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Original Research Article

From Static Restoration to Adaptive Resilience: Bio-Lime as a Material-Oriented Biomimetic Approach to Historic Heritage Conservation

(Case Study: Rab'-e Rashidi Tabriz)*,**

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Abstract

Problem statement: In recent years, the increasing frequency of natural and human-induced crises, such as earthquakes, war, and climate change, has created serious challenges for the conservation and reconstruction of historic architectural heritage. Conventional approaches to restoration and reconstruction are predominantly reproductive and form-oriented in nature, paying limited attention to adaptive, temporal, and resilient mechanisms at the material level. In this context, biomimetics, as an approach inspired by the behavioral and process-based logic of nature, can provide a theoretical foundation for rethinking the adaptive reconstruction of historic heritage, particularly when it moves beyond mere formal imitation and becomes oriented toward the behavior of materials.

Research objective: Focusing on Bio-Lime as an example of material-oriented biomimetics, this study seeks to explain the capacities of self-healing lime-based materials in the restoration and adaptive reconstruction of architectural heritage.

Research method: This study employed a comparative analysis and a systematic review of recent studies in the fields of self-healing materials, lime mortars, and bio-based additives. The selected studies were analyzed according to criteria such as material type, self-healing mechanism, degree of compatibility with historic restoration, and functional outcomes.

Conclusion: The findings indicate that, unlike conventional self-healing systems based on concrete, lime-based materials—and Bio-Lime in particular—possess an inherent capacity for gradual, low-energy, and historically compatible self-healing through natural processes such as carbonation, rehydration, and microstructural modification. The findings further suggest that bio-based additives can purposefully enhance this capacity and contribute to improving the durability and physical resilience of historic buildings without causing chemical incompatibility. Accordingly, this study proposes a conceptual framework for adaptive reconstruction based on material-oriented biomimetics, which can support a transition from static restoration toward adaptive and future-oriented reconstruction in historic sites in Iran, particularly Rabʿ-e Rashidi in Tabriz.

Keywords: *Biomimetics; Architectural Resilience; Historic Heritage; Adaptive Reconstruction; Bio-Lime.*

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Introduction

In recent decades, the significant increase in natural and human-induced crises, such as earthquakes, floods, wars, and climate change, has created fundamental challenges for the conservation and reconstruction of historic architectural heritage. Many historic cities in the Middle East and the Mediterranean are directly or indirectly exposed to these crises. At the same time, existing conservation policies have often focused primarily on physical reconstruction, while paying less attention to the cultural and adaptive dimensions of resilience (Esposito et al., 2021; Jeleński, 2018). Under such conditions, the concept of "resilient architecture" has emerged as a new paradigm at the intersection of design, technology, and cultural heritage.

Unlike conventional conservation approaches, resilient architecture does not merely aim to preserve the visual appearance of a building; rather, it emphasizes the capacity of architectural systems to dynamically adapt to changing environmental, social, and technological conditions (Fatigusoa et al., 2018). This approach has become particularly significant in post-disaster reconstruction, where it functions as a means of maintaining the cultural and functional continuity of historic buildings. However, one of the fundamental challenges in achieving resilience lies in identifying models that can strengthen adaptive and regenerative capacities while respecting the authenticity of heritage.

In this context, nature has been recognized as one of the most important sources of inspiration for resilient design. Biomimetic design, by drawing on biological mechanisms such as self-healing, dynamic equilibrium, and structural symbiosis, can offer an innovative response to the adaptive reconstruction of historic heritage (Bader et al., 2021; Zaki, 2023). As demonstrated in the study by Bader et al. (2021) on the reconstruction of the Port of Beirut, the imitation of natural structures such as trees and shells contributed to increased structural resistance and improved stability against environmental forces.

In parallel with these developments, recent studies have increasingly moved toward integrating biomimetic principles with advanced technologies such as digital modeling, nanobiotechnology, and virtual reality. For instance, Mocerino (2024),` through an examination of nano-materials inspired by natural processes in the restoration of historic structures, shows that the use of smart technologies can enhance the durability and physical sustainability of heritage buildings. Similarly, Lucanto et al. (2024) highlight the role of digital modeling and regenerative design in predicting climate-related risks and planning adaptive reconstruction.

Alongside technological innovations, numerous studies have emphasized the value of indigenous knowledge and traditional experiences. For example, Mackin (2020), through a study of traditional Arctic shelters, demonstrates that the use of local materials and natural forms not only responds effectively to harsh climatic conditions but also preserves a form of cultural and social resilience. These studies emphasize that integrating indigenous insights with biomimetic innovations can provide a balanced framework between historical authenticity and contemporary performance (Vegas et al., 2022).

A review of the existing literature indicates that, despite the diversity of studies on biomimetics and architectural resilience, most research lacks empirical data and quantitative assessment of the effectiveness of these approaches. Many studies have remained at the theoretical or conceptual level and provide limited empirical evidence regarding the actual performance of biomimetic models under crisis conditions (Mocerino, 2024; Fatigusoa et al., 2018). Moreover, a substantial portion of the existing research focuses on European contexts, while indigenous case studies from the Middle East, including Iran, have received comparatively limited attention.

