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Original Research Article

Identifying Challenges and Opportunities for the Integration of Bionic Architecture with Traditional Vernacular Practices (A Case Study of Bam City)*

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Abstract

Problem statement: The rapid transformations in the architectural landscape of Bam City following the catastrophic earthquake of 2003 have created a profound gap between modern construction methods and the city’s rich cultural and climatic heritage. Traditional architectural elements, developed over centuries in harmony with the hot and arid climate, have gradually been replaced by modern designs that neglect environmental and cultural values. This study seeks to answer the critical question: What are the opportunities and challenges of integrating bionic architecture with indigenous knowledge in Bam’s historical fabric, and how can ecological design principles be employed to create a sustainable and culturally harmonious environment in this unique climate?

Research method: To address this issue, a mixed-methods approach was adopted. Field studies and photographic documentation of historical structures were conducted to meticulously analyze the characteristics of vernacular architecture. Consultations with biologists provided insights into the ecological adaptations of native species. Interviews with ten architects and thirteen residents revealed traditional knowledge and their perceptions of nature-inspired design. Image preprocessing using OpenCV software facilitated geometric and textural analysis, which was subsequently reviewed by three architectural experts. Qualitative data from interviews were coded using Atlas.ti software, extracting themes related to the interplay of bionic principles and indigenous knowledge.

Conclusion: The study highlights the compatibility between Bam’s vernacular architecture and bionic strategies, including passive cooling systems and optimal material efficiency. However, challenges such as the adaptability of modern materials, economic constraints, and earthquake vulnerability were identified as barriers to integration. Addressing these challenges requires the development of hybrid solutions, combining modern and traditional materials, participatory urban planning, and nature-based approaches tailored to Bam’s specific socio-economic and environmental conditions.

Keywords: *Bionic Architecture, Vernacular Architecture, Ecological Resilience, Cultural Continuity, Bam.*

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Introduction

In recent years, growing attention to environmental crises such as ecosystem degradation, climate change, and limited natural resources has positioned ecological design as a core focus in urban planning and architecture research (Bayulken et al., 2021). This focus is particularly critical in regions with harsh climatic conditions, where challenges to human comfort and ecosystem sustainability are pronounced (Fallmann & Emeis, 2020; Heidari & Davtalab,2020; Oveisi Keikha et al., 2020, Heidari & Davtalab, 2024). Bam, located in southeastern Iran and emblematic of a hot and arid climate, offers a valuable setting for exploring sustainable architectural strategies. The city's heritage of adobe and clay architecture, developed over millennia in response to its severe climate, contains rich lessons in environmentally adaptive design (Mokhtari et al., 2019). On the other hand, innovative approaches such as bionic architecture, inspired by natural systems, promise the development of structures with optimal functionality and environmental harmony (Akrami & Damyar, 2017). Despite the high potential for integrating bionic principles into Bam's vernacular architecture, this process faces numerous obstacles. Economic and technical limitations, cultural resistance to change, and the absence of suitable legal frameworks are among the primary challenges (Farina et al., 2023). Nonetheless, there are opportunities to respect traditional architectural values while making strides toward creating more sustainable urban environments. Achieving this goal requires merging indigenous knowledge with innovative approaches and developing a comprehensive model (Javanmard et al., 2024) that preserves cultural identity while addressing contemporary needs—a subject explored in this discourse. Bam, as one of Iran's most valuable architectural legacies, finds itself at the intersection of two fundamental challenges: the necessity to preserve cultural identity and the demand for sustainable development amidst climate change. The city's historic fabric, relying on indigenous materials such as adobe and clay, has intelligently adapted to its harsh climatic conditions. However, rapid urbanization and environmental transformations threaten this invaluable heritage. Meanwhile, the need to meet sustainability standards in construction underscores the urgency of finding innovative solutions. Bionic architecture, inspired by nature and leveraging natural mechanisms, has emerged as a cutting-edge approach to sustainable architecture. By emphasizing energy efficiency and environmental harmony, it holds the potential to address many of the challenges facing Bam. However, the lack of a clear framework for integrating bionic principles with the city's vernacular architecture presents a knowledge gap. Moreover, understanding the perspectives of local residents and architectural experts on this innovative approach is crucial. Given the importance of preserving Bam's architectural heritage and adapting it to the demands of sustainable development, this study aims to identify and analyze the challenges and opportunities of integrating ecological design principles—particularly bionic architecture—into the city's fabric. Through field studies and interviews with architectural experts and local residents, this article seeks to propose solutions for developing a comprehensive model that both preserves the city's cultural identity and enhances the energy and environmental performance of its buildings.

What are the key opportunities and challenges in integrating bionic architecture with Bam's vernacular practices, and how can ecological design principles be employed to create a sustainable built environment harmonious with the culture of this hot and arid region?

Research Background

In recent years, studies focusing on bionic and ecological architecture in the historical city of Bam have been rare. Given the limited specialized resources in this field, the present research primarily relies on extensive studies centered on Bam's vernacular architecture. These studies have meticulously examined the historical, cultural, and environmental characteristics of the city's architecture, providing a robust framework for understanding sustainability principles and harmony with nature. This framework serves as a solid foundation for the present investigation into bionic and ecological architecture.

The historical city of Bam, a shining gem in the heart of the desert, stands as a unique example of the coexistence of humans and nature, with a rich heritage of architecture and ecology. The Bam Citadel (*Arg-e Bam*), the world's largest adobe structure, has been the city's beating heart, alongside its *sharestan* (urban center) and *rabaz* (suburban area), forming an intelligent and sustainable urban design (Mokhtari et al., 2019). Innovative water management systems, such as qanats, not only met the irrigation needs of agriculture but also supported the flourishing of economic activities like cotton and silk production, showcasing the sustainability embedded in the city's traditional design (ibid.).

Bam's cultural landscape—reflected in the house-garden, alley-garden, and city-garden scales—illustrates a harmonious coexistence of architecture and nature, enriching the cultural identity of the city (Einifar & Eshrati, 2018). Structures like the *Kooshk-e Rahimabad*, with symmetrical porticos and a quadrilateral garden, demonstrate the designers' mastery of advanced principles of blending aesthetics and functionality (Saremi Naeeni & Joodaki Azizi, 2014). Additionally, Bam's palm groves, beyond their practical functions, symbolize the city's cultural continuity and vitality, emphasizing the importance of their restoration for sustainable development and preserving the city's authentic spirit (Aslani et al., 2019).

Research into bionic architecture in Iran remains relatively scarce and fragmented, with most studies taking a theoretical and general approach rather than conducting in-depth explorations. However, related studies analyzing the application of bionic principles in architectural design provide valuable insights for this research.

Recent studies in bionic and ecological architecture underscore the remarkable potential of drawing inspiration from nature to enhance contemporary designs. Alemi (2022), in a comparative study, identified intriguing parallels between the spatial complexity and natural ventilation systems of termite mounds and the underground city of *Nooshabad*, presenting a valuable model for sustainable urban design. Nejad Ebrahimi & Tokhmchian (2021) highlighted the significance of using networked and adaptable structures inspired by the historical bazaar of Tabriz and rhizomatic plant forms in contemporary sustainable design. Gharooni et al. (2014) drew inspiration from the golden spiral geometry of abalone shells to design optimized and cost-effective building facades.

In another study, Goldust & Ahmadnejad Karimi (2021) examined load-bearing patterns in nature, from sturdy trees to delicate insect wings and complex bird nests. Their findings revealed intelligent adaptive mechanisms, including hierarchical arrangements and innovative designs for energy efficiency.

International research on bionic architecture has revealed significant potential for optimizing architectural designs and enhancing building sustainability. Dilshodovich (2024), utilizing concepts of isomorphism and homomorphism, bridged various sciences with architecture, demonstrating how nature-inspired forms and functions can lead to optimal designs. Farokhizad & Sabernejad (2016) analyzed the Tehran Water Museum, illustrating the intersection of hydrology and bionic architecture, and offered practical solutions for achieving environmental harmony and building resilience.

In another study, Wang et al. (2021) designed dynamic and adaptive facades inspired by the mechanisms of ladybug wings, capable of automatically adjusting to environmental conditions and significantly reducing carbon emissions. Jiang et al. (2024) introduced biomimetics as a tool for creating sustainable industrial and architectural designs while addressing challenges such as widespread adoption and the lack of standardized methods in the field. Similarly, Solano et al. (2023) explored projects like Zimbabwe's Eastgate Centre and the Desert Forest project, showcasing how nature-inspired design can drastically optimize energy consumption and conserve water resources in hot and humid regions.

Theoretical Foundations

The theoretical framework of the present discourse is based on two fundamental and intertwined concepts: environmental sustainability and cultural continuity. These concepts, as the theoretical foundation, provide a framework for examining the integration of nature-inspired architectural principles with traditional construction methods in the historical context of the city of Bam, Iran. The ultimate goal of this research is to achieve innovative architectural designs that, while being rooted in local culture and addressing environmental challenges, preserve the authentic identity of the region.

