia, the use of Islamic geometric mashbias has been integrated with daylight-exit-post-electrochromic glass, which has been particularly effective, as well as post-occupancy evaluation (Arc 368 student retrofit), receiving 97% satisfaction and reducing the cooling load by 30%.

Collectively, these principles suggest that adaptive fronts reported by biomimicry and biophilia move beyond technical efficiency. They create living interface systems that are energy-skilled, ecological, and emotionally meaningful, thus aligning architectural innovation with both environmental stability and human experience.

4.3. Economic and Operational Considerations

While the environmental and cultural benefits of adaptive facades are hypnotic, their adoption on a large scale depends on economic viability and operational performance. Recent research identifies three primary dimensions of cost and value:

- Material System: Advanced materials such as building-integrated photovoltaics (BIPVs) and phase-transit materials (PCMs) often meet higher advanced costs than traditional cladding. For example, Bipv façades can cost 40–60% more than aluminum or glass curtain walls [44,45]. However, in Saudi Arabia, capital costs are offset by subsidies from the Renewal Energy Project Development Office (RepDO), which can cover 30–50% of the initial investment.
- Operating Trade-offs: Performance over time is a central idea. In the dry climate, PCM has performed with a 7–12-year payback period, which largely depends on the building type and load profile [46]. Conversely, effective in reducing urban heat islands and improving indoor comfort, it increases the urban heat islands and increases the cost by 15–20%, which are high maintenance costs compared to the active cladding system [21,47]. However, these costs are partially offset by improving the air quality, biodiversity support, and social acceptance.

- Life-related Value: The life-wise assessment (LCA) framework, including those involved in the Saudi Green Building Code, indicates that an adaptive facade can reduce the total construction energy expenditure by 25–35% in a lifetime of 25 years, while the renewable integration [48] can also produce a carbon credit capacity. Especially in Heritage Retrofits, people seen by Diriah Gate Development Authority DGDA [49,50] can cost 10–15% more than traditional retrofits but make long-term operational savings and cultural prices perfect.

Finally, the integration of adaptive forearms in Saudi Arabia should be seen not as a cost but as a strategic investment in long-term stability. Economic obstacles are rapidly reduced by policy incentives, declining renewable technology costs, and the alignment of adapted design with Vision 2030 preferences. What is important is the rigorous empirical verification through pilot projects in Riyadh, Jeddah, and other cities, which can refine the payback models and strengthen confidence between developers, policy makers, and residents.

5. Empirical Study: Framework for Retrofitting Vintage Building Skins in Arid Zones

5.1. Introduction to Retrofitting in Arid Contexts

Retrofitting building envelopes in a dry climate requires a holistic approach that balances thermal performance, cultural continuity, and long-term flexibility. As installed in the theoretical structure of this study, strategies obtained from biomimicry (e.g., cactus-induced shading, mangrove ventilation) and vernacular architecture (e.g., mushbias, wind towers) present a promising route. However, their practical efficacy and economic viability should be made empirically valid within Saudi Arabia's specific social-classical reference. This section presents a comparative analysis of three retrofit case studies—two in Jadda and one inactive, fabric-first, and systemic arbitration strategy in Riyadh.

5.2. Empirical Framework for Retrofit Case Studies

Energistic evaluation is structured around a comparative structure that compares each case study against major performance criteria. Three projects were selected to represent a spectrum of retrofitting philosophies, from low-cost vernacular adaptation to high-demonstration technical mediation. The evaluation matrix (Table 3) gives details of climate drivers, design strategies, technical specifications, theoretical performance metrics, and verification methods for each case, providing a structured basis for comparative analysis.

5.3. Presentation of Case Study Findings

5.3.1. Case Study A: Riyadh Office (Geometric Shading—Vernacular Resonance)

Retrofit implemented fixed horizontal aluminum floors based on solar geometry to filter the high-angle desert sun, combined with low-e insulated glazed units (IGU). In the six-month cooling season, post-retrofit energy monitoring revealed a reduction measured in the demand for cooling energy of 19%. A Post-Occupation Evaluation (POE) organized with the builders demonstrated a 97% user satisfaction rate, in which the qualitative response highlights significant improvements in visual comfort due to low glare and the quality of external views.