Therefore, there is a growing need to develop an integrated framework in which biomimetic principles are positioned alongside concepts of adaptive sustainability and indigenous knowledge. Such a framework can facilitate the reconstruction of architectural heritage in response to natural and human-induced crises and contribute to the formation of a model of "cultural–environmental resilience" in the regeneration of historic urban fabrics. In this regard, the present study considers Rabʿ-e Rashidi not merely as an applied case study, but as the problem context and the basis for extracting criteria for conservation intervention. Accordingly, due to its compatibility with lime-based materials, breathability, gradual self-healing capacity, and alignment with the principle of minimum intervention, Bio-Lime is proposed as a material-oriented option for strengthening the physical and cultural resilience of the site. Fig. 1 presents a summary of the conceptual framework for the application of bio-lime in the adaptive reconstruction of Rabʿ-e Rashidi, Tabriz.

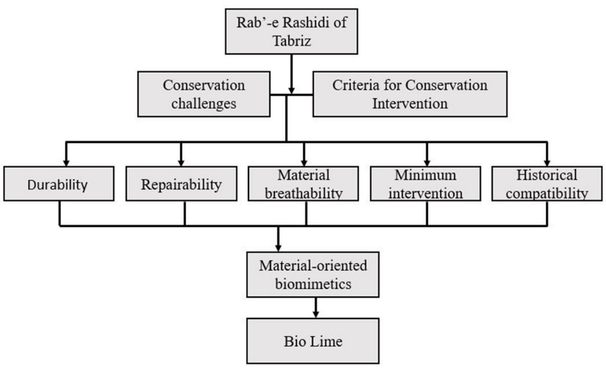

Fig.1. Conceptual Framework for the Selection of Bio-Lime in the Adaptive Reconstruction of Rabʿ-e Rashidi, Tabriz. Source: Authors.

Literature review

Despite significant advances in the conservation and restoration of architectural heritage, conventional approaches to post-disaster reconstruction remain largely reproductive and static in nature, paying limited attention to the dynamics, learning capacity, and adaptability of architectural systems (Esposito et al., 2021; Jeleński, 2018). This is while contemporary crises—from earthquakes and floods to climate change and human conflicts—have become increasingly complex, multidimensional, and unpredictable. Under such conditions, the mere preservation of the physical fabric of a building cannot guarantee its cultural and identity-based continuity. Rather, the resilience of architectural heritage must move beyond the physical level and encompass functional, cultural, and technological dimensions as well. Recent studies also indicate that biomimetic principles, particularly when integrated with emerging technologies such as digital modeling, nanobiotechnology, and virtual reality, can enhance the capacities of adaptive reconstruction in historic buildings (Bader et al., 2021; Mocerino, 2024; Lucanto et al., 2024). However, a large proportion of these studies remain at the level of theory or conceptual design, and only limited empirical evaluations have been conducted regarding the actual effectiveness of these models in local contexts or in interaction with cultural conservation systems. The lack of practical models and localized frameworks has hindered the effective application of global findings in the historic contexts of the Middle East and Iran, where natural and human-induced crises simultaneously affect architectural heritage.

On the other hand, many biomimetic approaches have been limited to structural and formal aspects, while the relationship between the biological logic of nature and the principles of cultural sustainability has not yet been adequately articulated (Fatigusoa et al., 2018; Zaki, 2023). Although studies such as Mackin (2020) and Vegas et al. (2022) have demonstrated that indigenous and traditional mechanisms can themselves be regarded as manifestations of nature’s logic in responding to crises, no systematic model has yet been proposed for integrating indigenous knowledge, biological inspiration, and advanced technologies into the process of adaptive reconstruction. This absence causes conservation policies and interventions to remain more reactive and short-term than dynamic and future-oriented.

In recent decades, the concept of “resilient architecture” has emerged as one of the fundamental axes of contemporary approaches to the conservation of historic heritage. By focusing on adaptive and regenerative mechanisms, this approach seeks to establish a connection between environmental sustainability, structural performance, and cultural continuity in the process of post-disaster reconstruction. Based on a systematic review of studies conducted between 2015 and 2024, an increasing trend can be observed in the application of biomimetic design principles in the design and restoration of historic buildings. This trend regards nature not merely as a source of formal inspiration, but as a behavioral and functional model for resilience against environmental threats (Bader et al., 2021; Mocerino, 2024).

Mackin (2020), through an examination of indigenous shelters in Arctic regions, demonstrates that the use of local materials and natural forms can lead to the creation of structures that are both climatically sustainable and culturally capable of preserving a sense of belonging and continuity of identity. In the same vein, Bader et al. (2021), in the reconstruction of the Port of Beirut, drew upon biological structures such as trees, bamboo, and shells to enhance structural resistance and reduce the destructive impacts of the explosion. These two studies indicate that biomimetic principles can function, under crisis conditions, as instruments of physical and social regeneration.