- **Ecological resilience: A paradigm for sustainable architecture**

Ecological resilience, as defined by Gunderson (2000), refers to the inherent ability of a system to absorb disturbances and disruptions, while maintaining its fundamental structure and functions or even transforming into states that are more compatible with new conditions. In the field of architecture, this concept refers to the creation of built environments that can anticipate environmental changes such as resource scarcity and climatic fluctuations and mitigate their destructive impacts (Tian et al., 2018, 57). Ken Young (Young & Duchicela, 2020, 882), a pioneer of ecological design thought, believes that architecture should go beyond reducing environmental harm and contribute significantly to the restoration of ecosystems and the improvement of overall environmental health (Fig. 1). On a global scale, the persistent pursuit of environmental sustainability has led to remarkable innovations in the architecture of arid and semi-arid regions—areas where environmental pressures are particularly severe. A prominent example is the city of Masdar in the UAE, which stands as a testament to the transformative potential of adaptive technologies and renewable energy in urban design (Rietmann, 2021). On the other hand, architects like Francis Kéré in the heart of the African desert have integrated passive cooling strategies and community-based design processes, blending tradition and modernity (Deglon et al., 2024). These examples illustrate the universal nature of resilience in architecture and provide a suitable foundation for adapting it to local conditions.

In the vast expanse of Iran, traditional architecture has always been a prominent manifestation of environmental sustainability (Davtalab et al., 2022; Heydari & Davtalab, 2020; Davtalab & Heidari, 2020). The complex qanat systems and intelligent windcatcher structures (Heidari & Davtalab, 2022)

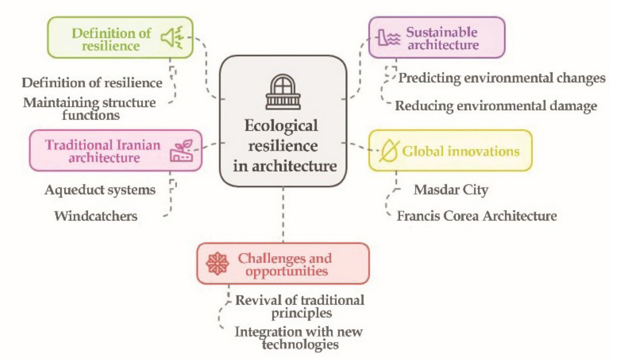


Fig. 1. Key themes related to ecological resilience in architecture. Source: Authors.

in central Iran are evidence of ancestors' innovations in optimizing water resource management and adapting to harsh and challenging climatic conditions (Hashemi Zarj Abad & Masudi, 2013). These historical examples reflect the Iranian understanding of peaceful coexistence with nature, an understanding that is often overlooked in contemporary Iranian architecture. The historical adobe city of Bam stands as a living example of passive resilience, demonstrating remarkable capabilities in regulating internal temperatures and optimizing resource consumption. However, the devastating earthquake of 2003 revealed the vulnerability of these structures to seismic forces, highlighting the urgent need for resilient and adaptive measures.

Key Indicators of Ecological Resilience with a Special Emphasis on the Integration of Bionic and Local Architectural Principles in the Historical Context of the City of Bam (Fig. 2).

- Diversity and Redundancy: Diversity, much like the intertwined roots of a tree, enhances the stability and strength of a system. In the complex urban fabric, diversity in architectural typologies, energy systems, and resource utilization methods serves as a guarantee for the sustainability and survival of the system. This diversity functions as a safety net, preventing the collapse of the system under sudden shocks.

- Adaptability: Resilient systems, like living organisms, can adapt to changing environmental conditions. In the historical fabric of Bam, this capability translates into the use of flexible architectural forms and the creation of dynamic interactions with the local community to address challenges arising from climatic and geological changes.

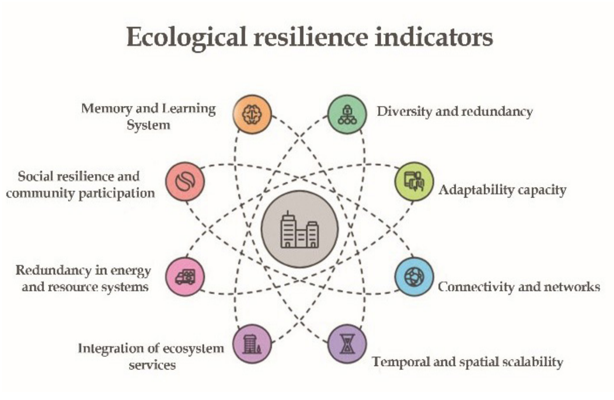


Fig. 2. Key Indicators of Ecological Resilience. Source: Authors.

- Connectivity and Networking: Just as vital veins deliver nutrients to organs, urban networks facilitate the flow of resources and contribute to the overall system's sustainability. Green corridors, public spaces, and water distribution systems, as the lifeblood of the city, prevent the fragmentation of the urban fabric and help create a unified and coordinated whole.

- Scalability in Time and Space: Resilience is a phenomenon that manifests at different temporal and spatial scales. In the city of Bam, construction approaches must be designed to respond to immediate risks, such as earthquakes, while also being resilient to long-term climatic changes.

- Synergy of Ecosystem Services: Optimal utilization of valuable ecosystem services, such as water supply, temperature regulation, and meeting cultural needs, ensures complete alignment of urban design with environmental requirements. This approach not only contributes to environmental sustainability but also improves the quality of life for citizens.

- Diversification of Energy and Material Sources: Reliance on renewable, distributed energy resources and cyclical waste management systems increases the resilience of the urban system to fluctuations and crises. This diversification reduces dependence on centralized, vulnerable resources and guarantees energy security.

- Social and Environmental Convergence: The active participation of citizens and local stakeholders in decision-making ensures the successful implementation of resilience strategies. This participation fosters a sense of ownership and shared responsibility, enhancing the community's capacity to respond to future changes and challenges.

- Learning from the Past and Preparing for the Future: Resilient systems, like living organisms, learn from past experiences and adapt to new conditions. In the case of Bam, the bitter experiences of the earthquake have provided an opportunity to integrate traditional knowledge with modern technologies, creating a more resilient and sustainable city (Scheffer et al., 2015; Dakos & Kéfi, 2022; Spears et al., 2015; Day et al., 2018; McGrath & Lei, 2021; Alberti & Marzluff,2004).

- **Bionic architecture: A novel approach for enhancing ecological resilience**

Bionic architecture is rooted in the imitation of nature, drawing inspiration from complex and efficient biological systems to seek innovative solutions to contemporary challenges (Bantserova & Kasimova, 2023, 940). Janine Benyus (1997) defines biomimicry as a process in which nature's proven strategies are used as valuable models to solve complex human problems. Research by pioneers like Barthlott et al. (2016, 19) has shown that fundamental life principles, such as self-healing, adaptability, and energy optimization, can inspire the creation of innovative and groundbreaking architectural designs. The integration of bionic principles with local design can lead to the creation of unique architectural forms in the city of Bam, enhancing environmental sustainability while preserving the region's rich cultural heritage. Dynamic mudbrick façades that can regulate temperature based on environmental changes, water collection systems inspired by the adaptability of desert plants, and earthquake-resistant foundations inspired by load distribution patterns in living organisms are examples of such innovative achievements.

Recent innovations in bionic architecture have led to the development of materials such as self-healing concrete, inspired by repair mechanisms in living organisms, which have the ability to autonomously repair damage. Furthermore, the emergence of smart building envelopes, inspired by natural structures such as pine cones, which can regulate indoor conditions based on environmental changes, marks a significant step in this field. Major advancements in material science, including the development of phase-change materials and biocomposites, have paved the way for a transformative integration of sustainability concepts into architectural forms.

In the historic region of Bam, bionic principles provide innovative solutions to environmental challenges—solutions that not only preserve the city's cultural identity but also contribute significantly to its sustainability (Fig. 3). For example, mudbrick structures inspired by nature, such as moisture-absorbing coverings modeled after desert plants or load-distributing foundations inspired by biological structures, can achieve greater sustainability and stability. Additionally, implementing passive cooling systems inspired by the intelligence of termite mounds will create a remarkable transformation in regulating the internal temperature of buildings in Bam. The combination of these innovations with local elements, such as cool courtyards and shaded alleyways, will result in a harmonious blend of tradition and modernity, ensuring a sustainable future for this historic city.

• Bionic architecture and ecological architecture: Distinguishing concepts and approaches

Although both bionic architecture and ecological architecture seek to create built environments that interact harmoniously with nature, there are significant differences between them in terms of theoretical approaches and practical methodologies (Fig. 4). Ecological architecture focuses on reducing the harmful impacts of humans on the environment, aiming to create buildings and structures that sustainably coexist with natural ecosystems (Williams, 2007). This approach emphasizes resource efficiency, the use of renewable energy, and the design of buildings that are adapted to climatic conditions. In other words, ecological architecture views buildings as part of a larger ecological system, striving to create a balance between human needs and nature (Yannas, 2011). Pioneers such as Ken Yang (2021) emphasize the importance of aligning built environments with natural ecosystems, believing that through establishing symbiotic relationships between humans and nature, environmental health can be improved. This approach often relies on empirical analysis of environmental systems and uses quantitative performance criteria to evaluate the sustainability of buildings (Orr, 2007).

