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Harnessing Local Wisdom for Sustainable and Resilient Architecture: Insights from Sana'a Old City

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Abstract

Clear evidence of increasing interest in vernacular architecture, driven by its energy efficiency and sustainability, can be observed in the research community and global architecture projects that have adopted strategies from vernacular architecture. This trend arises from climatic and environmental challenges and issues in the global building sector, including rising temperatures, increased CO_2 emissions, and resource depletion, all of which necessitate the adoption of sustainable architectural practices. However, a review of the content, themes, and findings of existing studies on vernacular architecture reveals an uneven geographic and climatic distribution of the research. This study aims to highlight the main domains of sustainable and resilient architecture in the Old City of Sana'a, a renowned heritage city that has received limited scholarly attention regarding its vernacular strategies for sustainability. This study combines archival and thematic analysis methods to investigate the sustainability and resilience domains of vernacular architecture. The results identified four interconnected domains that function as a unified systemic framework of sustainability and resilience in the city: traditional construction materials and techniques, climate-responsive design, spatial and functional efficiency, and architectural aesthetics. Together, these domains constitute an integrated system that has underpinned the longevity of the city over the centuries. By leveraging modern technology, such as digital documentation and simulation tools, these findings can provide pathways across design practice and offer transferable insights from this integrated system to contemporary contexts.

INTRODUCTION

The critical issues of global housing and its significant impacts on the environment and natural resources, rapid urbanization, and climate change can't be ignored, particularly the beneficial role of vernacular architecture, which warrants attention(Vellinga & Asquith, 2005). The emerging global energy and environmental challenges necessitate a significant transformation in building design philosophies, strategies, technologies, and construction methods. Vernacular architecture, shaped by cultural traditions, emerge from extensive trial and error and the expertise of local builders who understand their environmental context. These structures are significant for advancing climate-specific passive building technologies in contemporary architecture (Zhai & Previtali, 2010). Vernacular architecture, by definition, purpose, and design, represents the most harmonious architectural style in relation to the surroundings. Two significant aspects of vernacular architecture can serve as resources for contemporary design: a profound regard for and harmonious integration with the natural environment, as well as a comprehensive understanding of user demands (Creangă et al., 2010). Numerous studies of Vernacular architecture examine the features of residential structures within specific regions and the various social and cultural influences that have shaped their development (Oliver, 2006).

A substantial amount of literature was discovered regarding vernacular building traditions. The most comprehensive document is the Encyclopedia of Vernacular Architecture, a 4000-page compilation of studies by over 750 writers from 80 nations, assembled by Professor Paul Oliver of Oxford University and released in 1997 (Nabakov & Nabokov, 1999). Comprising two volumes dedicated to climate and the "vernacular responses" of numerous civilizations, alongside another volume centered on materials, resources, and production, it stands as the preeminent source for research in this field. A significant work is A Pattern Language: Towns, Buildings, Construction, by the architect and theorist Christopher Alexander (Alexander et al., 1977). He asserted that human societies had developed a universal and enduring architectural "language," which he refers to as "a quality without a name." (Alexander, 1979). His conceptual framework outlines essential patterns and ideas that have maintained the durability of human groups. Although these concepts have garnered both praise and criticism, they demonstrate the significance of integrating historical architectural knowledge into academic research and professional practice. Nonetheless, this knowledge is considerably underutilized in modern architectural and urban development.

Traditional knowledge, especially in ancient cities, provides established frameworks for ecological solutions, spatial efficiency, and communal resilience. Vernacular design encompasses ecologically adapted ideas that have developed throughout generations (Miri, 2016). Incorporating these concepts into modern sustainable design effectively addresses current global concerns while maintaining the inherent sustainability found in vernacular forms, particularly in context-specific applications. Consequently, vernacular solutions provide a significant supplementary foundation for promoting sustainable building design. The Old City of Sana'a, a UNESCO World Heritage Site, illustrates vernacular architecture characterized by the utilization of local resources, adaptability to climate, and social utility. The architectural designs and construction techniques reflect centuries of accumulated knowledge, effectively addressing environmental limitations and socio-cultural influences. This study presents two principal research questions: (1) What are the key domains of local wisdom practices in the vernacular architecture of Sana'a Old City that generate sustainable and resilient architecture? and (2) What insights can be taken from Sana'a's local wisdom practices to enhance sustainability and resilience in contemporary architectural goals without resorting to nostalgia or neglecting contemporary needs?

This study analyses the architectural sustainability and resilience practices inherent in the built heritage of Sana'a. It also highlights transferable concepts that may inform contemporary architecture, particularly in the context of developing countries.

LITERATURE REVIEW

Vernacular Architecture

Vernacular architectural heritage encompasses residences and other structures built by indigenous communities/peoples. Owners of the community typically construct vernacular structures. Experts do not design them; rather, they emerge from a collective process involving multiple generations, grounded in empirical knowledge. Vernacular architecture is frequently referred to as communal, popular, or folk architecture, even termed "architecture without architects." (Philokyprou et al., 2025; Rudofsky, 1987). In alignment with this viewpoint, vernacular architecture is frequently regarded as the antithesis of high or monumental architecture. Nonetheless, "vernacular" continues to be the prevailing term employed by researchers (Francaviglia & Rapoport, 1969; Oliver, 1997). It is intricately connected to cultural and social dimensions, and Vernacular (Genadt, 2019) intellectual resources, and has minimal ecological impact, thereby ensuring sustainability.

Vernacular architecture globally is vibrant and encompasses both concrete and intangible elements that actively contribute to current society by providing a morphological response to the socioeconomic and cultural characteristics of communities (Philokyprou, 2017).

Resilience in Architecture

Architectural resilience was defined by (Genadt, 2019) as a building's ability to assist a community in regaining stability following a large organizational shift or upheaval. A community may be a village, a city, or a country. This article defines architectural resilience as both a single structure and its larger surroundings. This description encompasses architecture's physical, aesthetic, and symbolic qualities. The concept of 'resilience' in urban and architectural science denotes the capacity of human environments to endure shocks and disturbances without significant changes to their functional, physical, social, and economic systems. The concept of resilience perceives the environment as always changing; thus, resilient architecture necessitates a dynamic framework, predominantly defined by flexibility and adaptation. Vernacular architecture, rooted in responses to dynamic elements such as microclimate, local materials, and indigenous cultures, can fulfill the criteria for resilience (Correia et al., 2014; Dipasquale et al., 2025).