In the field of emerging technologies, numerous studies have addressed the role of digital tools in enhancing the resilience of architectural heritage. Lucanto et al. (2024) discuss the application of digital modeling and regenerative design in climate risk analysis for historic urban fabrics, showing that advanced technologies such as digital prototyping and regenerative design can support informed decision-making in restoration through multi-scenario simulation. Mocerino (2024) also emphasizes the use of nanobiotechnology, self-cleaning surfaces, and smart materials, which, inspired by natural mechanisms, can improve the durability and thermal performance of historic buildings. These studies reflect a paradigm shift from passive conservation toward intelligent and data-driven reconstruction.

Furthermore, studies such as Esposito et al. (2021) and Fatigusoa et al. (2018) emphasize the necessity of developing multi-risk frameworks for heritage conservation. By combining hazard modeling, structural performance assessment, and the analysis of social behavior, they propose a framework for adaptive decision-making in historic contexts. However, as indicated in the systematic analysis of these studies, existing approaches remain predominantly theoretical and qualitative, with limited attention given to empirical data and quantitative assessments of the effectiveness of biomimetic methods.

In the field of indigenous knowledge and cultural heritage, Mackin (2020) and Vegas et al. (2022) show that traditional and local mechanisms in vernacular architecture inherently embody biomimetic principles. For instance, in adobe structures or domed forms in arid regions, one can observe the same self-regulating and environmentally adaptive patterns that nature employs in biological systems. In an international study of vernacular architecture in Spain, Morocco, and China, Vegas et al. (2022) emphasize that the use of local resources, the formation of climate-adaptive patterns, and the reproduction of natural materials are rooted in the human biological understanding of the environment. By emphasizing the synergy between tradition and technology, these studies point to the significance of integrating indigenous knowledge and biomimetic innovation in heritage conservation.

At the same time, a comprehensive review of recent studies indicates that, despite the breadth of the subject, no unified conceptual model has yet been developed for integrating biomimetic principles, digital technology, and cultural resilience within the process of adaptive reconstruction (Mocerino, 2024; Lucanto et al., 2024). Most studies have been conducted at the case-based or laboratory scale and have paid less attention to integrating theories of adaptive sustainability with the biological logic of nature. Therefore, a significant gap remains in the scientific literature regarding the integration of biomimetics with localized frameworks for the regeneration of architectural heritage in crisis-affected regions.

Accordingly, it can be concluded that although the existing literature emphasizes the importance of resilience and inspiration from nature, it still lacks a comprehensive framework capable of linking bio-inspired design, smart technologies, and cultural identity. The present study, therefore, seeks, through a comparative approach, to propose a conceptual model for the reconstruction of historic architectural heritage in the face of natural and human-induced crises. In this model, biomimetic mechanisms, together with digital technologies and the principles of cultural sustainability, form the foundation of adaptive resilience. A review of studies related to the application of bio-lime in the restoration and conservation of historical buildings is presented in Table. 1.

Theoretical Framework

The theoretical framework of the present study is grounded in the fundamental assumption that the reconstruction of historic architectural heritage in the face of natural and human-induced crises requires a transition from static and reproductive approaches toward dynamic, adaptive, and resilient models. In this context, the concept of "resilient architecture," as an emerging paradigm, emphasizes the capacity of architectural systems for gradual adaptation, functional continuity, and the preservation of cultural identity under conditions of uncertainty (Fatigusoa et al., 2018; Jeleński, 2018).

On the other hand, biomimetic design, inspired by the behavioral logic and biological mechanisms of nature—such as self-healing, dynamic equilibrium, and structural symbiosis—provides a conceptual framework for enhancing resilience in architecture; a

Table 1. Literature review. Source: Authors.

Research Limitations	Key findings	Biomimetic Approach	Types of crises	Type of Heritage Studied	Primary Research Focus	author / Yera
Lack of technological analysis and quantitative modeling	The interconnection between climatic sustainability and cultural resilience	Natural materials and nature-inspired forms	Cold-climate conditions and climate change impacts	Traditional Vernacular Architecture	Reconstruction of vernacular shelters in the Arctic region	Mackin (2020)
Limited to a case study and lacking generalizability	Biomimetics as a tool for social and structural regeneration	Imitation of the structure of trees, bamboo, and shells for structural strength	Earthquakes, explosions, and tsunamis	Historic Urban Fabric	Reconstruction of Beirut Port after the crisis	Bader et al. (2021)
Theoretical focus; without empirical data	Application of data-driven modelling in climate risk analysis	Digital prototyping and regenerative design	Climate change impacts and flood events	Historical Building in Italy	Digital Design and Modelling	Lucanto et al. (2024)
Lack of long-term field evaluation	Improved durability and structural performance	Nanobiotechnology and self-cleaning surface technologies	Erosion, seismic events, and climate change impacts	Historic Buildings and Cultural Landscapes	Nanotechnology and the digitalization of heritage	Mocerino (2024)
Theoretical-model limitation	Adaptive decision-making framework for heritage conservation	Modeling of performance and social behavior	Natural hazards and climate-related disasters	Historic Urban Fabrics	Urban Heritage Analysis	Esposito et al. (2021)
Lack of quantitative evaluation of the results	Emphasis on the integration of conservation and change	Adaptive systems inspired by nature	Environmental degradation and erosion	Traditional stone-built fabrics (Matera, Italy)	Theoretical Framework for Resilience in Historical Heritage	Fatigusoa et al. (2018)
Need for an integrated conceptual model	Integrating local resources and technology	mplicit biomimetic approach through bioclimatic design	Seismic events, flooding, and urban pressures	International Vernacular Architecture (Spain، Morocco، China)	Architectural resilience of vernacular traditions across different regions	Vegas et al. (2022)
Focus on modern contexts rather than historical heritage	Enhancement of energy performance and structural integrity	Biomimetic imitation of DNA structure and bird feathers	Natural hazards and climate change impacts	Modern Buildings (Asia and America)	Biomimetic approaches in modern resilient design	Zaki (2023)
Lack of technological and biomimetic perspectives	Integration of physical and identity-based reconstruction	Adaptive conservation and functional revitalization	War-related destruction and crisis-induced damage	Historic Urban Complexes	Reconstruction of heritage after crisis in Poland	Jeleński (2018)