In contrast, bionic architecture goes beyond merely coexisting with nature, actively imitating the ingenuity and mechanisms of living organisms (Yuan et al., 2017). This approach, through the use of biomimetic knowledge, leads to the design of buildings that replicate adaptive, self-sufficient, and regenerative mechanisms found in nature (Vorobyeva, 2018). For

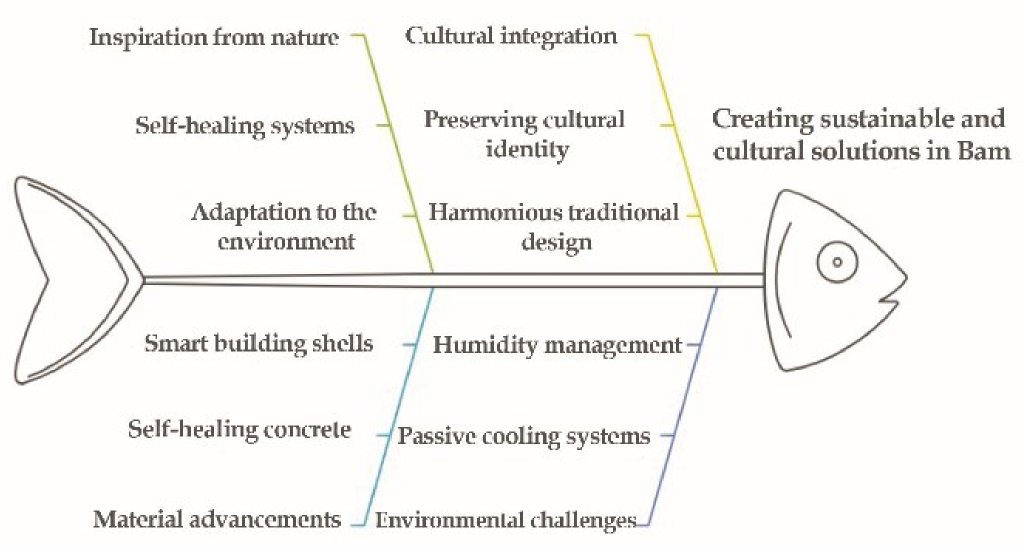


Fig. 3. Principles and Innovations Related to Bionic Architecture. Source: Authors.

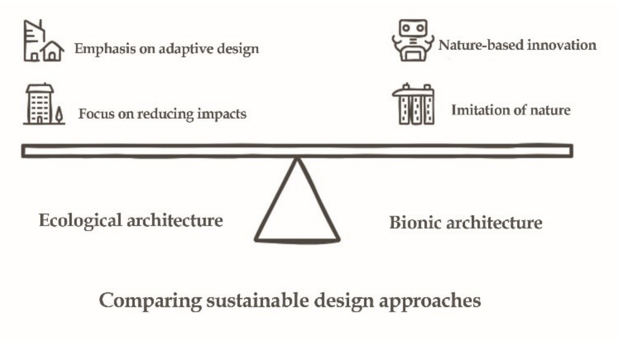


Fig. 4. Distinction Between Bionic and Ecological Architecture Principles. Source: Authors.

example, buildings inspired by termite mounds can autonomously regulate internal temperature, and materials inspired by the lotus leaf possess self-cleaning and water-repellent properties (Abd Ullah et al.,2018). This approach, by prioritizing innovations based on biological principles, integrates scientific advancements in material science, robotics, and systems engineering, leading to the creation of architecture that is not only compatible with its environment but also has the ability to predict and adapt to changing environmental conditions (Sardá et al., 2023).

• Cultural continuity: Preserving collective identity through architecture

Cultural continuity ensures that architectural practices honor and transmit the historical, social, and aesthetic values of a society to future generations. The works of Christopher Alexander (2004) (such as in "The Timeless Way of Building,") emphasize the importance of incorporating cultural and historical narratives into architectural designs. This integration not only strengthens a sense of belonging and identity among individuals but also meets functional and environmental needs (Alexander, 2007, 14). The architectural heritage of the city of Bam, which has been shaped using mudbrick and courtyard-centered designs, is a clear reflection of how multiple generations have adapted to environmental and social conditions. Today, this valuable heritage faces challenges such as urban expansion, modernization, and globalization. The pioneering works of Nader Khalili in Iran demonstrate the potential of intelligently integrating traditional techniques with contemporary innovations to preserve the cultural integrity of this city. Concepts like "Superadobe," invented by Khalili, are prime examples of reviving traditional materials and methods for contemporary use (Daie'ollah & Anjom-Sho'a, 2010).

Bionic architecture, inspired by nature, serves as a bridge between the preservation of cultural heritage and the achievement of environmental sustainability. Adaptive designs, shaped by native motifs and materials, not only align with the historical identity of Bam but also respond to contemporary challenges (Wahl, 2006). The "Cradle to Cradle" design principles are based on the belief that simply recycling resources is not enough; cultural practices and social interactions must also be considered in the design and construction process to achieve truly sustainable architecture (Braungart et al., 2007). According to Bruckmeier & Pires (2018, 211), truly sustainable architecture must pay attention not only to environmental performance but also to the cultural values of the building (Fig. 5).

The theoretical framework of this discourse focuses on the integration of two fundamental principles—ecological resilience and cultural continuity—in architectural design, particularly in the historical fabric of Bam. These two principles, interacting with one another, provide a comprehensive approach to merging bionic architectural principles with vernacular architecture. Ecological resilience ensures that buildings are capable of adapting to the harsh climatic conditions of the region while minimizing their environmental impact. Conversely, cultural continuity guarantees that these innovative designs respect and enhance the historical and cultural identity of the city. Fig. 6 illustrates the theoretical model derived from the literature review of the study's framework. The proposed model is a novel synthesis of bionic architecture, ecological resilience, and cultural identity, aimed at creating sustainable designs that align with the local context of Bam. Inspired by nature and rooted in indigenous knowledge, this model offers an innovative solution to address environmental challenges while preserving the cultural identity of cities. In this approach, ecological resilience is achieved through strategies such as adapting to the arid and desert climate, utilizing local materials, and

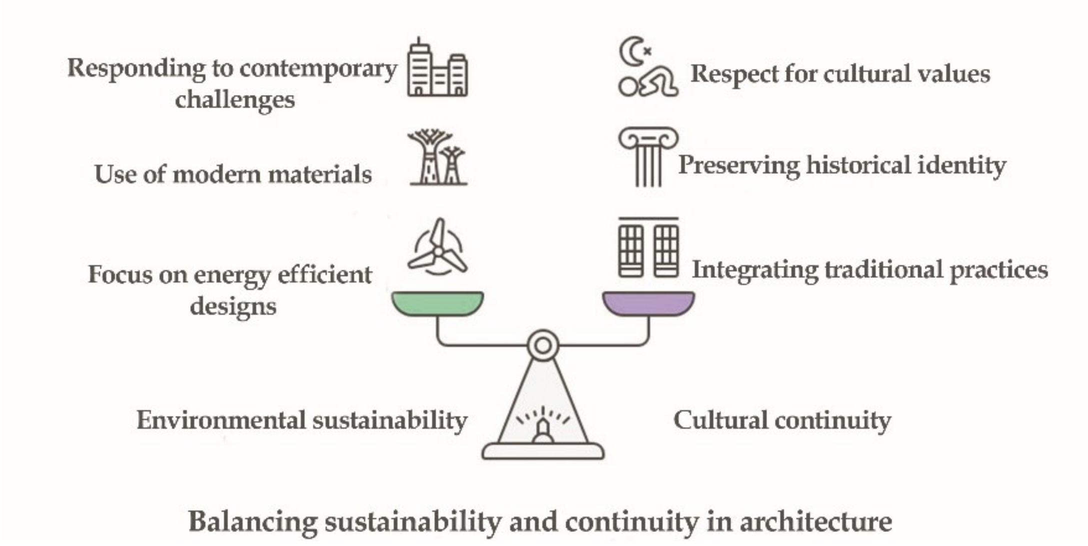


Fig. 5. Conceptual Model of the Balance between Environmental Sustainability and Cultural Continuity. Source: Authors.