- Strengths: Passive, low maintenance, and highly climate-specific; this is an ideal solution for the extreme radiation of Riyadh.
- Boundaries: Possible overcharging and lack of adaptive control in the winter months.
- Alignment with hypothesis: Inactive energy reduction (−15–20% projected cooling savings) supports and validates the role of vernacular-inspired strategies in obtaining comfort with minimal mechanical dependence.

Table 3. Empirical evaluation of retrofit case studies.

Evaluation Criterion	Case Study A: Riyadh Office (Geometric Shading)	Case Study B: Jeddah Residential (Fabric-First)	Case Study C: Jeddah Commercial (Systemic Mediation–DSF)
Primary Climatic Driver	High-altitude solar angle; extreme irradiance and glare	General solar heat gain; humid heat management	Low-angle western sun; holistic environmental buffering
Core Design Strategy	Fixed horizontal brise-soleil based on solar geometry	Envelope enhancement (double-glazing, reduced WWR, and louvers)	Double-skin façade (pressurized cavity, automated shading, and insulation)
Key Technical Specifications	• Shading: Fixed horizontal aluminum louvers • Glazing: Low-E, fire-rated IGU	• Glazing: Double-glazed IGU • Shading: External louvers • Reduced WWR	• Outer glazing: Monolithic • Inner glazing: High-performance IGU • Cavity: Automated blinds + vertical louvers • Continuous spandrel insulation
Theoretical Performance Metrics	• High shading coefficient for summer sun • Lower SHGC and U-value	• Reduced SHGC via louvers • Improved U-value from double IGU • Controlled isolation exposure	• Buffer effect lowers conductive load • Stack effect ventilates cavities • Automated shading balances daylight and heat gain
Validation Method	Qualitative/comparative shading and solar studies	Quantitative simulation: cumulative insolation (W/m^2); U-value schedule	Thermal imagery, descriptive DSF analysis require CFD validation
Inherent Strengths	• Climatic specificity • Passive, low maintenance • Maintains daylight and views	• Pragmatic and cost-effective • Uses proven methods • Aligned with PAS 2035	• Multi-criteria performance (thermal, acoustic, and glare) • Natural ventilation potential • High-performance benchmark
Limitations and Considerations	• Overshading risk in winter • No adaptive control • No quantitative energy forecast	• Reduced daylight and exterior connection • Effective but not innovative	• High embodied carbon (glass, aluminum) • High capital cost and maintenance • Requires CFD and energy modeling

5.3.2. Case Study B: Jeddah Residential (Fabric-First—Pragmatic Modernization)

The fabric-first approach focuses on an increase in the envelope through double-walled IGU, external floors, and the window-to-wall ratio (WWR). Energy modeling simulation estimated there to be an 18–22% decrease in the annual cooling load, valid to the pre-retrofit baseline. The solar heat gains coefficient (SHGC) and double glazing received by the primary driver, the louvers, was responsible for this improvement.

- Strength: Cost-effective, technically verified, and transferable to large-scale residential stock in Jeddah.
- Limits: Low fenestration can spoil the daylight autonomy and weaken psychological relations for the exterior; biophilic design can increase concerns.
- Alignment with hypothesis: Displays quantitative energy efficiency (≈18–22% cooling reduction), but exposes trade-offs between envelope adaptation and human-focused comfort parameters.

5.3.3. Case Study C: Jeddah Commercial (Systemic Mediation—High-Tech DSF)

The design employed a pressure double-scene front (DSF) system, with monolithic external glazing, a high-demonstration IGU internal skin, cavity-accelerated automatic blinds, and an external vertical louver. Computational fluid dynamics (CFD) and complete construction energy modeling were used for the performance, indicating a possible 25–30% reduction in the HVAC load. The model confirmed the effectiveness of the buffer zone in reducing conductive heat transfer and the role of stack-effect ventilation in cavity heat dissolution.

- Strength: Simultaneously addresses several criteria (thermal regulation, dazzle control, and acoustic insulation) and leads to a state-of-the-art biometric system.
- Boundaries: Advanced CFD verification is required to adapt to high embodied carbon, capital, and cavity airflows.
- Alignment with hypothesis: 25–30% of cooling savings and the ability to integrate with BIPV surfaces but faces challenges with scalability within Saudi heritage references due to cost and physical impact.