Local Wisdom and Vernacular Architecture

Local cultural wisdom is a perspective on life and information on various aspects of life that are embodied in community activities, which have been carried out for generations from ancient times and have endured to this day. Cultural traditions have guided this life. Local wisdom in its various forms can be values, norms, or rules and methods that all community members use, understand, and share in their interactions (Pratiwi & Wikantiyoso, 2022). Local wisdom plays a fundamental role (Syuryansyah & Habibi, 2024) in vernacular architecture. Local wisdom is often a distinctive trait of a community that frequently recognizes and articulates it in diverse contexts. The community recognizes and transmits elements such as values, norms, ethics, beliefs, traditions, and regulations (Pajarianto et al., 2022). Local wisdom encompasses the community's comprehension of human beings and social interactions, as well as the understanding of the relationship between humans and nature, and the methods for establishing sustainable relationships with the environment (Hidayati et al., 2020). Modernism served as both the dominant architectural doctrine and its aesthetic expression throughout the past century, originally aimed at innovatively re-imagining and reconstructing the physical environment using novel materials and rapid processes, with detrimental consequences for the human environment.

It can be contended that architectural Modernism emerged as a globally predominant ideology, shaping the discourse of architecture while largely disregarding and marginalizing alternative perspectives, thereby constraining the evolution of traditional architecture and ultimately relegating it to the status of a mere 'heritage artifact (Samalavičius & Traškinaitė, 2021). In his book "The Architecture of Communities," Leon Krier discussed the impact of modernism on architecture and urbanism, stating that modernists claimed to have solved all built environment concerns only 50 years ago, whereas Modern architecture lacks essential elements such as privacy, grandeur, decoration, craftsmanship, history, and tradition (Krier, 2009). Krier has frequently contended that the primary issue lies not in architectural Modernism itself, but rather in its hegemony and global dominance since the latter portion of the twentieth century. The primary damage attributed to architectural modernism occurred when this ostensibly innovative style began to dominate all other architectural approaches. According to Krier, the critical inquiry should shift from determining the victor of the war to enhancing quality across all factions through the establishment of intelligent, democratic competition, pluralistic education, and nonpartisan, effective criticism.

Vernacular Architecture and Sustainability

The steady growth of the global population causes a high need for rapid construction in a short time, which puts pressure on natural resources. These speeds and pressures to cope with the needs led to the emergence of enormous, serious problems on different scales. For instance, waste production, elevated energy usage, and both internal and external pollution, CO2 (Hall) emissions, environmental degradation, and reliance on non-renewable resources (Al-Gahtani et al., 2016). As a result, the sustainability movement has emerged as a viable strategy for addressing the ecological crisis by incorporating environmental, cultural, and economic factors. Thus, modernist architecture has comprehensively integrated sustainable development principles (Bhatt & Macwan, 2016). Consequently, sustainable architecture emerged as a prominent trend in the early twenty-first century (Mousavi & Mahdavinejhad, 2013) to create structures that are both practical and aesthetically pleasing while also being environmentally responsible. Numerous sustainable design approaches, standards, and evaluation tools have been established globally to promote energy efficiency, occupant well-being, and resource conservation in architecture across various scales (Mba et al., 2024).

For instance, these encompass the United Nations Sustainable Development Goals (UN-SDGs), the European Performance of Buildings Directive (EPBD), ASHRAE Standard 189, initiatives from the International Energy Agency (IEA), and programs by the Chartered Institution of Building Services Engineers (CIBSE) in the UK (Abdelrazek & Yılmaz, 2020; ; Li et al., 2019; Mousavi & Mahdavinejhad, 2013). Nonetheless, many current design approaches and standards originate in developed nations, often requiring significant technological advancements, resources, and infrastructure for implementation. Such requirements can limit their applicability in diverse settings, particularly in developing countries where access to advanced technology and resources may be restricted. Thus, examining and analyzing the core principles and methodologies of sustainability is crucial in architecture. Start with a deep investigation into the sustainability embedded in vernacular architecture, which has evolved through the utilization of local resources and technologies to foster a harmonious relationship between buildings and their surrounding environments (Dabaieh et al., 2021a; Gou & Xie, 2017; Nasir & Kamal, 2021). Vernacular architecture emphasizes efficient resource use, reducing energy and material consumption while reflecting environmental, cultural, and social values (Rosaleny Gamón, 2020).

Modern buildings account for over 40 % of global energy consumption and 30 % of annual greenhouse gas emissions; on the other hand, vernacular design has shown significant potential in minimizing energy and material consumption (Dabaieh et al., 2021a, 2021b; Miri, 2016). Vernacular design principles and strategies act as a complementary framework for attaining sustainable building designs. Furthermore, Vernacular architecture has the potential to be a valuable source of inspiration and learning material to promote more influential and meaningful modern architectural strategies (Al-Sallal & Rahmani, 2019; Dabaieh et al., 2021a; Yazici & Aslan, 2019). Incorporating vernacular concepts into sustainable architecture effectively promotes sustainability and addresses contemporary global concerns while maintaining the intrinsic sustainability of vernacular design within its specific setting (Amiri & Vatandoost, 2017). A multitude of studies positively recognise the environmental sustainability of vernacular architecture.
This fact has increasingly gained significance in advancing a sustainable future for the built environment, as emphasised by Tomovska and Radivojević (2017) (Tomovska & Radivojević, 2017) and Keskin and Erbay (2016) (Keskin & Erbay, 2016). A substantial body of scholarship exists on vernacular architecture Fig.1 in Asia and Europe, although the other continents have a markedly lower volume of scholarly publications on the subject, according to the synthesis and evaluation of sustainable features of vernacular architecture.

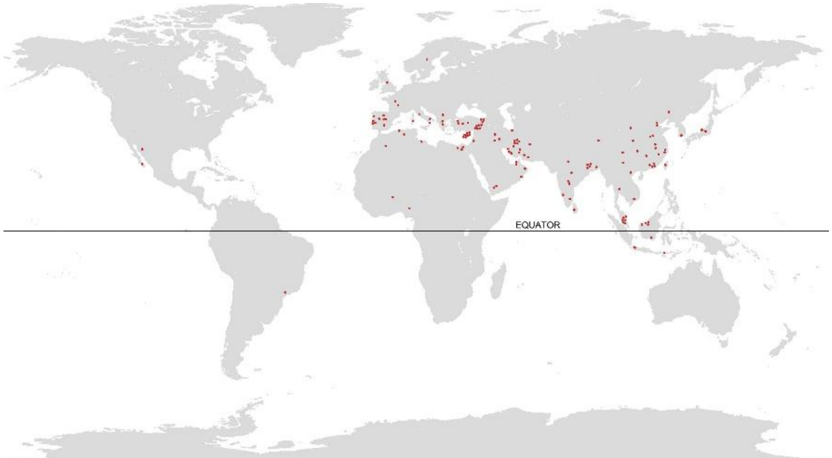

Fig. 1. The distribution of the studies on vernacular architecture until August 2018
Source: (Nguyen et al., 2019)

Therefore, this study aims to address the lack of geographical and climatic considerations in the global discourse on sustainable vernacular architecture through thematic analysis of the local knowledge of vernacular architecture in Sana'a old city. Existing research on Sana'a's old city has narrowly focused on materials and passive design. This study argues that vernacular knowledge operates across multiple other domains that remain undiscovered, such as cultural practices, social structures, and environmental adaptations that influence sustainable architecture in the region. Vernacular architecture, a substantial library of enduring design concepts, provides essential insights for modern sustainable construction techniques (Al-Sallal & Rahmani, 2019). A plethora of sustainable architecture examples worldwide inspires architects to draw from historical antecedents (Alelwani et al., 2020).