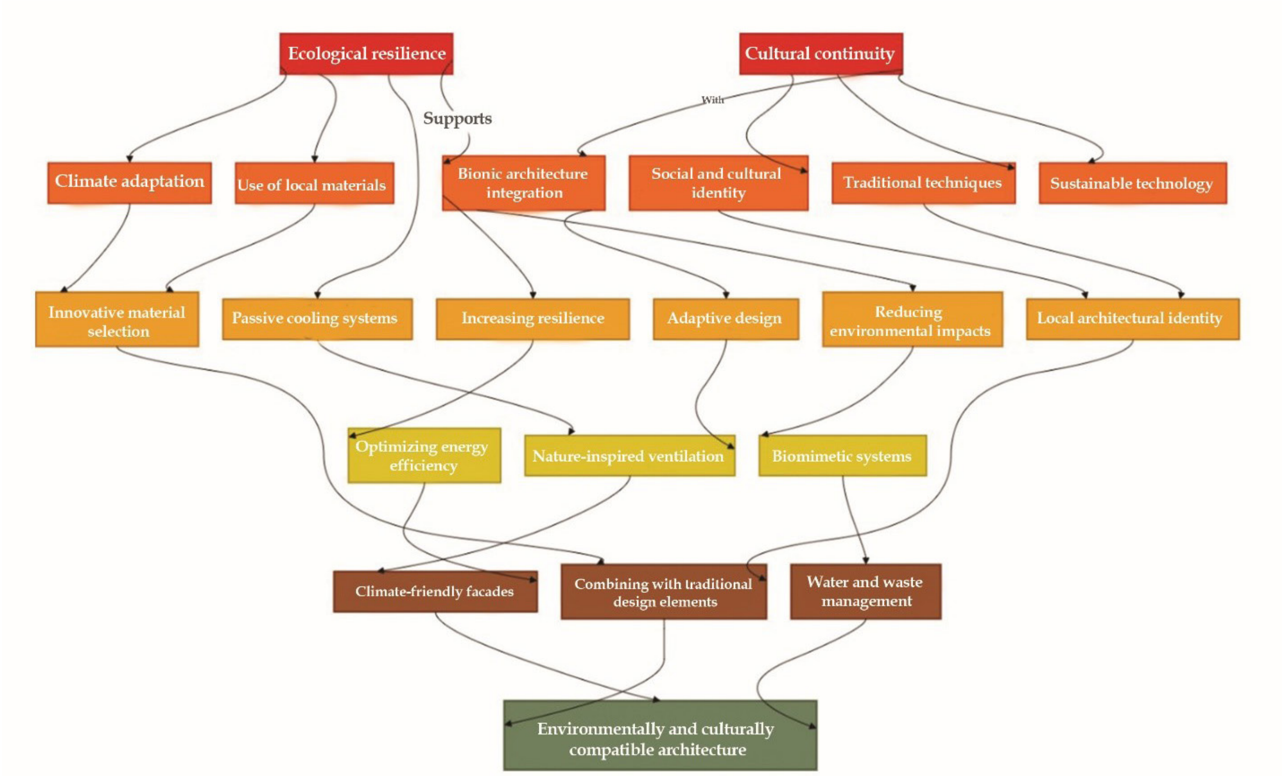


Fig. 6. Theoretical Model of the Study. Source: Authors.

harnessing renewable energy sources. Simultaneously, cultural continuity is reinforced by preserving traditional architectural elements and indigenous behavioral patterns. Bionic architecture, serving as the bridge between these two components, draws inspiration from natural mechanisms to provide innovative solutions for designing buildings and urban spaces. This approach not only enhances energy efficiency and reduces environmental impacts but also revitalizes cultural identity and fosters a sense of belonging among residents. In this model, buildings are envisioned as living entities that dynamically interact with their surrounding environment. By using local materials and traditional construction techniques, buildings can adapt to the region's harsh climatic conditions while ensuring thermal comfort for occupants. Additionally, by incorporating advanced and smart technologies, these structures can optimize their energy performance and contribute to minimizing energy consumption.

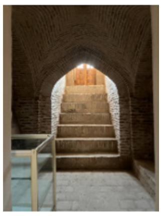
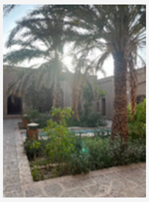
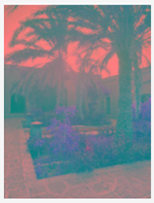
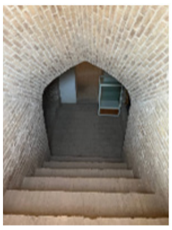
Research Method

In this study, an integrative approach was adopted to identify challenges and analyze opportunities for integrating bionic architecture with traditional vernacular architectural practices in Bam, one of the cities in Iran's hot and dry climate. The adopted approach involved simulation, field studies (observation), and interviews with experts and local residents. Initially, a one-week field study was conducted to collect comprehensive data on the region's native biological species, including plants, animals, and insects in Bam. This data was supplemented by consultations with three local biology experts and the use of written resources to examine the biological characteristics and context of the region, as well as their adaptation to Bam's hot and dry climate. Additionally, photographic documentation was undertaken of the remaining examples of traditional architecture in Bam, many of which survived the devastating 2003 earthquake. These photographs highlighted significant contrasts between modern architectural designs and the remnants of vernacular architectural styles. The captured images were prepared for specialized analysis following a complex pre-processing stage using OpenCV software. Initially, the images were normalized to adjust for variations caused by lighting and clarity. Subsequently, structural and decorative features were extracted using the Canny algorithm. Filtering techniques, including Gaussian and median filters, were applied to reduce noise while preserving critical details. Texture analysis was performed using Local Binary Patterns (LBP) to quantify unique textural variations in vernacular architecture. Additionally, primary geometric patterns were extracted using the Hough transform to identify dominant shapes such as arches and domes, along with their proportions. This pre-processing aimed to standardize the data, eliminate potential biases from environmental conditions during photography, and enhance the precision of architectural and specialized analyses by experts. In the next phase, semi-structured interviews were conducted with ten specialists and local architects. Of these, six were residents of Bam, including faculty members from Islamic Azad University and consulting engineers specializing in vernacular architecture. The remaining four were based in Kerman, comprising three faculty members from the University of Kerman and Islamic Azad University of Kerman, with expertise in bionic and ecological architecture. The pre-processed images, along with data collected on native biological species in Bam, were shared with these experts to facilitate guided discussions and analyses on the alignment of extracted patterns with ecological and bionic design principles. Purposeful and snowball sampling methods were employed to select research samples. For an in-depth analysis of the architectural plan of the Ameri House, the expertise of three prominent Kerman-based specialists was utilized. Consultations with these experts provided new insights into the spatial organization, material selection, and climatic strategies used in this historical building. This collaborative approach offered a comprehensive perspective on how principles of bionic and ecological architecture were implemented, either consciously or subconsciously, in the structure. To gain a deeper understanding of public perceptions and local perspectives, semi-structured interviews were conducted with 13 elderly residents of Bam. These interviews aimed to extract indigenous knowledge and local interpretations regarding the integration of biological principles into vernacular architecture. The qualitative data obtained from both groups of interviews were analyzed using ATLAS.ti software, enabling thematic coding and the extraction of key design principles.

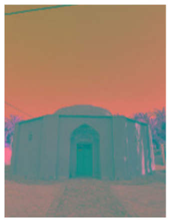
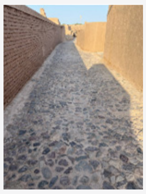
Research Findings

The initial sub-study utilized field studies, computational image analysis, and expert interviews to explore the biological species and their characteristics, the vernacular architecture of Bam, and how bionic architecture and its principles could be integrated with the vernacular architecture of the city. The findings of this section are summarized in Table 1.

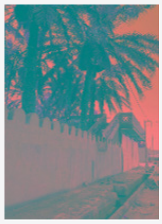
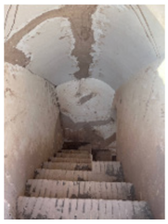
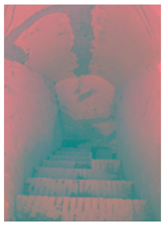
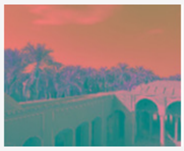
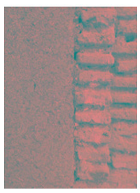
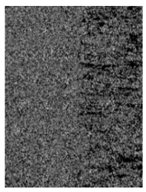
Table 1. Biological inspirations and proposed bionic solutions for vernacular architecture in the city of Bam. Source: Authors.

No.	Examples of Vernacular Architecture in Bam	Biological Pattern (Bionic)	Integration of Bionic Architecture with Vernacular Architecture in Bam	Processed Images		
				Original Image	Lab Colour Space	Edge Detection
1	- It is wind resistant and distributes structural loads evenly. - Passive cooling and natural air circulation in the interior are easily achieved. - Controlled air circulation is possible for internal cooling without additional heat input. - It is protected against sand intrusion in desert climates.	- Turtle shell: Optimal strength-to-weight ratio. - Cactus form: Adaptation to harsh climates for heat dissipation. - Termite mounds: Ventilation towers for maintaining internal thermal balance. - Bird nests: Strategic positioning of openings for airflow regulation.	- Use of heat-reflective materials inspired by cactus skin to enhance cooling. - Design of aerodynamic domes to resist wind in arid regions. - Optimized ventilation openings based on termite mound models for airflow control. - Development of adjustable ventilation mechanisms inspired by bird nests for climatic adaptation.			
2	- Vaults and arches in the vernacular architecture of Bam (such as bazaars and historic houses) utilize brick patterns to enhance thermal comfort and structural stability. - These spaces maintain cooler temperatures by reducing heat accumulation.	- Termite mounds Utilizing internal channels to regulate airflow and reduce heat accumulation. - Palm roots: Providing stability in loose soils through interconnected underground structures.	- Creating ventilation pathways in vaulted spaces, inspired by the airflow systems of termite mounds, to naturally reduce heat accumulation. - Employing interconnected brick patterns, inspired by palm roots, to enhance structural stability and earthquake resistance.			
3	- Traditional Iranian gardens, such as those in Bam, feature courtyards with water features and vegetation to create microclimates that mitigate heat. - Palm trees provide shade, reduce wind speed, and contribute to cooling the environment.	- Palm leaves (Gutterman, 20002): Overlapping structures optimize shading and enable ventilation. - Desert plants: Adaptations for water storage and heat resistance, such as waxy leaves and deep roots.	- Implementing shading systems inspired by palm trees to extend the shading effect on building façades and roofs. - Adopting desert plant strategies in courtyard landscaping design to reduce water consumption while maintaining cooling benefits.			
4	- Vaulted roofs in Iranian architecture, such as the historic buildings of Bam, reduce heat transfer and enhance structural efficiency. - Brick materials possess high thermal mass, stabilizing interior temperatures.	- Termite mounds: Utilizing ventilation networks for passive cooling. - Beetle exoskeleton: Lightweight yet robust layering to enhance structural stability.	- Designing airflow pathways in vaulted roofs inspired by the ventilation systems of termite mounds to improve air circulation and cooling. - Reinforcing vaulted structures with layered brick patterns resembling the exoskeleton of beetles to enhance earthquake resistance.			