framework that moves beyond formal imitation and focuses instead on processes and system behaviors (Bader et al., 2021; Zaki, 2023).

Accordingly, by emphasizing material-oriented biomimetics and the role of self-healing lime-based materials, particularly Bio-Lime, the present study seeks to propose a theoretical framework for the adaptive reconstruction of historic heritage, in which material acts as an active agent in the process of physical and cultural resilience.

- **Rabʿ-e Rashidi, Tabriz: the historical, physical, and climatic context of the study**

Rabʿ-e Rashidi in Tabriz is one of the major historical and charitable-endowment complexes of the Ilkhanid period. It was established by order of Khwaja Rashid al-Din Fazlullah Hamadani in the early eighth century AH and has also been referred to in historical sources by names such as "Rashidiyya," "Rashidabad," and "Abwab al-Birr Rashidi." The remains of this complex, covering an area of approximately 13 hectares, are today located in the north-eastern part of Tabriz, on Kanān-Kuh and on the slopes of Mount Surkhab. The site was registered on Iran's National Heritage List in 1975 under registration number 943. According to the Rabʿ-e Rashidi endowment deed, this township was not merely an architectural space, but rather a scientific, service-oriented, religious, and residential complex organized with the aim of accommodating groups from different cities and regions and providing public, educational, and medical services. Historical and archaeological evidence indicates that Rabʿ-e Rashidi initially formed part of the Rawḍa-ye Rashidi and the charitable-endowment complex of Khwaja Rashid al-Din during the Ilkhanid period. In later periods, however, it underwent changes in function, destruction, reconstruction, and the accumulation of multiple residential and military layers (Ajorloo et al., 2024).

The significance of Rabʿ-e Rashidi is not limited to its scholarly and endowment-related status; rather, its historical and architectural multilayeredness has turned the site into a complex case for the study of conservation and adaptive reconstruction. Following the decline of the Ilkhanids and subsequent destructive events, the complex acquired a military function during the Safavid and Ottoman periods. In particular, during the years known as the "Roman Interregnum of Tabriz" (Fetrat-e Rumiyeh-ye Tabriz), the Ottomans, given the strategic location of Kanān-Kuh and its command over the Mehran-Rud and the Tabriz plain, constructed a large fortress in this area and built the large southern tower as part of its defensive structure. Moreover, studies on the stepped structure of the eastern hill indicate that Rabʿ-e Rashidi possessed important water-supply infrastructures, including a water reservoir, qanats, and a network of ceramic pipelines. These elements demonstrate the role of the complex in water provision, settlement sustainability, resilience under siege, and the organization of urban services. Therefore, Rabʿ-e Rashidi can be understood as a historical, physical, and infrastructural context in which the question of conservation is not limited to the preservation of architectural remains alone, but is connected to the interpretation of its Ilkhanid, post-Ilkhanid, Safavid, and Ottoman layers, as well as to the understanding of the site's materials, functions, water-supply system, and defensive logic (Roshan et al., 2024). Fig. 2 illustrates the location and physical remains of Rabʿ-e Rashidi.

- **Biomimetics as the fundamental logic of resilience in architectural heritage**

In this study, biomimetics is positioned as the theoretical backbone; however, it is understood not as the formal imitation of nature, but as an approach inspired by the behavioral logic, adaptability, and self-regulation of biological systems. Numerous studies have shown that nature ensures survival under critical conditions through mechanisms such as self-healing, dynamic equilibrium, redundancy, and structural symbiosis (Bader et al., 2021; Zaki, 2023). Transferring this logic to heritage architecture requires a focus on processes and behaviors, rather than merely on form or technology.

- **The Transition from formal biomimetics to material-oriented biomimetics in historical reconstruction**

One of the key points derived from the analysis of the literature is that a substantial part of biomimetic

Fig. 2. Rab'-e Rashidi of Tabriz. Source: Authors.

approaches in architecture has remained limited to the structural or formal level, while the layer of "material behavior" has received considerably less attention. The theoretical framework of the present study addresses this gap by focusing on material-oriented biomimetics, where building materials themselves possess bio-inspired capacities for adaptation and repair. From this perspective, material is not regarded as a passive element, but rather as part of the resilient architectural system that interacts with its environment over time.