Fig. 2. Contemporary high-tech architecture incorporating elements of vernacular practices.
A: Estidama Mosque, Abu Dhabi; B: Bahrain World Trade Center (BWTC), Bahrain; C: Arab World Institute Museum, Paris.
Source: [(Parametric Architecture 2025)]

For example, Adobe construction, utilizing clay or mud, has served as a primary building material for millennia across many inhabited regions globally (Bodach et al., 2014; Saljoughinejad & Sharifabad, 2015; Yorulmaz, 1981).

Contemporary architecture utilizes numerous vernacular practices, including courtyards, wind catchers, thick walls, and Mashrabiya, for passive design. The Bahrain World Trade Center (BWTC) adapted the traditional wind tower function. It incorporates three large wind turbines between its twin towers in application projects shown in Fig. 2, which can supply up to 15% of the building's energy needs. Estidama Mosque certification through the adoption of passive design solutions, such as perforated panels that function such as Mashrabiya in vernacular architecture, to achieve a 50% reduction in energy consumption. The same strategies were applied to the Arab World Institute museum, where motorized diaphragms with sensitive sensors were opened and closed to control the amount of light and heat entering the building (Albinali, 2025; El Amrousi, 2017; Saeed, 2017). These projects proved that knowledge acquired from indigenous architecture is exceedingly valuable and infeasible to employ vernacular architectural models in a formulaic fashion within contemporary culture (Nguyen et al., 2019).

METHODS

This study combined two research methods: archival research and a document-based thematic method. First, archival research was conducted to collect studies on sustainable and resilient features of vernacular architecture in general and on Sana'a Old City in particular. The collected materials included visual and Cultural documentation, historical records, previous academic studies, and textual sources. These materials were obtained from database resources to which the authors were granted access rights. This method is a common one applied to architecture studies. Subsequently, a document-thematic approach was used to organize findings into four thematic domains. Many studies have utilized this method (Jain et al., 2022; Li et al., 2023; Sentia et al., 2023; Zhu et al., 2023). To ensure the validation, sources were limited to verified archives, academic databases to which the author has access, UNESCO documentation, and historical books about Sana'a's old city.

A systematic keyword search was conducted using the terms: vernacular architecture, sustainability, resilience, traditional construction, Sana'a old city, passive design, and vernacular principles. And then applied Adopted (Braun & Clarke, 2006) definition of the thematic analysis method for analyzing and reporting themes within data (Boyatzis, 1998). Through six-phase to identify the main themes of the local practices and knowledge in Sana'a vernacular architecture as shows in Figure 2. (1) familiarization archival data, (2) generating initial codes that selecting features of vernacular knowledge and practices in architecture,(3) searching of the themes by extracting the significant vernacular elements in Sana'a old city,(4) review the elements for preparing the themes, (5) defining and naming the themes according to their functions, (6) and finally pronouncing the themes that refer to the main domain of vernacular practices and knowledge of the sustainability and resilient architecture. These domains work in a bidirectional manner, express the practices, knowledge, and lead to the sustainability and resilience of vernacular architecture.

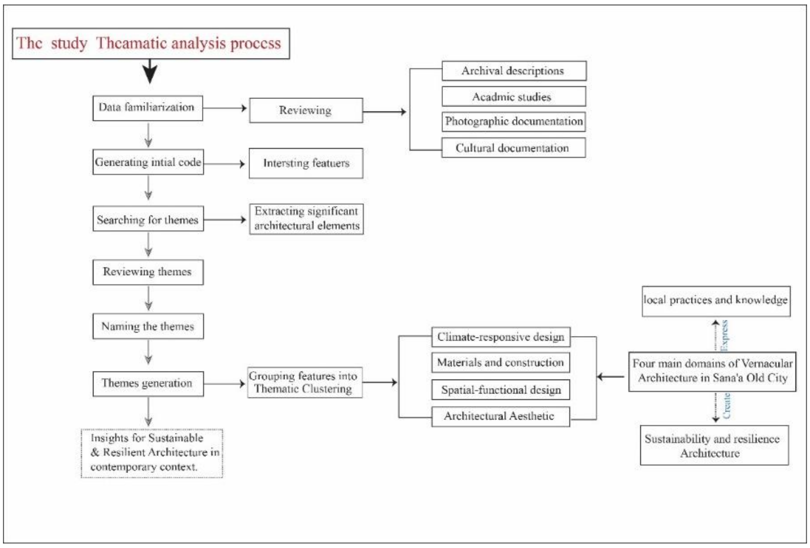

Fig. 3. Study thematic analysis
(Source: authors)

Study Subject

This study analyzes the residential architecture in Sana'a Old City, a UNESCO World Heritage Site since 1986, which is famous for its distinctive architectural style and complex urban fabric. Sana'a Old City is located in Sana'a, the capital of Yemen, a country in Southwest Asia (UNESCO World Heritage Centre, 2023). Fig.4 illustrates the geographical location of Sana'a Old City. The old city of Sana'a was selected for several reasons, first as a heritage site renowned for its distinctive architecture situated in a hot-arid climatic zone at an elevation of 2200 m for over 2,500 years, which embodies numerous design practices to respond to this condition and remain standing for today.

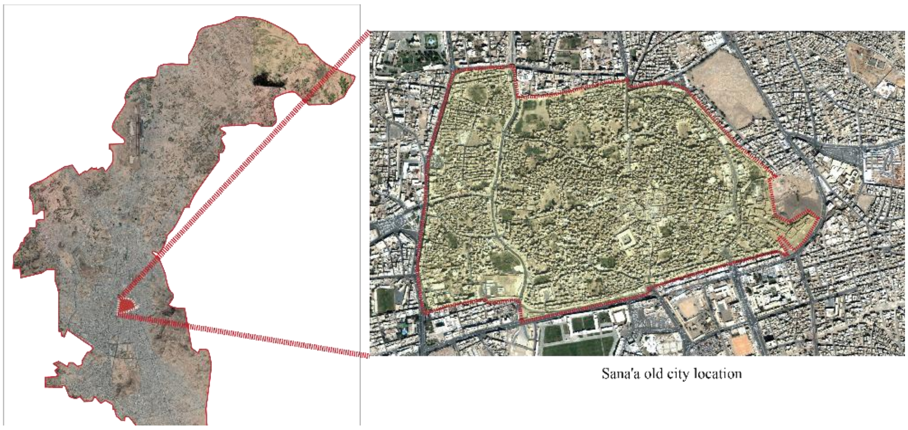

Fig. 4. Location of the study area
(Source: authors)

Second, most studies have primarily focused on its materials and passive strategies design while overlooking the other dimensions of the city's adaptation. Moreover, Sana'a, the capital city, currently experiences inefficient contemporary construction while possessing valuable, remarkable inherited knowledge on traditional buildings in the old city. These reasons make Sana'a's old city meaningful to identify the main domains of vernacular knowledge and strategies on Architecture and how insights can be transferred in the contemporary context. Sana'a's residential buildings, known as tower houses, are characterized by their multi-story design and are shaped by various environmental, natural, social, economic, cultural, and religious factors. Their resilience and functionality result from established principles, rules, standardized planning, and architectural and construction strategies, along with environmentally compatible building materials and techniques. Figure 4 shows the vernacular architecture style of Sana'a's old city.