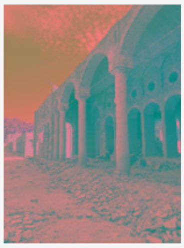
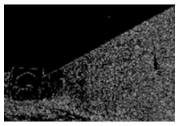
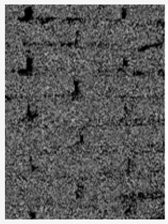
Rest of Table 1.

No.	Examples of Vernacular Architecture in Bam	Biological Pattern (Bionic)	Integration of Bionic Architecture with Vernacular Architecture in Bam	Processed Images		
				Original Image	Lab Colour Space	Edge Detection
5	- Traditional courtyards in Bam utilize vegetation such as palm trees and shrubs to reduce heat and create shaded areas. - The palm tree canopy serves as a natural element for shading and improving microclimatic conditions.	- Palm canopy: Provides overlapping shade and reduces direct solar radiation. - Citrus trees: Cool the air through evaporative transpiration and offer fruit in traditional Iranian gardens.	- Developing lightweight pergolas inspired by palm leaves to extend shading in courtyards. - Introducing a mix of drought-resistant plants, such as citrus trees and shrubs, to enhance air cooling and reduce water consumption.			
6	- The domes of Bam, similar to those used in icehouses, feature compact and insulated geometries that minimize solar heat absorption. - Thick adobe walls with high thermal mass remain cool during hot days and retain warmth during cold nights.	- Desert snail shell: Reduces heat absorption through reflective surfaces and a spiral shape. - Cactus spines: Dissipate heat and provide shading.	- Applying reflective coatings to dome surfaces, inspired by desert snail shells, to reduce solar heat absorption. - Adding grooves or protrusions on exterior walls, inspired by cactus spines, to dissipate heat while preserving the traditional aesthetic of the dome.			
7	- Narrow pathways, a characteristic of traditional Bam architecture, are designed to create shade, reduce solar radiation, and provide cooling while preventing direct exposure to sunlight. - Stone paving is highly durable in arid conditions, minimizing dust and heat reflection. - Adobe walls with high thermal mass stabilize interior temperatures and mitigate extreme external temperature fluctuations.	- Desert ant tunnels: These tunnels maintain airflow and temperature regulation within a compact design. - Camel skin: Acts as an insulator, reducing heat absorption and moisture loss. - Snake skin: Its overlapping structure minimizes heat absorption while providing durability and flexibility.	- Incorporating ventilation pathways within adobe walls, inspired by desert ant tunnels, to enhance airflow and cooling in passageways. - Reinforcing stone paving with textures inspired by snake skin to reduce slip hazards and improve heat dissipation. - Applying bio-coatings inspired by camel skin to enhance wall insulation, minimize cracking, and reduce maintenance needs.			
8	- Adobe walls represent traditional thermal insulation, effectively moderating extreme heat conditions. - Palm tree shade provides passive cooling, protecting the walls from direct solar radiation. - Proximity to vegetation, such as palm groves, creates microclimates and lowers ambient temperatures.	- Desert fox fur (Whitford, 2002): Dense, light-colored fur reflects sunlight and regulates internal body heat. - Cactus ribs: Provide shade, dissipate heat, and enhance airflow. - Baobab tree roots: Store moisture and endure prolonged dry periods.	- Applying bio-coatings with reflective and insulating properties, inspired by desert fox fur, to enhance thermal regulation. - Introducing bio-inspired designs for wall extensions (such as shading ribs modeled after cactus spines) to improve airflow and cooling. - Incorporating moisture storage reservoirs at the base of walls, inspired by baobab roots, to regulate ambient humidity and enhance the microclimate.			

Rest of Table 1.

No.	Examples of Vernacular Architecture in Bam	Biological Pattern (Bionic)	Integration of Bionic Architecture with Vernacular Architecture in Bam	Processed Images		
				Original Image	Lab Colour Space	Edge Detection
9	- Adobe walls with high thermal mass are highly effective for thermal insulation, making them essential in hot and arid climates like Bam. - The shade provided by palm trees creates a cooling effect and reduces surface temperatures. - Integrating vegetation improves air quality and contributes to the formation of a localized microclimate.	- Spider silk: A strong yet lightweight material for creating tensile-shaded structures. - Cactus structure (Ward, 2009): Optimized for water storage and shading.	- Planting drought-resistant vegetation modeled after cactus systems near walls to create a continuous cooling barrier. - Introducing tensile shade structures inspired by spider silk to expand shaded areas and reduce material costs.			
10	- Vaulted roofs are highly effective in structural stability, evenly distributing loads, and reducing temperature fluctuations. - Stairwells, naturally cooler and less exposed to sunlight, help minimize damage to wall plaster while preserving its reflective and thermal insulation properties.	- Beehive structure: hexagonal designs efficiently distribute loads while maintaining ventilation. - Termite mounds: Enable natural airflow and heat dissipation within compact designs.	- Reinforcing vaults with hexagonal structural patterns inspired by beehives to enhance strength and reduce structural weight. - Creating small airflow channels inspired by termite mounds to ensure proper ventilation and reduce internal heat.			
11	- Dense palm groves act as natural windbreaks, reducing sandstorms and providing cool shade. - The vaulted architecture ensures structural stability and minimizes the direct penetration of sunlight into buildings. - This integration of nature and design exemplifies a harmonious relationship between the built and natural environments.	- Palm structure: Efficient water storage and resilience in arid climates. - Bat wing membrane: Thin yet durable layers that maximize airflow with minimal material. - Turtle shell: Layered structures for load distribution and thermal insulation.	- Designing lightweight roof membranes inspired by bat wings to enhance airflow beneath vaults. - Introducing layered composite materials inspired by turtle shells to strengthen roofs and improve insulation. - Utilizing palm fibers in construction for environmentally friendly and climate-adapted applications.			
12	- The texture of the walls reflects local adobe bricks, highlighting traditional techniques adapted to Bam's hot and arid climate. - The natural spacing and irregularities on the surface enhance insulation and ventilation.	- Ant hills: Intricate tunnels designed for thermal regulation. - Woodpecker beak structure: Layered design resistant to impact.	- Introducing double-layered walls inspired by ant hill designs to enhance passive cooling and thermal performance. - Adding shock-absorbing properties to adobe by incorporating bio-based materials such as straw and clay, inspired by the layered structure of a woodpecker's beak.			

Rest of Table 1.

No.	Examples of Vernacular Architecture in Bam	Biological Pattern (Bionic)	Integration of Bionic Architecture with Vernacular Architecture in Bam	Processed Images		
				Original Image	**Lab Colour Space**	**Edge Detection**
13	- Arched designs and column-based frameworks demonstrate structural stability and efficient load distribution. - This design creates shaded spaces and reduces solar heat radiation in hot and arid climates like Bam.	- Honeycomb geometry: High strength-to-weight ratio and efficient use of materials. - Camel hump: Energy storage and temperature regulation.	- Applying honeycomb geometry to enhance structural integrity while reducing material consumption, creating lighter yet stronger columns. - Integrating heat storage systems inspired by camel humps, enabling walls to effectively regulate internal temperatures.			
14	- Mass and material composition of walls (mud or adobe) provide excellent thermal insulation, making them well-suited for hot climates such as Bam. - Openings function as simple vents for air circulation or heat dissipation.	- Termite mounds: Efficient thermal regulation and ventilation systems. - Cactus spines: Reduce heat absorption and provide structural integrity.	- Designing advanced passive ventilation systems inspired by termite mounds, incorporating a network of interconnected air passages. - Adding surface patterns inspired by cactus spines to reduce solar heat absorption on external surfaces.			
15	- The arranged brick pattern reflects traditional construction methods that provide structural strength and thermal mass. - The spacing between bricks enhances the potential for air ventilation or material movement, improving insulation.	- Beehive: Efficient material arrangement for strength and ventilation. - Snake skin: Overlapping patterns for flexibility and thermal protection.	- Utilizing honeycomb-inspired arrangements to create lightweight yet durable materials and enhance insulation. - Developing modular brick systems that mimic the overlapping patterns of snake skin for adaptive thermal regulation.			
16	- They efficiently distribute structural loads while maintaining stability and reducing material usage. - Additionally, they promote airflow and natural light, making them well-suited for hot climates.	- Spider web: Structural efficiency with minimal material usage. - Leaf veins: Distribute loads through minimal yet robust patterns.	- Incorporating adaptive vaulted shapes inspired by leaf veins to create stronger and lighter load-bearing systems. - Implementing solar shading devices within vaults to regulate sunlight intensity effectively.			