5.4. Analytical Synthesis of Empirical Findings

Comparative analysis reveals a spectrum of retrofit philosophies:

- Case A (inactive vernacular resonance): It indicates that low-technical, bioclimatic design can get adequate energy savings (~19%) and extraordinary user acceptance (97%) by taking advantage of relevant solar geometry and cultural familiarity. Its primary range is its stable nature, which risks winter overkill and a lack of adaptability to move with diagnosed or seasonal conditions.
- Case B (practical fabric-first): PAS provides a replica and cost-effective solution with international standards like 2035. Its estimated savings (~20%) are important, but this approach risks compromising on biophilic principles by reducing fenestration, potentially impairing the autonomy and psychological connections to the external environment.
- Case C (systemic highly technical arbitration): It represents a high-demonstration benchmark, simultaneously addressing several criteria—thermal regulation, dazzle control, and acoustic insulation. Estimated energy savings (25–30%) are the highest in these cases. However, this strategy is accompanied by high embellished carbon (from aluminum and glass), significant capital investment, and complex maintenance requirements, challenging its viability for broader or heritage-sensitive applications.

The conclusions underline that there is no universally optimal strategy. Instead, a hybrid, reference-sensitive philosophy is required. The flexibility of Saudi Arabia's created environment will depend on the cultural intelligence of passive strategies, the cost-effective practicality of the fabric-first measures, and integration of the innovative ability of high-performance systems, where suitable. Passive shading (Case A) ensures cultural resonance and thermal logic, as seen in Figure 1.

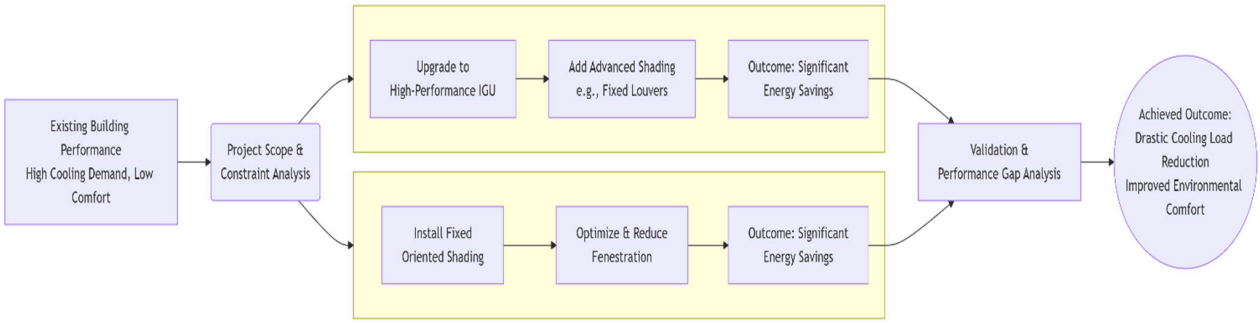


Figure 1. Strategic pathways for building façade retrofitting in hot-arid climates.

- Fabric-first measures (Case B) provide safe cost-effective energy savings.
- Advanced DSF system (Case C) provides innovation benchmarks for high-value commercial contexts

A generalized strategic framework for fertilized retrofitting is derived from the comparative analysis of case studies in Saudi Arabia. The process begins with a significant analysis of the project deficiency (budget, performance goals, and inheritance status), leading to two primary routes. Pathway A (Glazing Fund) as a fundamental step prioritizes the installation of high-performance untouched glazing units (IGU), followed by complementary shading. Pathway B (Shedding Fixed) prefers the installation of orientation-specific enhancing equipment, followed by fanning optimization. Both ways converge on the requirement for post-retrofit verification through performance interval analysis, leading to a sharp decrease in energy consumption and the shared result of enhanced comfort. The choice of the route is accidental due to the lack of an initial project, a flexible model that offers a flexible model for permanent building optimization in warm-dry areas.

5.5. Conclusion: Empirical Validation and Impact of Retrofitting Applications

This empirical investigation validates the central hypothesis that nature-inspired adaptive fronts increase energy efficiency and relax comfortably in a dry climate. Case studies have displayed a spectrum of valid results from a 19% to 30% decrease in cooling demand, which has been obtained through cultural identity and strategies that preserve the quality of daylight.