Shorter section, fewer grammar issues overall, but there's a structural problem (Figure 4 referenced twice for two different things) and a couple of sentence-level fixes needed. Here's the revised version:

Fig. 5. Old Sana'a's vernacular architecture
(Source: UNESCO World Heritage Centre, 2025)

RESULTS AND DISCUSSION

Thematic Analysis and Discussion

Through the thematic analysis of the academic references and the archival documents of Sana'a old city. Local wisdom of vernacular architecture across the globe comprises skills and accumulated knowledge that are shaped by various factors, including environmental, cultural, social, and religious factors. These generate practices and strategies that meet the people's needs and respect the surrounding environment. That generated sustainable and resilient architecture. Looking at Sana'a's old city as shown in Fig 6. The core concept of local practices and knowledge in the architecture of Sana'a Old City, and the leading principles of sustainability and resilience.

The local practices and accumulated knowledge collaboratively establish a cohesive framework that shapes the various architectural elements and systems. Thus, functioning as an interrelated system, where spiritual beliefs, ethical standards, Values, norms, traditions, and regulations respond to the specifics of environmental, social, cultural, and religious conditions. These then express a reflection of local knowledge and indigenous wisdom in Architecture. This wisdom is then expressed across four thematic interconnected domains of Sana's Old City architecture: (1) climatic-responsive design, (2) materials and construction, (3) spatial-functional organization, and (4) architectural aesthetics and symbolic expressions. Each main domain has secondary branches of elements that play a critical role in a living model of sustainable architecture characterized by adaptability, durability, resilience, and resource efficiency.

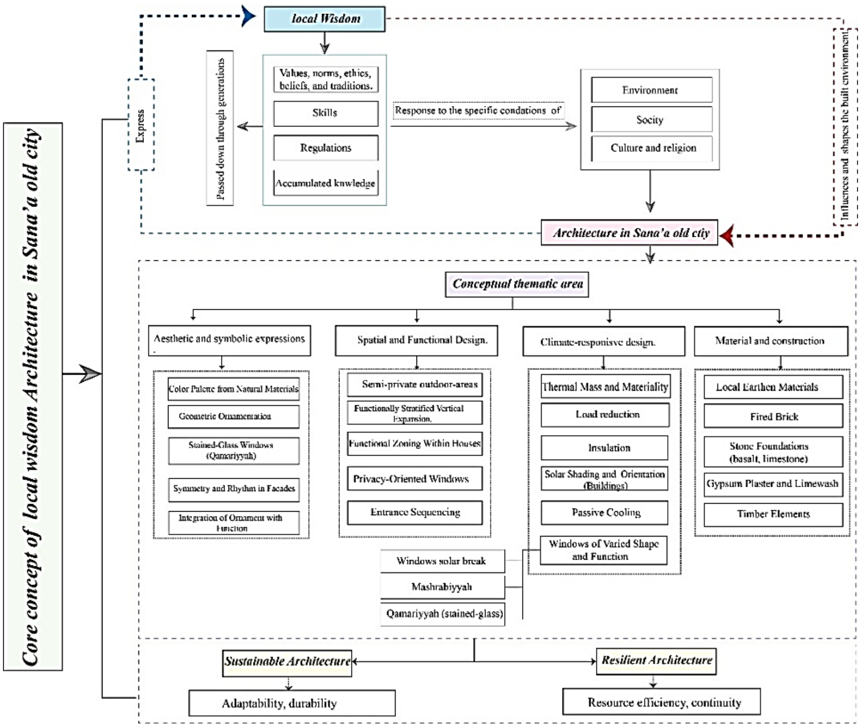

Fig. 6. The core concept of local practices and knowledge in the architecture of Sana'a Old City, and the leading principles of sustainability and resilience
(Source: authors)

Traditional Construction Materials and Techniques

In ancient civilizations, individuals built their dwellings according to cultural conventions, available resources, geographical features, and specific needs. Individuals constructed them independently, based on the trials and errors of experience. Which, in turn, significantly influences the development of architecture. Geographical variations thus engender diversity in architectural traditions globally (Tawayha et al., 2019). For example, the Indus Valley Civilization, originating around 3300 BCE, primarily utilized mud bricks and wood for construction (Kumar & Gidwani, 2021; Panambur et al., 2012). Early Egyptians employed mud brick in their buildings, while palatial structures in ancient Egypt were crafted from stone and featured courtyards, a passive design strategy that mitigated heat (Spencer, 2023). Mesopotamia is renowned for its mud-brick architecture and ziggurats (Awan et al., 2019; Van de Mieroop, 1997). In Neolithic Çatalhöyük, Turkey, inhabitants built closely clustered mud-brick houses with flat roofs and no street-facing doors; instead, they accessed the interiors via the roofs (Kuijt, 2018). Teepees, utilized by Native American Plains tribes, are cone-shaped tents constructed from animal skins and wooden poles. Their design facilitates easy assembly and disassembly, making them suitable for nomadic lifestyles and enabling mobility across the plains(Wissler, 1927). Other civilizations are not detailed here, as neither the scope nor the space of this study will not be detailed here.

Thus, the physical and ecological environments profoundly influenced the architectural evolution of ancient civilizations (Awan et al., 2019). That is why traditional architecture is often considered a model for sustainable architecture. Additionally, many strategies that form the foundation of sustainable building are derived from the inherent qualities and adaptive characteristics of architectural traditions (Fernandes et al., 2014). Building techniques have been meticulously developed to align with the available materials, leading to the evolution of traditional principles over time in nearly all countries, tailored to the specific environmental conditions of each location. In Sana'a Old City, traditional construction demonstrates a remarkable fusion of functionality, aesthetic appeal, and environmental sustainability. Builders employed locally sourced materials combined with centuries-old techniques that have been preserved and transmitted across generations. Using basic tools, wooden scaffolding, and manual labor for carving and erecting structures, construction methods have remained largely unchanged for hundreds of years (Soltanzadeh & Moghaddam, 2015). Tower houses are constructed through a stratified system of local materials, a layered material that integrates local resources, climate adaptation, and aesthetic functions. The study categorizes these into four layers as follows: (1) Foundations layer: Basalt, sandstone, and white stone; entrances constructed with black volcanic stone (Habash), (2) Walls layer: Ajur (baked bricks) with clay-soil mortar and gypsum finishes, including belts of Ajur and gypsum, as well as plaster work moldings that adorn window edges and decorative motifs on the facades. black stone; walls, floors, and ceilings finished with gypsum plaster, carvings, shelves (safif), and tracery (takhrim) for window fanlights (‘aqd), (3) Interiors layer: Alabaster and marble panels in some openings; staircases and structural elements reinforced, and (4) Upper layer: Timber beam structures with clay and sand–lime mortar, covered with gypsum-based finishing coats. Exterior protection layer: Qudad plaster and rainwater gutters. The roles of the material layers in responding to the climate and their constructional functions are presented in Table 1, and further elaborated under the second thematic point, Climate-responsive design**.**