The integration of bionic architectural principles with the traditional texture of Bam opens new horizons where a sustainable and culturally harmonious environment emerges in the heart of the desert. The vernacular architecture of Bam—with its adobe walls, narrow alleys, vaulted, and domed roofs—is a treasure trove of natural cooling strategies and the effective use of thermal mass. These elements, aligned with bionic principles, draw inspiration from biological systems such as termite mounds, cacti, and desert snails, which excel in airflow management, heat dissipation, and moisture retention in harsh climates. For instance, emulating the ventilation systems of termite mounds and the layered outer structure of beetles in the design of vaulted and domed roofs not only enhances their thermal performance but also ensures structural integrity. Additionally, incorporating cactus-inspired spines for heat dissipation and reflective coatings modeled after snail shells to reduce heat absorption introduces innovative solutions for improving the climatic performance of buildings while preserving their traditional aesthetics. This synergy not only safeguards the architectural heritage of this ancient city but also increases its resilience to climatic challenges. However, this convergence faces multifaceted challenges, necessitating special attention to material compatibility, cultural heritage preservation, and scalability. Transitioning from traditional materials such as adobe to bio-inspired composites or nanocoatings raises concerns about maintaining aesthetic integrity and structural authenticity. Moreover, employing bionic adaptations, such as nature-inspired airflow systems or self-healing materials, requires extensive research and testing to ensure their long-term efficiency in harsh climatic conditions, including high temperatures, strong winds, and potential earthquakes in the Bam region. Another challenge is balancing the environmental benefits of bionic designs with the economic feasibility of implementing these advanced technologies in a historically significant but underprivileged area. Addressing these challenges calls for a multidisciplinary approach that integrates heritage preservation with advances in material science, structural engineering, and environmental psychology, providing solutions that are both contextually compatible and ensure long-term sustainability.

From an environmental and cultural perspective, incorporating bio-design principles in Bam's architecture offers an opportunity to rethink urban sustainability and safeguard the heritage of this historic city. Environmentally inspired designs, drawing from natural systems such as palm groves and termite mounds, can optimize shading, ventilation, and water management, directly enhancing the microclimate. For instance, designing courtyards with drought-resistant vegetation and nature-inspired shading systems can enhance thermal comfort while reducing water consumption. Furthermore, integrating elements like green walls modeled after baobab tree roots and bio-reflective coatings on adobe surfaces can significantly lower heat stress, improve energy efficiency, and enhance indoor comfort. By leveraging nature-based solutions that align with the spatial and aesthetic values of Bam's traditional architecture, this approach fosters a harmonious blend of environmental, cultural, and architectural sustainability. The 2003 earthquake dealt a severe blow to the traditional architecture of Bam, leaving a profound rift in the cultural and environmental identity of this desert gem. The post-earthquake reconstructions primarily relied on modern architectural approaches, often disregarding the fundamental principles of indigenous architecture that had evolved over centuries in harmony with Bam's hot and arid climate and its rich cultural fabric. Amid these transformations, the remaining examples of ancient architecture, such as the historic Ameri House (Fig. 7), provide a gateway to understanding environmental strategies and drawing inspiration from nature in historical designs. This section of the article analytically examines the architectural layout of the Ameri House, a distinguished example of vernacular architecture in Bam, exploring its alignment with bionic and ecological architectural principles—whether consciously or unconsciously.

The design of the Ameri House, centered around the courtyard (Howzkhaneh) as a pivotal element, stands as a testament to the profound understanding of sustainable architectural principles by Iranian architects. This courtyard, functioning as the beating heart of the building, incorporates a water basin and garden, creating a microclimate within the structure. The evaporation of water from the basin, combined with the expansive shadows cast by the surrounding structures, significantly cools the courtyard and adjacent

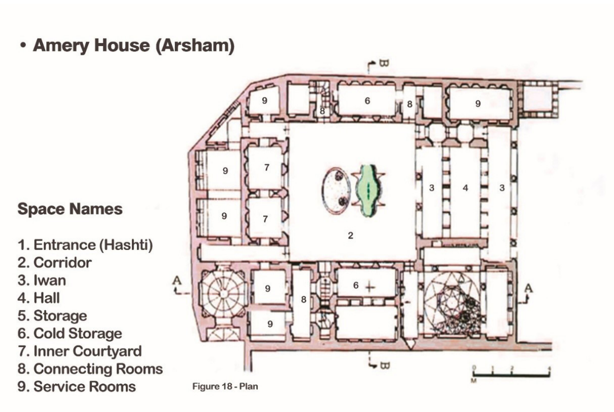


Fig. 7. A view of the architectural plan of Ameri House in the city of Bam. Source: Golpayegani, 2007.

spaces. This natural cooling mechanism minimizes reliance on artificial cooling systems, exemplifying a clear model of nature-inspired design and biomimicry in architecture. The floor plan of the Ameri House narrates a gradual spatial sequence that begins at the entrance vestibule (Hashti) and progressively transitions to semi-private and private spaces. This thoughtful spatial hierarchy acts as a protective layer, shielding the building's core from harsh climatic conditions while creating a tranquil and comfortable environment for its occupants. The use of multi-door systems (three-door and two-door arrangements) enhances the building's flexibility, allowing air and light flow to be adjusted according to seasonal variations. This meticulously calculated spatial segmentation bears a remarkable resemblance to adaptive strategies in biological systems, where layers and membranes are designed to optimize interaction with the environment. This unconscious alignment with bionic design principles underscores the ingenuity of Iranian architects in integrating indigenous knowledge with inspiration from nature. The robust domes and arches, iconic features of traditional Iranian architecture, prominently feature in the Ameri House's layout. These structures efficiently distribute loads while reducing material usage, showcasing the brilliance of Iranian architectural ingenuity. This structural approach is inspired by nature, resembling the precise and efficient geometry of tree canopies and shells, which protect living organisms. The rhythmic repetition of service rooms and the proportional harmony of various architectural elements echo self-replicating patterns and fractal geometries observed in living organisms. This resemblance is not coincidental but rather reflects the deep understanding of Iranian architects in optimizing performance with minimal resources—a fundamental concept in bionic architecture.

In the second phase of the study, interviews were conducted with 13 elderly natives of Bam who traditionally possessed extensive knowledge of local architecture. These interviews aimed to collect in-depth and experiential perspectives on the influence of natural elements, such as native plants and animals, on traditional construction methods in Bam. Specifically, efforts were made to gain a profound understanding of their views on leveraging nature-inspired features, such as date palms, desert animals, and their survival strategies, in traditional architecture. The interviews provided a deep understanding of indigenous and local knowledge regarding the formation of sustainable architectural practices in Bam, achieved through generational knowledge transfer. Residents often described buildings designed by drawing inspiration from natural cooling and sheltering mechanisms observed in plants and animals. Examples included thick walls, shaded courtyards, and subterranean spaces. This community-based perspective enriched the study's findings, demonstrating how nature had a practical and deeply cultural influence on Bam's traditional architecture. The results from the interviews with local residents are presented in Table 2 and Fig. 8.

- **Key findings from the interviews**

Unconscious Imitation of Biological Adaptations: Many interviewees highlighted striking similarities between Bam's traditional architecture and the adaptive strategies of desert animals such as snakes, desert foxes, and lizards. Features like thick mudbrick walls, deep courtyards, and subterranean rooms functioned as cooling environments and shelters, akin to the natural burrows and hideouts of these animals.

The Importance of Date Palms and Natural Shade: Interviewees emphasized the critical role of date palms and other vegetation in creating shade and cooling residential spaces. This approach closely mirrors the survival strategies of desert plants and animals, which rely on shade to withstand extreme heat.

Table 2. Categorized Results from the Interviews. Source: Authors.

Participant	Occupation	Perspective on Using Plant and Animal Features in Traditional Architecture	Examples and Specific Explanations
Male, 70	Self-employed	Believes architects mimicked desert animals' survival instincts	They built thick walls like a camel's skin to keep heat out, and just like a snake's burrow underground, our homes had cool cellars.
Female, 68	Retired employee (Teacher)	Focuses on the cooling properties of plants	We always had date palms and small gardens in the courtyard. Trees provided shade and cooled the air.
Male, 74	Retired employee (Railways)	Thinks design unintentionally reflects nature	The way we built houses was just common sense. Like animals seeking shade, we built narrow alleys and deep courtyards to escape the sun.
Female, 65	Homemaker	Highlights the use of date palms for shade and water preservation	Date palms not only provided shade but helped keep water cool in clay pots placed near them.
Male, 72	Self-employed	Relates domed structures to animals' natural shelters	Domed roofs were like hills and dunes were animals resting underneath. They protected us from the sun and kept the interiors cool.
Female, 71	Homemaker	Points to mimicking animals' behaviors for survival	We learned from lizards and mice how they hide from heat. Our homes had thick walls, like how these creatures find cool spots.
Female, 61	Homemaker	Notes natural ventilation inspired by animals' adaptations	Windcatchers worked like the big ears of desert animals, bringing cool air into the house.
Male, 69	Retired employee (Telecommunications)	Strongly believes nature influenced traditional construction	We built homes the way the desert taught us. Like animals and plants living in the desert, we used shade, water, and thick walls to keep heat out.
Female, 66	Homemaker	Sees trees, especially date palms, as essential cooling elements	Without date palms, the heat would have been unbearable. We had them around the house to keep spaces cool, just like animals hiding in their shade.
Male, 76	Self-employed	Emphasizes practicality of materials based on local plants and animals	We didn't use concrete or other materials. Everything was made of mud, straw, and clay, just like how animals and plants live simply with what's around them.
Female, 72	Retired employee (Nurse)	Refers to cooling techniques inspired by plant behaviors	Winds passing through trees and cooling the air inspired how we built windows and vents to let air flow through houses.
Female, 69	Homemaker	Mentions combining water and plants for cooler spaces	We used small fountains and surrounded them with trees, just like plants growing near water in the desert. It kept the courtyard much cooler.
Male, 63	Self-employed	Links construction techniques to natural cooling mechanisms	Like animals hiding in cool sand, we built our houses with mud bricks to stay cool during the day and warm at night, just like desert animals.