• Self-Healing lime-based materials and compatibility with conservation interventions

Lime-based materials, particularly mortars based on air lime and natural hydraulic lime, hold an important position in conservation interventions due to their mineral nature, breathability, controlled permeability, and chemical compatibility with many historic materials. Unlike modern cementitious materials, which—because of their high stiffness, low permeability, and behavioral incompatibility with historic substrates—may lead to stress concentration, moisture entrapment, and accelerated deterioration, lime mortars exhibit a more gradual and compatible behavior in relation to traditional materials. These characteristics allow lime to be understood not merely as a binding material, but as part of the conservation logic of restoration; a logic that emphasizes minimum intervention, relative reversibility, compatibility with the historic context, and the preservation of the behavioral continuity of materials. From this perspective, lime-based materials can enable a gentle, gradual, and adaptable intervention in the reconstruction and stabilization of damaged components of architectural heritage, without imposing heterogeneous mechanical behavior on the historic fabric (Bader et al., 2021; Zaki, 2023).

One of the most significant capacities of lime-based materials in relation to contemporary conservation approaches is their intrinsic self-healing ability. This capacity is mainly activated through processes such as recarbonation, secondary hydration, dissolution, and reprecipitation of calcium-based compounds, and the gradual filling of microcracks and active pores. In this process, when exposed to moisture, carbon dioxide, and environmental changes, the material gradually repairs part of its microscale damage and achieves greater microstructural stability. The significance of this feature in the restoration of historic buildings lies in the fact that healing occurs not through an aggressive external intervention, but in continuity with the natural behavior of the material over time. It is therefore aligned with the principles of heritage conservation, particularly compatibility, minimum intervention, and the avoidance of incompatible added systems (Beatty et al., 2022). Accordingly, Table 2 presents and compares different types of self-healing materials, their healing mechanisms, advantages, limitations, and their degree of relevance to conservation interventions.

• Bio-Lime as a material-oriented strategy for enhancing the resilience of historic heritage

At a more advanced level, Bio-Lime is introduced as

Table 2. Self-Healing Materials. Source: Authors.

Self-Healing Material Type	Self-Healing Mechanism	Scale of crack healing	Advantages	Limitations	Refrences
(Autogenous Concrete)	Rehydration, Carbonation, and Crystalline Additives and SAP	Small (≈ 100–150 µm)	Simple, system-independent, and cost-effective	Limited self-healing capacity and high moisture dependency	De Belie et al., 2018
Capsule-based exogenous self-healing concrete	Release of healing agents from microcapsules upon crack formation	Medium (≈ 300 µm)	Active self-healing and rapid functional recovery	Chemical incompatibility and challenges in industrial-scale production	Minnebo et al., 2017
(Vascular Concrete)	Biologically inspired tubular networks	Medium to Large (≤ 1 mm)	Multiple healing cycles and high recovery of mechanical strength	High complexity and limited compatibility with historic conservation	Minnebo et al., 2017
Endogenous Self-Healing Lime Mortar	Carbonation, Rehydration, and Pore Filling	Small (micro-cracks)	Historical compatibility, gradual performance, and reversibility	Slow healing rate and dependence on environmental conditions	Garijo et al., 2023
Lime Mortar Incorporating Crystalline Additives	Accelerating natural self-healing processes	Small to Medium	Enhancement of durability without significantly compromising authenticity	Limited availability of quantitative data	Nardi et al., 2020
Lime Mortar with Microcapsules	Release of lime-based binder upon crack formation	Small	Active self-healing within a historic substrate	Reduction in early-age compressive strength	Nardi et al., 2020
(Bio-Lime Mortar)	Bio-additives for enhancing carbonation and microstructural properties	Small (Gradual)	Cost-effective, non-toxic, and consistent with biomimetic principles	Greater emphasis on durability rather than direct crack-healing performance	Manoharan et al., 2022
Advanced Bio-Inspired Materials (Nano- and Smart Materials)	Self-Cleaning Surfaces and Nano-Biological Reactions	Variable	Enhancement of durability and environmental performance	High implementation cost and lack of long-term field-based evidence	Mocerino, 2024; Zaki, 2023

a strategy for strengthening the natural capacity of lime-based materials. Fermented bio-based additives, by modifying the microstructure of lime mortars, accelerating the formation of stable carbonate phases, and increasing material homogeneity, can facilitate a form of gradual, low-energy self-healing that is compatible with the historic substrate. Within the theoretical framework of this study, Bio-Lime is understood not merely as a technology, but as the simultaneous manifestation of the biological logic of nature and the indigenous knowledge embedded in traditional materials. This quality makes it a suitable option for the adaptive reconstruction of historic heritage (Vegas et al., 2022; Mackin, 2020).