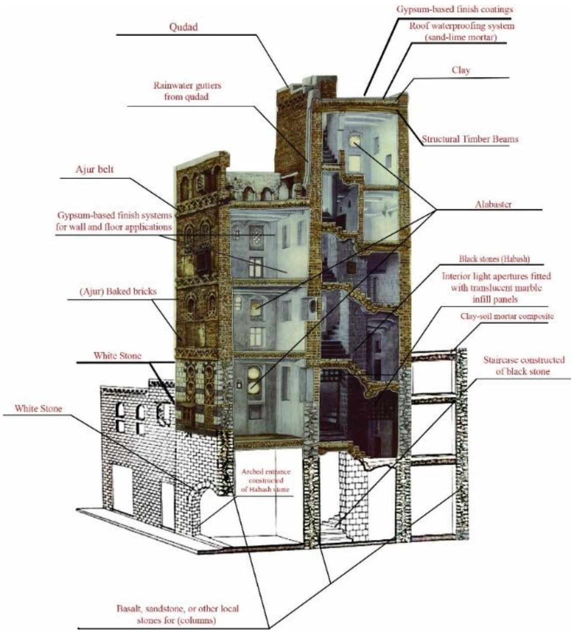

Fig. 7 Typical juxtaposition and layering of building materials in vernacular architecture (stone, brick, timber, lime, plaster, etc.) (Source: author)

Table 1. Building Materials and Their Architectural Roles

Local Name	Raw Materials	Properties	Use
Stone	- Basalt, sandstone - Habash (black lava stone). -Waqis (hewn stone) - Limestone.	-Strong and durable. - Retains heat. - Colors: white, dark grey, light grey, wheat, yellow, desert yellow, or black.	- Foundations and lower levels. - Foundation walls (50-60 cm). - Columns, arches, bathroom floors, stairs. - Decorative elements. - Stone mashrabiyas. - Arches, belts, muqarnas.
Ajur	Burnt clay bricks / baked bricks.	- Light reddish-brown. - Earthy aesthetic. - Excellent thermal insulation.	- Upper floors (25-30 cm walls). - Minaret bodies. -Decorative belts, arches, bands. - Ajur mashrabiya.
Qudad	Volcanic ash and lime-based coating.	- White/charcoal- grey. - Durable and water-resistant.	- Protective layer for mud bricks.
Qass	Gypsum.	- White or grey. - Easy to carve and shape.	- Wall/ceiling plaster. - Decoration: geometric patterns, window outlines.
Al-malaj (clay)	Clay mixed with straw/organic materials	-Color varies by minerals.	-Fills gaps between stones/bricks.
lime	Slaked lime (calcium hydroxide).	- White powder. - Expensive material.	-Wall/roof painting and refinishing.
Earth			Surface levelling

Local Name	Raw Materials	Properties	Use
Wood	Trunks, branches, and twigs of local timber (juniper, acacia, Al-Alab, etc.)	- Lightweight. -Natural insulation.	-Doors, windows, ceilings. -Decorative carvings.
Alabaster	A translucent stone	- White and yellow colors. - Soft texture. -Light-diffusing properties.	-Used in Qamariyyah (light-diffusing screens). - Creates a soft, warm glow. - Decorative panels.
Stained Glass	Stained Glass	-Vibrant colours: blue, green, red, yellow. - Translucent.	- Coloured glass pieces are intricately arranged in geometric patterns in Qamariyyah -Adding colour and intricate detail in Qamariyyah windows.
Iron and other metals	Iron and other metals	-Dark grey to lead grey. - Highly mouldable, sculptable, and capable of interlocking formations	Used on all floors, with low density in residential buildings and relatively higher density in defensive structures.

Source: (Al-Kahtani & Al-Darzi, 2007; Al-Taher, 2005; Lamprakos, 2005; Lewcock, 1986)

Climate-Responsive Design

The ecological design of Old Sana’a presents a sustainable framework developed over 2,500 years by Indigenous populations, specifically adapted to the region’s semi-arid environmental constraints. At the core of this knowledge system is climate-responsive architecture that integrates load-reduction techniques, high-performance insulation, solar shading, and passive cooling strategies. This comprehensive system demonstrates a deep understanding of the environment and achieves a harmony between structural stability and environmental responsiveness. For instance, Ajur (fired bricks) is used as the primary wall due to its optimized density and high thermal capacity. A typical 30-cm-thick fired-brick wall exhibited significant thermal mass, with conductivity ranging from 0.6 to 1.0 W/m·K depending on the clay composition and vitrification process. These walls provide a thermal lag of 8 to 12 hours, effectively reducing temperature variations.

Table 2. Properties and Values for 30 cm thick fired bricks.

Features	Value\Description
Materials	Clay is fired at approximately 900-1000 °C
Density	Approximately 1,800-2,000 kg/m³
Compressive Strength	7-20MPa
Thermal Conductivity (λ)	0.6-1.0 W/m·K
Specific Heat Capacity (c)	Approximately 840J/kg·K
Thermal Diffusivity	Approximately 3.5×10^{-7} m²/s
Thermal lag (30cm wall)	8-12 hours
U-Value (30 cm wall)	Approximately 0.8-1.2 W/m²·K
Moisture Regulation	Less breathable than adobe
Durability	Resistant to rain and weathering

(Source: The Chartered Institution of Building Services Engineers [CIBSE], 2009; CIBSE, 2015; Minke, 2021)

To evaluate the hydrothermal performance of using local materials in Sana'a's old city, this study synthesized property data from established construction literature (Table 3), addressing the scarcity of site-specific empirical analyses regarding their role in Sana'a residential typologies. Volcanic and basalt stones, with densities ranging between 1800 and 2970 kg/m³ and thermal conductivity of 1.0–4.2 W/m·K, act as robust structural cores. These materials store and slowly release heat with an 8–12-hour transfer delay. Furthermore, low properties provide a natural barrier against humidity ingress, ensuring long-term stability despite limited insulating properties. Medium-density stones, such as sandstone and limestone (1500–2700 kg/m³), combine adequate strength (20–150 MPa) with moderate thermal conductivity (1.3–3.0 W/m·K), supporting both durability and thermal buffering.