Nature-Inspired Ventilation Systems: Windcatchers, one of the most prominent elements of traditional architecture in Bam, were often compared to the large ears of desert animals like foxes. This similarity underscores how traditional architects designed efficient natural ventilation systems inspired by nature.

Use of Local and Simple Materials: Interviewees highlighted the widespread use of natural materials such as mud, adobe, and straw in constructing traditional buildings. This approach aligns with the philosophy of simplicity and environmental harmony observed in many desert creatures.

Interaction of Water and Plants for Evaporative Cooling: The common practice of incorporating small fountains and planting trees nearby was a traditional method of

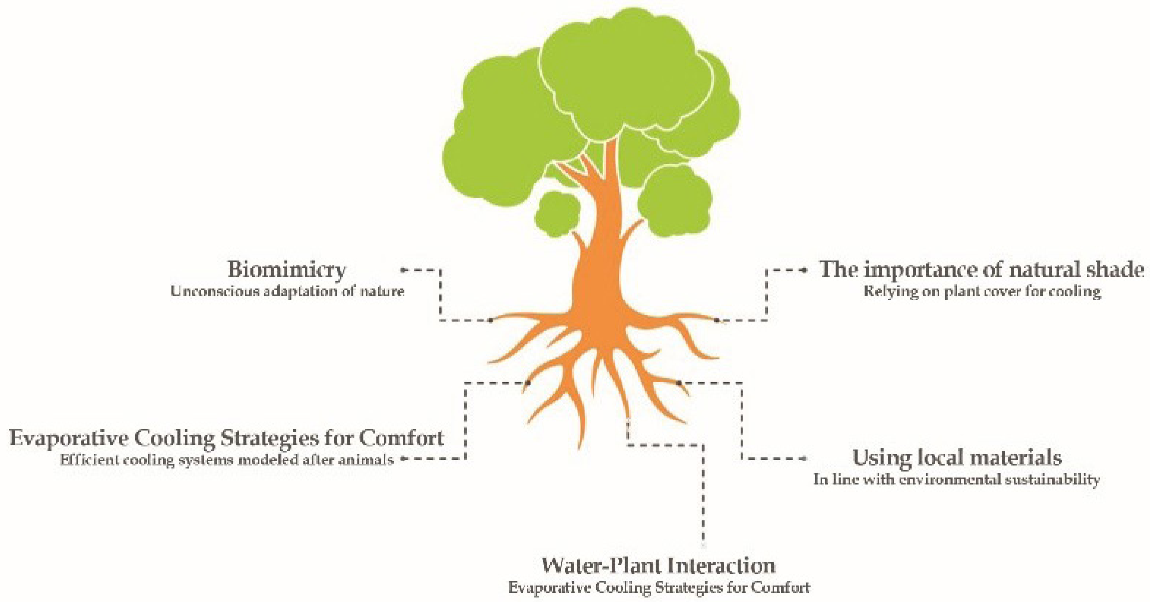


Fig. 8. Biological Influences and Natural Inspirations in Traditional Architectural Design in Bam. Source: Authors.

creating evaporative cooling in courtyards. This method mirrors the survival strategies of desert plants that grow around limited water sources to retain moisture and create a cooler environment.

Discussion

The Vernacular Architecture of Bam; An Unparalleled Model of Nature-Inspired Design: Previous studies, such as those by Mokhtari et al. (2019) and Einifar & Eshrati (2018), have revealed that Bam's historical architecture exemplifies passive resilience by relying on natural mechanisms like thermal mass, spatial hierarchies, and precise microclimate control. The findings of this research further demonstrate the alignment of Bam's architectural elements—such as central courtyards (Howzkhaneh), shaded iwans, and windcatchers—with biological systems like termite mounds and cacti. This profound adaptation reflects the deep understanding of Iranian architects regarding sustainable design principles and the integration of nature into their work. The findings of this study offer a golden opportunity to take significant steps toward reviving Bam's urban fabric through nature-inspired design without compromising its historical identity. The central courtyard of the Ameri House, for example, not only serves as an efficient climate regulator but also presents a layered spatial organization reminiscent of natural ecosystems. This clearly highlights the potential of biomimetic architecture to enhance urban sustainability, as evident in global examples like the Eastgate Centre in Zimbabwe (Solano et al., 2023).

Material Science and Nature-Inspired Innovations; Keys to Sustainable Revival in Bam: Material science and biomimetic innovations open new doors to addressing the challenges of traditional construction in the historic city of Bam. Previous research (Goldust & Ahmadnejad Karimi, 2022) has shown that complex load-bearing patterns in tree trunks and insect wings inspire the design of advanced adobe composites. For instance, self-healing materials, modeled after the repair mechanisms of living organisms, could significantly extend the lifespan of adobe structures. Similarly, light-reflective coatings, inspired by the structure of beetle shells, could reduce heat absorption in buildings and improve thermal comfort for residents. These innovations not only enhance the performance of buildings but also align with the cultural identity and aesthetic heritage of Bam.

Bam; A Model for Nature-Based Urban Sustainability: The historical coexistence of qanat irrigation systems, lush palm groves, and shaded gardens in Bam provides a solid foundation for applying biomimetic principles to urban architecture. The study's findings indicate that this rich heritage can inspire the design of modern urban infrastructures that harmonize with nature. For example, shading systems could mimic the functionality of baobab trees, while urban green corridors could resemble the root networks of desert plants. Such approaches would not only significantly mitigate urban heat island effects but also enhance biodiversity and restore the region's environmental balance. These findings align closely with the environmental resilience indicators proposed by Gunderson (2000) and Spears et al. (2015).

Bionics; A Bridge Between Past and Future, Preserving Bam's Cultural Identity: The application of bionic principles in the vernacular architecture of Bam offers a dual opportunity: it aids in the physical revival of this ancient city and strengthens its cultural and identity roots. Field research reveals that Bam's residents have a profound connection with their traditional architecture, deeply appreciating its adaptation to climatic conditions, such as mimicking the thermal properties of desert animal burrows. By integrating this indigenous knowledge with modern technologies and nature-inspired designs, architects can create plans that align with the spirit of Bam's past while addressing contemporary needs. This approach is entirely in line with Alexander's (2004) perspective, which emphasizes the significance of cultural continuity in sustainable architecture.

Challenges in Merging Modern Knowledge with Tradition; Obstacles and Opportunities: Implementing bionic principles in Bam's historic fabric, despite its numerous advantages, comes with significant challenges. One major obstacle is ensuring the compatibility of modern materials and structures with the city's traditional architecture. Previous studies (Jiang et al., 2024) highlight that combining advanced materials such as composites and nano-coatings with indigenous materials like adobe requires meticulous attention. While these materials can improve the durability and performance of structures, they risk altering the sensory and visual characteristics of the buildings, potentially compromising their cultural authenticity. Another challenge lies in the economic and technical limitations of the region. Advanced technologies, such as phase-change materials or nature-inspired structural systems, require significant investment and specialized technical expertise, which may not be readily accessible to all communities. The findings of this research suggest that success in this endeavor demands solutions that are both technically efficient and economically and socially viable. This approach aligns with global discourse on accessible and sustainable design (Rietmann, 2021).

Climatic and Seismic Challenges in Applying Biomimetic Principles in Bam: With its harsh climate and history of seismic activity, Bam poses a unique testing ground for the effectiveness of biomimetic architectural innovations. While ventilation systems inspired by termite mounds and shading mechanisms resembling cacti appear promising for addressing climatic challenges, their long-term sustainability against strong winds, sandstorms, and frequent earthquakes remains a critical question. Adapting these global strategies to the specific geological and climatic conditions of Bam is an unavoidable necessity.

Adherence to Identity; Social and Cultural Challenges: Beyond technical hurdles, incorporating bionic principles into Bam's architecture faces social and cultural resistance. The local community's deep ties to traditional architecture and indigenous knowledge may lead to opposition against external innovations and fundamental changes to the city's historic fabric. Therefore, the active participation of residents, local architects, and policymakers throughout the design and implementation stages is crucial. This inclusive approach not only enhances the acceptance of new designs but also ensures their alignment with the city's cultural values and identity. To achieve environmental and cultural resilience in Bam, an integrative strategy is proposed that blends indigenous knowledge with modern technologies. This balanced approach ensures that the revival of Bam's urban fabric remains respectful of its historical identity while embracing innovations that address contemporary challenges.

Coexistence of Tradition and Innovation in Building Materials: A practical approach involves integrating traditional materials like adobe with advanced nature-inspired composites. For instance, natural-based coatings can be developed to mimic desert plants by absorbing excess moisture and protecting structures from humidity and related damage. Additionally, modular and flexible construction systems inspired by nature can facilitate the gradual restoration and enhancement of buildings, significantly aiding in preserving Bam's architectural identity.

Creating an Optimal Microclimate Inspired by Nature: To improve comfort conditions within buildings, natural solutions can be employed. For example, cooling systems inspired by termite mounds can be designed as passive cooling mechanisms that reduce indoor temperatures without external energy sources. Similarly, reflective surfaces modeled after desert vegetation can prevent excessive heat absorption in buildings. On an urban scale, green walls and intelligent shading systems can improve air quality, reduce energy consumption, and create an optimal microclimate for residents.