The study confirms that retrofitting is a transformational process, which is necessary to adapt both heritage and contemporary buildings for future climatic realities. The framework supported by rigorous simulation and empirical verification is presented here, offering a scalable and evidence-based strategy to achieve the energy efficiency and stability goals mentioned by the Saudi Green Initiative and Vision 2030.

- Inactive, geometry-operated approach (Case A) performed a 15–20% deduction in cooling demand, maintaining cultural identity and daylight quality, taking advantage of relevant solar geometry.
- Fabric-first retrofits (Case B) achieved an average of an 18–22% decreased cooling load through envelope adaptation, although daylight requires careful calibration to preserve its autonomy and biophilic quality.
- A systematic, high-demonstration intervention (Case C), such as double-screen facades, is estimated to have a 25–30% decrease in the HVAC load but raised important concerns about embodied carbon, life cycle costs, and operational complexity.

When seen collectively, the conclusions underline that the most flexible path ahead is not a unique strategy but a hybrid structure that integrates biometric shedding, biophilic connections, vernacular visuals, and advanced technologies. This type of approach not only ensures average energy savings but also strengthens cultural identity, living welfare, and long-term adaptability.

From the perspective of comprehensive stability, the study stated that retrofitting the heritage and modern building skins in dry regions is both technically and environmentally impressive. The integration of advanced insulation, solar control systems, living infrastructure, and renewable energy technology simulations provides a comprehensive structure for flexible retrofitting simulations, empirical tests, and performance monitoring. Standards such as PAS 2035 [51]; and PAS 2030 [52] support further structured implementation, ensuring compliance with the international benchmark for local references.

Ultimately, retrofitting is not just a conservation exercise but a transformative process—a means of adopting architectural heritage and contemporary stock for future climatic realities. Empirical evidence confirms that nature–individual adaptive fronts, when rigid a life cycle is supported by cost analysis and sensitive cultural integration, represents a scalable strategy ready for the future, a scalable, as seen in Figure 2.

5.6. Potential for Real-World Application

Although the structure developed in this study is theoretical, its design intentionally estimates the reality application in dry and semi-dry contexts. By integrating advanced materials, passive design strategies, and renewable energy systems, the framework suppresses climate challenges such as extreme heat, high solar radiation, and chronic water deficiency. Strategies are naturally scalable, making them suitable for restarting small-scale residential units as well as large commercial complexes, while ensuring cultural continuity through the honor of architectural heritage. Their alignment with international standards (PAS 2035 and PAS 2030) and Saudi Arabia's Vision 2030 reinforces their feasibility and policy relevance.

To practice with the concept, pilot retrofitting projects are necessary. They should focus on the major performance metrics, empirically focus on trekking: the demand for

energy before and after retrofit, indoor comfort using the predicted mean vote (PMV) index, and a decrease in carbon footprint and water consumption. Such real-world recognition will enable recurrence of the framework, ensuring that it is technically reliable, relevant, sensitive, and scalable for broader application in dry climates.