Finishing layers, including Qudad and gypsum plasters, have lower conductivity values (0.3–1.0 W/m·K) and vapor permeability, allowing walls to “breathe” while preventing water ingress. Conversely, while Gypsum plaster is susceptible to dampness and lacks insulating value, its high interior reflectivity enhances natural illumination and aesthetic quality. Clay mortar is used to fill gaps and smooth surfaces for cladding due to its proficiency in moisture regulation. To protect the roofs from seasonal rains, the roof system integrates timber, clay, and Qudad to offer thermal insulation and moisture protection. For the interior, alabaster functions as translucent and reflective, adding light.

Table 3. Traditional Building Materials in Sana'a's Old City and Their Climate-Responsive Performance

Category	Material	Density (kg/m³)	Thermal conductivity (W/m·K)	Compressive strength (MPa)	Humidity Response
Natural Stones	Yemeni volcanic Stone (Al-Habash)	1800-2400	1.0-2.0	20-80	Low permeability
	Basalt (Dense)	2600-2970	1.8-4.2	80-200	Very low permeability
	Sand stone	1500-2700	1.3-2.5	20-170	Varies with prosperity
	limestone	2200-2700	1.5-3.0	25-150	Low to moderate permeability
	Gypsum Rock	2100-2400	1.3	20-40	Soluble in water
Mortars \& Plasters	Quada plaster	1800-2000	0.8-1.0	8-15	Waterproof yet vapor-permeable
	Gypsum plater	1200-1500	0.3-0.4	2-5	Moisture-absorbing
	Clay/Soil mortar	1600-1800	0.6-0.9	1-3	High hygroscopic regulation

Source: (Al-Jolahy et al., 2017; Prakash & Pham, 2023)

The composite building envelope with the materials mentioned above minimizes thermal exchange, providing high thermal lag between the interior and exterior environments. Helping to reduce internal temperature variations, thus ensuring thermal stability throughout the day. Study by (Ghalib 2010) The thermal simulation analysis of vernacular buildings in Sana'a's Old City demonstrated significant thermal performance. Internal conditions reveal limited temperature variation, approximately 1.5°C in summer and 1.4°C in winter; external conditions display significant fluctuations, approximately 13.2°C in summer and 11.9°C in winter. This demonstrates how local materials effectively serve as a passive thermal regulator. (Table 4) presents a summary of the simulation results regarding the performance of traditional building envelopes in the Old City of Sana'a.

Table 4. Thermal Performance of Traditional Building Envelopes in Sana'a's Old City

Temperature Characteristics				
Season	Temperature(°C)	Internal Disparity(°C)	External Disparity (°C)	Internal-External Difference(°C)
Summer	Internal: Max 25.5-Min 24.0 External: Max31.6-18.4	1.5	13.2	7.6
Winter	Internal: Max21.1-Min19.7 External: Max23.6-Min-11.6	1.4	11.9	9.2

Source: Authors adapt (Ghalib, 2010)

The rectangular morphology of the Sana'a house is a critical component of its orientation strategy. By aligning the elongated axis of the building structure stretches from east to west. The longer sides of the building face north and south, maximizing the surface area available for controlled solar gain and natural ventilation. Shorter facades oriented east and west to reduce exposure to intense low-angle solar radiation. Table 5 summarizes the shape and orientation of the building.

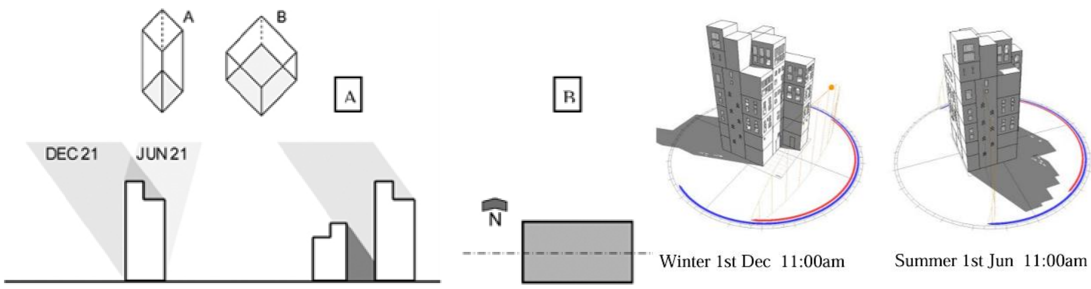

Fig. 8. Building shape and solar orientation, (a) The effect of the tower building shape, (b) The sun path in traditional Sana'a on the thermal gain in winter and summer
Sources: (Alabsi 2013, reda Abdallah, Hassan et al. 2020)

The size and shape of apertures (windows and vents) in tower buildings respond to climatic conditions. This responsiveness is manifested through a range of aperture types. Figure 8 illustrates the various aperture elements' roles and interactions in their function as a dynamic airflow system; natural lighting minimizes radiation.

Qamariyyah, typically circular, semi-circular, or rectangular in shape, serves to diffuse and filter light, thereby improving indoor illumination. Mashrabiyyah facilities: Cooling airflow, providing shading, and enabling privacy through one-way visibility. By contrast, observation windows serve a more social function, allowing residents to monitor street activities while remaining unseen. Tiny vents (Alshaqaus) facilitate passive air convection, while water-cooling apertures have historically been used to preserve food and cool water through evaporative processes. For directing air inside the building and enhancing effective cross ventilation during both day and night, Malqaf was used for this purpose, which is the local name for wind catchers. In addition, wooden solar breakers, both horizontal and vertical, integrate ventilation and shading. They serve dual roles: shielding interior spaces from intense sunlight and rain while also regulating the flow of hot or cold air across the facade.

Table 5. Bioclimatic Design Strategies in Sana'a's Old City: Solar Orientation and Environmental Response

Design Parameter	Environmental Observation	Architectural Response and Performance
Building Massing	Rectangular Prism morphology	Thermal mass optimization and construction efficiency.
Façade Orientation	Elongated north-south elevation; minimized east-west exposure.	Reduced solar gain on high-radiation facades year-round.
Winter Solar Performance	High solar radiation on the southern façade, minimal exposure on the northern façade.	Strategic southern orientation for passive solar heating in the cold season.
Summer Solar Performance	Increased radiation on the northern façade; the southern façade is largely self-shaded.	Overheating mitigation through optimal seasonal orientation and self-shading of the southern façade.
Wind Exposure	Prevalent cold northerly and north-easterly winds during winter.	Southern orientation avoids cold winter winds while capturing low-angle solar radiation.
Fundamental orientation principle	Predominantly south-facing configuration	Annual thermal balance: winter heat capture vs. summer heat rejection.