As an emerging approach in sustainable architecture and construction, Bio-Lime encompasses a range of biologically enhanced lime-based systems whose primary objectives are to reduce environmental impacts, increase durability, and improve the adaptive performance of materials. According to this report, Bio-Lime technologies include four distinct yet complementary approaches: hemp–lime composites, bio-cementitious systems based on microbially induced calcium carbonate precipitation (MICP), lime mortars incorporating fermented organic additives, and biologically enhanced lime-based protective layers. The common feature of these approaches is their reliance on biological mechanisms to activate the natural processes of lime—such as carbonation, microcrack healing, and moisture regulation—

rather than the complete replacement of the logic of traditional materials. The findings of the report indicate that Bio-Lime is not so much a single material as a material-oriented framework, in which each subsystem responds to different architectural needs, ranging from non-structural and coating applications to the conservation and restoration of historic heritage (Lawrence et al., 2012).

From a theoretical perspective, the significance of Bio-Lime can be explained through its simultaneous connection to environmental sustainability, gradual self-healing, and compatibility with historic contexts. The report shows that in many applications—particularly in the restoration of historic buildings—properties such as breathability, moisture regulation, and the natural healing of micro-damage take precedence over high mechanical strength. In this regard, lime mortars with fermented bio-based additives and biologically enhanced lime coatings demonstrate the highest degree of compatibility with heritage conservation principles, due to their chemical affinity with traditional materials and their gradual behavior over time. The report further emphasizes that, despite the mechanical limitations and scalability challenges associated with some Bio-Lime technologies, their greatest practical success has been achieved in areas requiring minimum intervention, reversibility, and long-term durability. This reinforces the theoretical position of Bio-Lime as a material-oriented and bio-inspired strategy for the adaptive reconstruction of architectural heritage (Booth & Ljiljanam, 2022).

- **The historical–climatic context of Rabʿ-e Rashidi as a framework for adaptive interpretation**

In this study, Rabʿ-e Rashidi in Tabriz is approached not as a case for definitive practical intervention, but rather as a historical, climatic, and identity-based context for the adaptive interpretation of the theoretical framework. Due to its location in the cold climate of Tabriz, the vulnerability of its historic remains, its conservation sensitivities, and its connection to the cultural memory of the city, the site requires an approach in which conservation intervention is accompanied by the principles of compatibility, minimum intervention, gradual durability, and respect for the logic of traditional materials. From this perspective, lime-based materials, and Bio-Lime in particular, can be interpreted as a material-oriented strategy for strengthening the physical and cultural resilience of Rabʿ-e Rashidi.

The theoretical framework of the study does not limit resilience merely to the material or structural level, but understands it in relation to cultural resilience and indigenous knowledge. Studies of vernacular architecture show that many traditional construction patterns inherently possess a biomimetic logic and have provided resilient responses to crises through local materials, climate-responsive forms, and gradual construction processes (Mackin, 2020; Vegas et al., 2022). From this perspective, the use of lime-based materials and Bio-Lime is not only a technical choice, but also a cultural and identity-based one.

Methodology

The present study is analytical–comparative in nature and applied–developmental in terms of its objective. It seeks to propose a conceptual framework for the adaptive reconstruction of historic architectural heritage based on biomimetic inspiration and emerging technologies through a systematic analysis of previous literature and studies. The research is grounded in qualitative content analysis and comparative inference to theoretically and structurally explain the relationships among the three main axes of the study: biomimetics, adaptive sustainability, and cultural resilience.

In the first stage, the research data were collected through a systematic review of scientific literature published between 2015 and 2024. For this purpose, the Semantic Scholar, OpenAlex, and Elicit databases were used, and a total of 50 articles related to the keywords Resilient Architecture, Biomimetic Design, Adaptive Reconstruction, and Cultural Heritage were identified. Following a screening process based on criteria such as a focus on historic heritage, the application of biomimetic principles, and relevance to contexts of natural or human-induced crises, ten reliable studies were selected for final analysis, including works by Mackin (2020), Bader et al. (2021), Lucanto et al. (2024), and Mocerino (2024). The qualitative data extracted from these articles were coded and classified according to indicators such as type of heritage, type of crisis, biomimetic principles employed, technologies used, and empirical outcomes.

In the second stage, the extracted findings were evaluated through comparative analysis in order to identify similarities and differences among biomimetic approaches across different contexts. Then, using conceptual derivation and comparison among existing theoretical concepts, a conceptual model of adaptive reconstruction based on biomimetics and digital technologies was developed. This model was organized around four main components: biomimetics, adaptive sustainability, digital technology, and cultural resilience. Finally, the theoretical validity of the model was assessed through comparison with the frameworks proposed in the studies of Mocerino (2024) and Fatigusoa et al. (2018), to evaluate its coherence and transferability to the context of Iran's architectural heritage. A synthesis of the findings derived from the review of previous studies, along with the theoretical orientation of the article, is presented in Table 3.