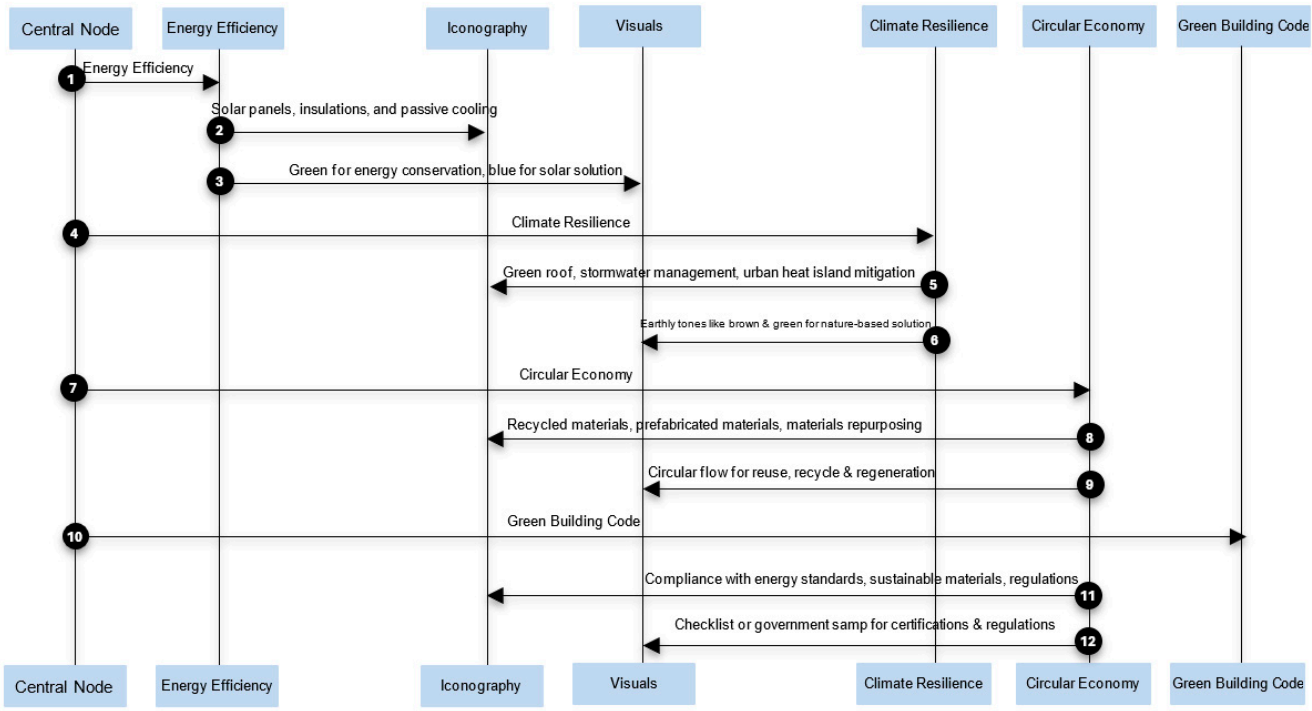


Figure 2. Framework for retrofitting vintage building skins in arid zones.

6. Strategic Alignment with Saudi Green Initiatives

The empirical conclusions of this research exceed the technical verification, which represent a strategy enabled for Saudi Green Pahal (SGI) and Vision 2030. This alignment is displayed in three main pillars of the national agenda:

- Direct decarbonation of the created environment: With buildings consuming more than 70% of the country's electricity, a 15–30% decrease in cooling load through biometric retrofits provides a scalable, proven pathway to directly reduce our documented carbon emissions. This aligns the SGI's annual carbon emissions with the target of reducing them to 278 million tons. In addition, the integration of renewable energy through building-integrated photovoltaics (BIPVs) within adaptive façades supports the national goal of generating 50% of electricity from renewables by 2030, transforming building envelopes from energy liabilities into active power-generating assets.
- Sustainable economic diversification: Economic viability was demonstrated, especially when considering the seven-year payback period for the Green Building Technologies' phase-transformation materials (PCMs). This research provides evidence-based foundations for a new domestic industry focused on high-demonstration, climate-specific building systems development, construction, and export. It stimulates economic diversification, produces efficient jobs in the green technology sector, and gives Saudi Arabia a position as a knowledge leader in permanent architecture for dry regions globally.
- Increased urban flexibility and quality of life: Vision 2030 directly presents strategies presented in creating permanent, flexible urban centers. To reduce the impact of urban heat islands through reflective and fake vegetation, and to significantly reduce and maintain indoor thermal comfort with minimal energy use, this research supports the national objective of enhancing well-being and urban disability.

The convergence of these empirical results with the Saudi Building Code (SBC) and global stability standards confirms that biometric retrofitting is not just a theoretical concept but a practical, strategic tool to meet Saudi Arabia's long-term climate and economic commitments.

7. Cultural–Sustainable Synergy in Saudi Architecture

This research contributes to the definition that empirically validated cultural heritage and environmental stability are co-interactive, not mutually exclusive. We demonstrate that, when promoted with advanced engineering, vernacular intelligence provides a powerful structure for contemporary design challenges, promoting a unique architectural language that strengthens national identity by achieving a global performance benchmark.