Source: (Authors)

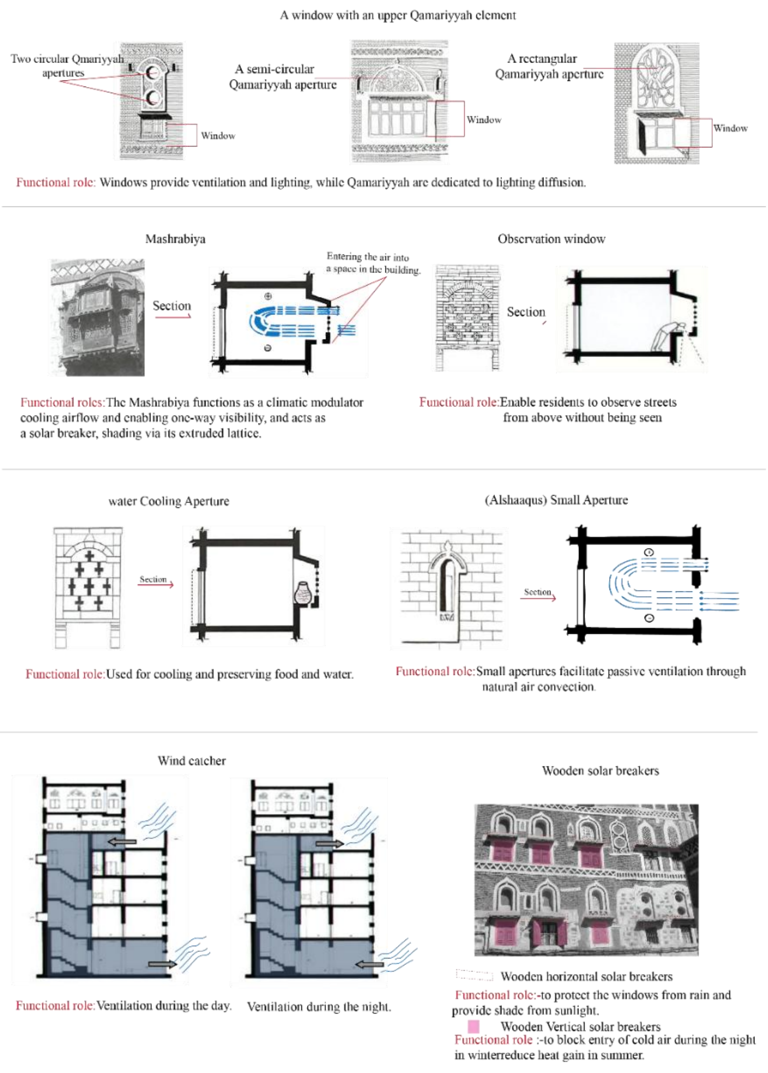

Fig. 9. The functional system of apertures in tower buildings regulates light, sunlight, ventilation, and privacy
Source: (Authors)

Building orientation, along with functional and structural requirements, influences the distribution of openings in external walls, including their ratio and size. The east-oriented facade features a large opening and a high window-to-wall ratio to enhance comfort and admit morning sunlight. The south-facing structure also has a high ratio, supporting passive heating through consistent sunlight. In contrast, west-oriented windows are smaller and fewer to mitigate heat gain from the afternoon sun. The north-facing direction has the fewest and smallest openings because it receives the least direct sunlight.

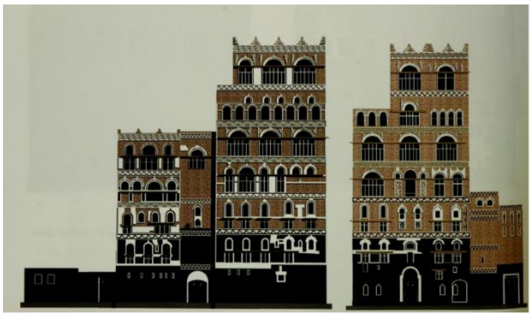

Fig. 10. The openings in the eastern and southern facades of the Ghamdan House
Source: (Al-Taher, 2005)

Spatial and Functional Design Wisdom

The vernacular housing of Sana’a embodies the cultural values of privacy, hospitality, and hierarchical spatial organization characteristic of traditional Yemeni society. The design choice for Sana'a's buildings has tended toward a closed system and a vertical construction orientation due to several factors, including planning, security, and social considerations. Planning factors include the limited space within the city walls, the dense urban context, and the need for adaptability to the highland environment. Security factor: This system achieves the required protection by providing effective sealing and control capabilities. The process is facilitated by the adhesion of the residential building to the adjacent building on one or both sides in a complete or restricted strip or wrap-around manner. As shown in Fig. 10 (a), this illustration depicts the contiguity of residential buildings with adjacent structures in a historical urban block, along with the elevations of tower buildings. Social factor: The Tower building achieved the concepts of family privacy, extended family, and social ties. Residential clusters are often arranged around green urban spaces, as shown in Fig. 10 (b), which provide semi-private areas for walking and relaxation, fostering both a sense of safety and controlled social interaction. Adjacent social squares function as venues for communal gatherings, including weddings, and as play areas for children.

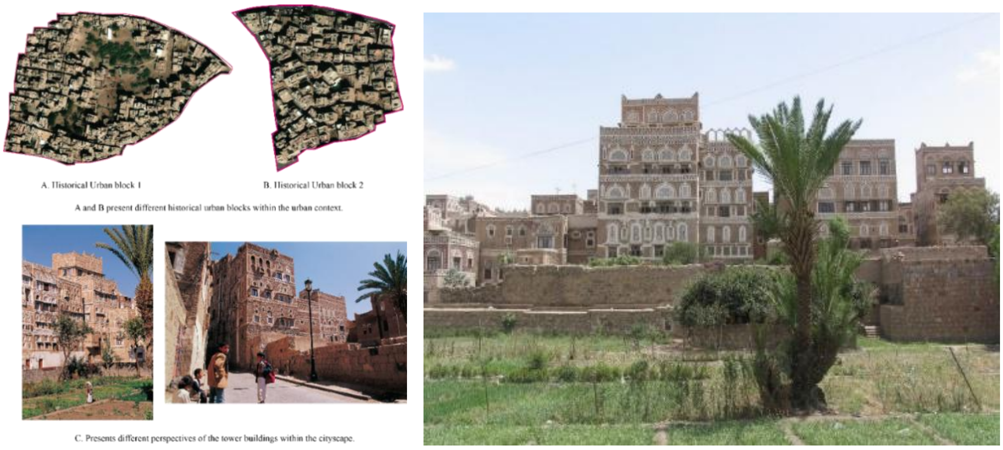

Fig. 11. The adjacent buildings to each other and the green space’s location
(Source: authors, (UNESCO World Heritage Centre, 2025)

Notably, the Sana'a tower building's architectural typology defines a vertical hierarchy organization that suits the San'ani lifestyle. Service and economic functions, including kitchens, are typically positioned on the second or third floors to facilitate both upward and downward service. The intermediate floors support family living and private functions. While the upper part (Mafraj) hosts male gatherings and formal receptions, maintaining strict separation from routine household activities (Figure 11, which shows the spatial organization of the multi-storey house). Furthermore, spatial distribution is dictated by solar orientations to optimize thermal comfort. Primary living areas are oriented toward the South, southeast, and west to maximize passive solar gain during the cooler months. In contrast, service function rooms are designed to be north-facing.