Findings and Discussion

The findings derived from the systematic review and comparative analysis of the studies indicate that the concept of architectural resilience in contemporary literature is often defined in direct relation to biomimetic principles. In this regard, nature is understood not merely as a source of formal inspiration but as a behavioral and functional model for responding to natural and human-induced crises (Mackin, 2020; Bader et al., 2021; Zaki, 2023). However, a closer examination of these studies reveals that a significant portion of biomimetic approaches in architecture remains limited to structural, formal, or digital-technological dimensions, with comparatively limited attention paid to the layer of "material behavior" and the role of materials in achieving resilience. This gap becomes particularly significant in the field of conservation and regeneration of historic heritage, where material is not only a carrier of structural performance, but also a bearer of identity and historical continuity.

The analysis of studies related to self-healing materials shows that, although self-healing has been introduced as one manifestation of resilient design, in practice it has largely remained confined to structural concrete technologies and has been less developed within the framework of conservation and regeneration of historic heritage. Common approaches, particularly autonomous systems based on capsules and vascular networks, despite their notable technical performance, have limited compatibility with heritage conservation principles and international charters due to their chemical incompatibility, implementation complexity, and irreversible nature. This indicates a meaningful gap between technological advances in smart materials and their applicability in sensitive historic contexts.

In contrast, the findings suggest that lime-based materials, owing to the natural logic of their formation and transformation, possess an inherent capacity for self-healing. This capacity is activated through processes such as rehydration, carbonation, and the gradual filling of pores, and, particularly under cyclic

Table 3. Synthesis of Findings and Theoretical Orientation. Source: Authors.

Relationship with the Proposed Model	Biomimetic-based approach	Crisis Type	Primary Focus	Author
Cultural Compatibility	Local Materials and Natural Forms	Climate-related	Vernacular Architecture	Mackin (2020)
Structural Compatibility	Nature-inspired design based on trees and shells	Explosion and seismic events	Beirut Port Reconstruction	Bader et al. (2021)
Data-Driven Support	Digital Modelling	Climate Change	Regenerative Design	Lucanto et al. (2024)
Enhanced Structural Performance	Smart and Self-Cleaning Surfaces	Seismic events and erosion	Nanotechnology in heritage conservation	Mocerino (2024)
Integration with Indigenous Knowledge	Traditional Bioclimatic Design	Multi-Risk	International Vernacular Architecture	Vegas et al. (2022)

loading conditions, leads to a significant increase in residual compressive strength and a reduction in microporosity. Such behavior indicates the activation of endogenous healing mechanisms within the material and positions lime-based materials as a compatible, gradual, and adaptable option for conservation interventions in damaged historic sites; an option aligned with the restoration philosophy of minimum intervention and reversibility.

The findings related to Bio-Lime and bio-based additives indicate that the integration of fermented organic materials with lime mortars can purposefully enhance this inherent capacity. Through the modification of pore structure, the acceleration of stable carbonate phase formation, and the improvement of microstructural homogeneity, biological compounds can provide the conditions for a form of gradual, low-energy, and sustainable self-healing. A notable point is that these processes operate without relying on complex technologies and in continuity with the biological logic of nature. This makes Bio-Lime a distinctive example of functional imitation of nature at the material scale and places it at the core of biomimetic and adaptive sustainability approaches.

From a theoretical perspective, the comparative analysis shows that self-healing lime-based and bio-based materials can be interpreted as a material-oriented manifestation of biomimetics in resilient architecture. Unlike many biomimetic approaches that remain limited to formal or structural imitation, here the material itself, similar to a biological system, is capable of responding, learning, and gradually adapting over time (Bader et al., 2021; Zaki, 2023). This characteristic establishes a direct relationship between biomimetics, material behavior, and physical resilience, demonstrating that resilience can be elevated from the level of form and system to the microstructural level of materials.

Finally, the results indicate that despite the considerable capacities of Bio-Lime and self-healing lime-based materials, the lack of quantitative evaluation frameworks and data-driven decision-making models has hindered the transfer of these capacities into practical strategies for the regeneration of historic heritage. Most existing studies have been limited to qualitative descriptions of improvements in material durability and performance, while the comparative assessment of intervention scenarios, the weighting of sustainability indicators, and the prediction of long-term material behavior have received less attention. This finding highlights the necessity of integrating bio-based self-healing materials with tools such as digital twins, data-driven modeling, and multi-criteria decision-making methods, in order to advance the adaptive reconstruction of architectural heritage from the conceptual level to a strategic and implementable level (Esposito et al., 2021; Lucanto et al., 2024).

Conclusion

The results of this study indicate that the reconstruction

Table 4. Relationship among the Main Components of the Biomimetic-Based Conceptual Model for Adaptive Reconstruction. Source: Authors.