Blending Knowledge and Practice; Educational Workshops and Collaborative Programs: Hosting educational workshops and participatory programs creates a platform for merging indigenous knowledge and the valuable experiences of local residents with modern innovations and technical expertise. This approach not only fosters a sense of ownership and belonging among the community but also ensures that the proposed solutions are not only technically viable but also culturally and socially aligned with local values.

From Example to Citywide Implementation; Scalable Urban Regeneration: Pilot implementations of bionic principles in landmark buildings like the Ameri House can serve as successful models for broader urban regeneration. This phased approach minimizes financial risks and provides opportunities for gradual refinement and improvement of designs. Such a strategy enables a confident progression toward larger and more complex projects, ultimately leading to sustainable urban revitalization.

Conclusion

The findings and overall results of this study indicate that the traditional architecture of Bam, through the integration of architectural elements, natural materials, and environmental design principles, exemplifies a prominent model of sustainable architecture. Analyzing this architecture reveals that the fundamental principles of bionic architecture, such as energy efficiency and environmental adaptation, are inherently embedded in the structure and functionality of the region's vernacular buildings. This research provides clear evidence of the significant potential of Bam's indigenous architecture as a source of inspiration for contemporary architectural design. One of the most distinctive features of Bam's traditional architecture is its intelligent use of spatial forms to address harsh climatic conditions. Central courtyards, acting as natural shelters, create shade, enhance airflow, and facilitate evaporative cooling, providing an efficient response to the region's intense heat and drought. Furthermore, spatial layering and the creation of intermediary spaces, such as porches and corridors, facilitate a gradual transition from exterior to interior spaces, significantly contributing to temperature and humidity regulation indoors. These characteristics demonstrate that Bam's traditional architects, with a profound understanding of the climate and human needs, designed spaces that ensured the constant comfort and well-being of occupants. Domed and vaulted forms, by uniformly distributing stress across their surfaces, mimic the exoskeletons of arthropods, providing maximum strength with minimal materials. These shell-like structures also optimize thermal insulation, enabling energy efficiency in buildings. Meanwhile, windcatchers, with their aerodynamic design, direct airflow into buildings, facilitating natural ventilation and cooling through mechanisms inspired by biological systems. This feature, particularly in hot and dry climates, creates a more comfortable indoor environment for residents.

Additionally, local materials such as adobe, clay, and straw, with their high thermal inertia and porous structures, create a stable temperature and suitable humidity indoors, ensuring thermal comfort for occupants. These materials, besides being environmentally compatible and reducing energy consumption, have the potential to be enhanced with modern technologies. For instance, reflective coatings inspired by the shells of desert animals can prevent excessive heat absorption by reflecting solar radiation, thereby reducing cooling loads. The connection between architectural elements and biological systems in Bam is deeply rooted in the city's cultural and environmental context. Planting date palms in central courtyards, in addition to providing shade and promoting evaporation, symbolizes life and vitality in the heart of the desert, reflecting the cultural beliefs of the people. This natural shading helps cool the environment and reduce heat stress, functioning similarly to the transpiration mechanism in plants. The design of windcatchers, with a deep understanding of airflow dynamics, mimics the thermal regulation mechanisms of animals like desert foxes. These structures direct prevailing winds into interior spaces and use pressure differentials to facilitate natural ventilation. Narrow alleys and tall walls, resembling the underground burrows of desert animals, create cool and shaded spaces that prevent excessive heat penetration and provide a suitable living environment. The use of local materials such as adobe and clay also contributes to the sustainability of buildings by creating a stable indoor environment. This complete alignment of architecture with climatic and environmental conditions illustrates the profound understanding of traditional architects regarding natural forces and the importance of harmonizing with nature. In summary, the findings of this discussion highlight that Bam's vernacular architecture inherently incorporates the principles of bionic architecture. The aerodynamic forms used in windcatcher designs, akin to bird wings, facilitate airflow and natural ventilation. The use of local materials such as adobe and clay, with their favorable thermal properties, helps maintain stable indoor temperatures while reducing energy consumption for heating and cooling. The thermal and structural performance of vaulted and domed spaces demonstrates that integrating natural forms into architectural design, similar to eggshells, can enhance structural strength while providing effective thermal insulation. Additionally, strategies such as using porous and reflective surfaces strengthen bionic approaches to reducing energy consumption and increasing sustainability (Fig. 9). Integrating bionic principles into modern architectural approaches, especially in a city like Bam with a rich cultural identity, requires a delicate balance between preserving heritage and embracing technological advancements. Developing bio-inspired materials, such as self-healing adobe inspired by the repair mechanisms in living organisms, and utilizing adaptive façades with functionalities akin to animal skins, can significantly contribute to the preservation and sustainability of Bam's historic fabric. Scaling these innovations at an urban level, considering the complexity of the historic fabric and the diverse needs of residents, poses one of the main challenges that demand interdisciplinary collaboration, appropriate investment, and the development of necessary infrastructure. Given the significant potential of Bam's vernacular architecture and recent advancements in the field of bionics, a sustainable and dynamic future can be envisioned for this historic city.

Conflict of Interest

The researchers emphasize that this study is free from any conflict of interest. All findings and results obtained from this research have been achieved in a completely independent and impartial manner, and no external or personal factors have influenced the research process or its outcomes.

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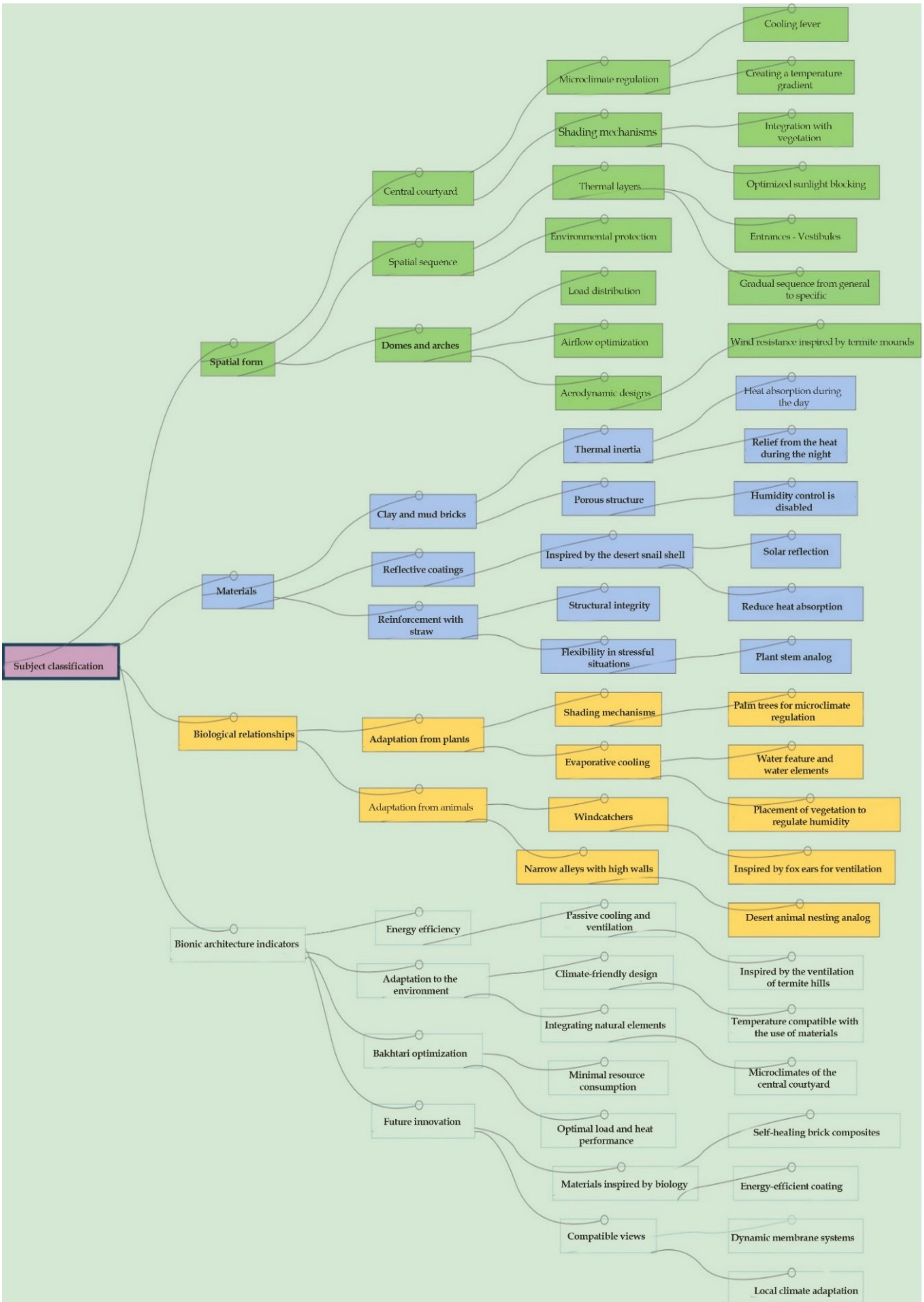

Fig. 9. Schematic Model of Integrating Traditional Architecture of Bam with Bionic Architecture Indicators Thematic Classification: Spaces, Materials, and Biological Inspirations. Source: Authors.

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