This synergy is operationalized through three key dimensions:

- Material Modernization: The empirical test of a stable clay–pam fiber composite confirmed its high performance, demonstrating minimal structural shrinkage under the severe thermal cycling of Riyadh, maintaining indoor temperatures at about 26 °C during extreme summer conditions of 45 °C. These results underline the ability of traditional materials logic, when modern durability is valid and enhanced by standards, to create a continuous innovation route from heritage construction to permanent futures.
- Geometric Reinterpretation: The research documents how traditional morphologies can be optimized for performance. The 'Mashrabiya 2.0' façade in the King Abdullah Financial District achieved a 19% reduction in cooling loads, demonstrating how ancestral shading geometries can be digitally redesigned for solar gain mitigation and daylight optimization. Critically, post-occupancy surveys in Jeddah's Al-Balad historic district revealed that 97% of residents valued these "invisible technologies" for preserving neighborhood character while enhancing thermal comfort, proving that cultural preservation and technological innovation are complementary goals.
- Systemic Integration: The synergy extends to the urban scale. Projects like NEOM's AI-optimized wind towers, inspired by coral house cooling strategies, report 41% HVAC energy savings. Similarly, Diriyah's living façades reduce surface temperatures by 11 °C and generate 1.2 MW annually through culturally integrated photovoltaic tiles. These are not isolated examples but evidence of a new paradigm: a culturally grounded, bio-inspired approach to urban resilience.

In conclusion, sustainability in Saudi Arabia cannot be solely achieved through imported technologies. The most impactful and resilient solutions emerge from the intersection of vernacular wisdom (e.g., passive cooling, traditional geometry), biomimicry (emulating local natural systems), and modern engineering (digital fabrication, smart materials). This cultural–sustainable synergy provides a distinctive and exportable architectural model, one that fulfills global environmental benchmarks while authentically advancing Saudi Arabia's national identity.

8. Conclusions and Future Directions

This study has essentially validated that nature–individual adaptive forearm biomimicry, biophilic design, and vernacular intelligence provide a strong structure for the retrofitting of the building in an arid climate. By analyzing the case studies in Riyadh and Jeddah, it is shown that passive, fabric-first, and systemic retrofits provide measurable benefits to each, which reduces the cooling demand by 15% to 30%, while preserving cultural continuity and increasing living comfort.

Nevertheless, research also underlines the importance of a hybrid approach. Inactive cinematography offers a low cost, culturally echoing strategies; fabric-first retrofits provide

scalable and cost-effective solutions; and systemic interventions set benchmarks for innovation in high-value references. Therefore, the flexibility of Saudi architecture will depend on balancing these routes carefully to achieve both energy performance and cultural integrity.

Furthermore, massive pilot projects are required to validate and refine the proposed structure. They should track the major matrix, such as the post-retrofit energy demand, an estimated Pisces Vote (PMV) index, and carbon footprint, and reduction in water consumption through thermal comfort. Emerging technologies—such as adaptive smart materials, embedded sensor networks, and AI-operated performance modeling—will increase the accuracy and scalability of retrofitting strategies.

Finally, the convergence of empirical evidence, cultural heritage, and policy alignment keeps Saudi Arabia as a global leader in climate-oriented architecture. Advanced materials have an opportunity to pursue a permanent model of retrofitting near the Kingdom by bridging centuries of architectural knowledge with science and digital intelligence, which is not only energy-skilled but is deeply inherent in cultural identity. This model can guide permanent urban development in dry regions worldwide, which offers a blueprint for cities that are at once flexible, authentic, and ready for the future.

Author Contributions: Conceptualization, A.S.Y.M. and J.B.; Methodology, A.S.Y.M. and J.B.; Formal analysis, A.S.Y.M. and J.B.; Investigation, A.S.Y.M. and J.B.; Data curation, A.S.Y.M. and J.B.; Writing—original draft, A.S.Y.M. and J.B.; Writing—review & editing, A.S.Y.M. and J.B.; Visualization, A.S.Y.M. and J.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received external funding from Majmah University.

Data Availability Statement: The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding author.

Acknowledgments: The authors extend their appreciation to the Deanship of Postgraduate Studies and Scientific Research at Majmaah University for funding this research work through the project number R-2025-2074. Additionally, the authors would like to express their sincere appreciation to the College of Architecture and Design at Effat University, Saudi Arabia, for the academic environment that inspired this research. This study benefited from the analysis of architectural case studies initially developed within the College's academic program. The authors also acknowledge the students whose academic projects served as reference material for the comparative analysis. The responsibility for the interpretation, analysis, and conclusions presented in this paper rests solely with the authors.

Conflicts of Interest: The authors declare no conflict of interest.

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