Role and Outcome in Adaptive Reconstruction	Examples / Cases	Core definition	Component
Enhanced Structural Resistance and Energy Efficiency	Structures of trees, shells, bamboo, and skin	Nature-Inspired Structural and Behavioral Principles	(Biomimicry)
Functional continuity and adaptation to environmental conditions	Adaptive and retrainable systems	Dynamic adaptability and temporal learning	(Adaptive Sustainability)
Risk Analysis, Simulation, and Evidence-Based Decision-Making	Digital Twin ‹HBIM‹ VR	Data-Driven Tools for Documentation and Modeling	(Digital Technology)
Meaningful reconstruction and the preservation of cultural continuity	Community participation and cultural revitalization	Continuity of Cultural Identity and Collective Memory	(Cultural Resilience)

of architectural heritage in the face of natural and human-induced crises requires a transition from reproductive and fabric-oriented approaches toward dynamic, adaptive, and material-oriented frameworks. Within such frameworks, "resilience" is not defined merely as physical resistance, but as the capacity for adaptation, gradual repair, functional continuity, and the preservation of meaning over time. The findings show that biomimetics, when it moves beyond formal imitation and relies on the behavioral and process-based logic of nature, can provide a theoretical basis for the adaptive reconstruction of historic heritage. In this regard, "material behavior" occupies a decisive position; in historic buildings, materials not only perform structural and protective roles, but also constitute part of the authenticity, historical continuity, and constructive logic of the building. From this perspective, the selection of conservation materials should be evaluated not only in terms of durability and performance, but also according to criteria such as chemical and mechanical compatibility, breathability, minimum intervention, the possibility of gradual repair, and coherence with the historic context.

Based on the comparative analysis of self-healing materials, it can be concluded that lime-based materials, compared with many contemporary self-healing systems—particularly concrete-based systems—demonstrate greater compatibility with the field of historic heritage conservation. Concrete-oriented self-healing systems, such as capsule-based, vascular, or industrial additive-based systems, may possess considerable technical potential at the scale of new structures. However, due to their high stiffness, implementation complexity, potential chemical incompatibility, reduced reversibility, and behavioral distance from traditional materials, they are not always suitable options for sensitive conservation interventions. In contrast, lime mortars and lime-based materials, owing to characteristics such as compatibility with historic materials, appropriate permeability and breathability, gentler mechanical behavior, the capacity for recarbonation, secondary hydration, and the gradual filling of microcracks, possess an inherent capacity for endogenous self-healing. Therefore, lime is not only a traditional and well-established material in restoration, but can also be redefined within the framework of material-oriented biomimetics as an active, time-dependent, and repairable material.

Within this framework, Bio-Lime, as an enhanced form of lime-based materials, provides the possibility of strengthening this natural capacity. Bio-based additives can improve the performance of lime mortar by modifying the microstructure, enhancing the carbonation process, increasing material homogeneity, and contributing to the gradual repair of micro-damage, without imposing an aggressive or heterogeneous intervention. The significance of this feature in restoration lies in the fact that the healing process, unlike many external technologies, is activated through the natural logic of the material itself and in interaction with environmental conditions. Therefore, lime-based materials and Bio-Lime, compared with hard, industrial, and incompatible materials, offer a more appropriate response to the requirements of historic restoration, as they establish a balance between durability, compatibility, minimum intervention, and long-term resilience.

The relationship between this framework and Rabʿ-e Rashidi in Tabriz can also be explained from this perspective. Rabʿ-e Rashidi, as a multilayered site with Ilkhanid, post-Ilkhanid, Ottoman, and Safavid historical backgrounds, contains diverse physical and infrastructural remains in which materials such as stone, brick, and lime-based mortars played an important role in the formation and continuity of architectural structures. The available evidence indicates that this complex is significant not only in historical and identity-based terms, but also in relation to materials, moisture, deterioration, climatic vulnerability, and the need for compatible intervention. It therefore provides an appropriate context for addressing the issue of self-healing lime-based materials. Accordingly, the reference to Rabʿ-e Rashidi in this study is not merely a case-based or decorative mention; rather, the site is introduced as a historical–physical context in which the central issue of the article—the necessity of selecting compatible, repairable, and low-intervention materials—can be understood in concrete terms.

On this basis, the use of lime-based and Bio-Lime approaches in the conservation reading of Rabʿ-e Rashidi can be proposed as a compatible strategy for adaptive reconstruction. This strategy is aligned with the logic of traditional materials, the principle of minimum intervention, breathability, chemical compatibility, and the need for long-term resilience. The study demonstrates that, compared with contemporary self-healing materials that are heterogeneous in relation to historic contexts, lime-based materials possess a greater capacity to connect indigenous knowledge, the natural behavior of materials, and the objectives of heritage conservation. Ultimately, the present study emphasizes the necessity of developing laboratory research, field evaluations, and performance assessments of lime mortars and Bio-Lime under the climatic and physical conditions of Rabʿ-e Rashidi, to transform this theoretical framework into an implementable strategy for the restoration and adaptive reconstruction of Iran's historic heritage.

EndNote

This article is derived from the ongoing doctoral dissertation of "Zahra Keynezhad" entitled "Material-Oriented Biomimetics in Resilient Historic Heritage Reconstruction: The Role of Bio-Lime as a Self-Healing Material in Adaptive Conservation (Case Study: Rabʿ-e Rashidi, Tabriz)." that under supervision of Dr. "Farhad Akhundi" at Tabriz Islamic Art University, Faculty of Architecture and Urbanism, Tabriz, Iran.

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