Fig. 12. Functional Zoning Within Houses and Functionally Stratified Vertical Expansion (Tower House)
(Source: (Alabsi, 2013; Veranda, 1982)

The Architectural Aesthetics

The aesthetics domain is evident in the city's urban landscape palette, which reflects its natural environment, dominated by an ochre hue (a reddish-brown earthy tone), as illustrated in Figure 13 (right side). This hue imbues the city with a warm, earthy character and serves as the principal color of the Old City. This reddish-brown shade results from the use of burnt bricks and clay in construction, harmoniously shaping the cityscape and symbolizing the city's deep connection to its land and history, while also reflecting themes of sustainability and resilience.

Aesthetics were also integrated into the design elements. Which carry elements of symbolic meaning, structural function, and aesthetic value. Such as Qamariyyah, as shown in Figure 12, a transparent polished marble, the name Al-Qamariyyah is derived from its association with light and resemblance to the moon. Viewed from the inside, it evokes the appearance of the moon. Figure 13 (left side) shows the improved version of Al-Qamariyyah with stained glass.

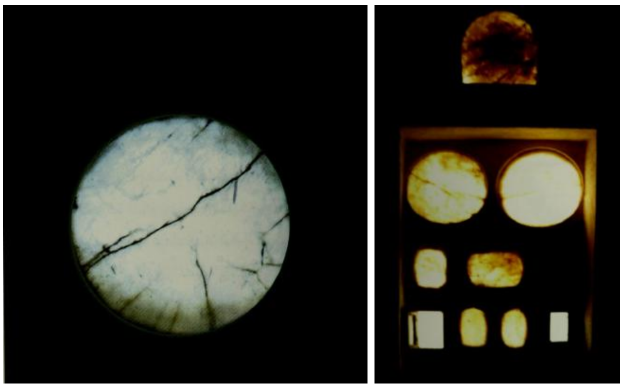

Fig. 13. Marble Qamariyya
(Source: Al-Taher 2005)

The external facade elements and motifs carry aesthetic, symbolic, and functional connotations. Many elements of external decorative formation constitute the cumulative product of abstracting ancient motifs with diverse subjects and connotations. These elements include brick or plaster bands adorning windows, separators between floors, vertical ornaments, and decorative frames (See Figure 14). Pre-Islamic architects often emulated realistic forms to explain the motifs and elements. The transformations in political, social, and cultural spheres after the adoption of Islam caused a major shift in architectural decorative formation. Thus, the post-Islamic period saw a movement towards abstraction, reducing forms to their simplest geometric states to convey symbolic meaning. This meaning is realized through the repetition of the motif within the overall composition.

Fig. 14. From left to right: the decorative element "Qamariyyah", the primary dominant ocher color (Source: (Bonnenfant, 2014)

Fig. 15. Decorative motifs on building facades (Source: Centre 2025)

The intended significance of ancient motifs was revealed through abstraction, allowing them to function as core elements that form cohesive units and decorative themes. In this capacity, they carry expressive Islamic political, social, and cultural connotations. A prime example is the ibex head motif from ancient Yemeni civilization, as shown in Figure D. 15, which was abstracted into a geometric shape and repeated to create a coherent form laden with meaning. The two motifs in unit (e) demonstrate a continuous system resembling the intertwined bodies of snakes, symbolizing their coiled movement. They additionally express an alternative significance, symbolizing a rosary for remembrance and glorification of God (Allah) in Islam. Unit (f) presents two more complex motifs which, upon systematic analysis, are identified as representing the branch of the sacred grapevine. Another prevalent motif, used extensively above windows, served the practical function of preventing water seepage into the building's interior. The semantic interpretation of this form can be associated with the rippling of water. Finally, the decorative motif in Figure (Z) exhibits a different organizational structure, employing vertical repetition. Within its complete system, the motif conveys its meaning through the representation of palm fronds, symbolizing the sacred, blessed tree.

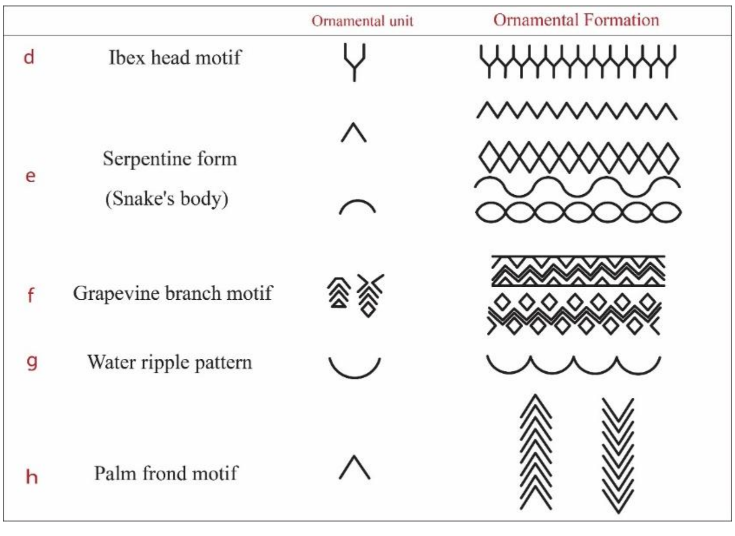

Fig. 16. Ornamental unit and formation Source (Source: authors adapted from (Al-Taher, 2005))

Sustainability and Resilience in the Vernacular Architecture of Sana'a Old City

The previous discussion of the four primary domains of local wisdom practices in vernacular architecture in Sana'a Old City reveals that an intrinsic harmony exists between the built environment and its spatial context (Nasir & Kamal, 2021). These practices established a socially cohesive, environmentally balanced, and energy-efficient environment long before the formal introduction of the term "sustainability" as a contemporary construct. Vernacular practices in Sana'a Old City inherently align with the Triple Bottom Line framework (Elkington, 1994), integrating the three pillars of environmental sustainability, social Cohesion, and economic viability with profound aesthetic considerations. The long-term survival of the city through climatic extremes and societal shifts exemplifies a high adaptive capacity (Folke et al., 2010) and social resilience (Adger, 2000), reinforced by passive design strategies that maximize inhabitant comfort (Olgyay, 2015).

Furthermore, the city also functions as a closed-loop system of materials and environmental cycles designed to maximize product longevity, favouring the appropriate technology (Schumacher, 1973). By utilizing available materials and honed skills, architectural forms remain easily maintained and adaptable. This resilience is rooted in the integration of architectural methods, wherein adaptable design utilizing local materials facilitates straightforward repair, renewal, and modification, along with optimized facade orientation, natural ventilation systems, and functionally stratified rooms that protect privacy (Lyle, 1996). In this manner, buildings thus operate in harmony with natural systems rather than depleting them. The cyclical and integrative relationship among theoretical principles, local wisdom, and architectural reality forms a loop of continuous adaptation (Figure 16). Sustainability and resilience are the principles that shape the vernacular architecture of Sana'a. This architectural system is dynamically influenced by local wisdom, which acts as the intellectual link to contemporary architectural practices. The red dashed arrow indicates the vital translation of traditional knowledge into modern elements, completing a cycle of ongoing urban renewal and stability.

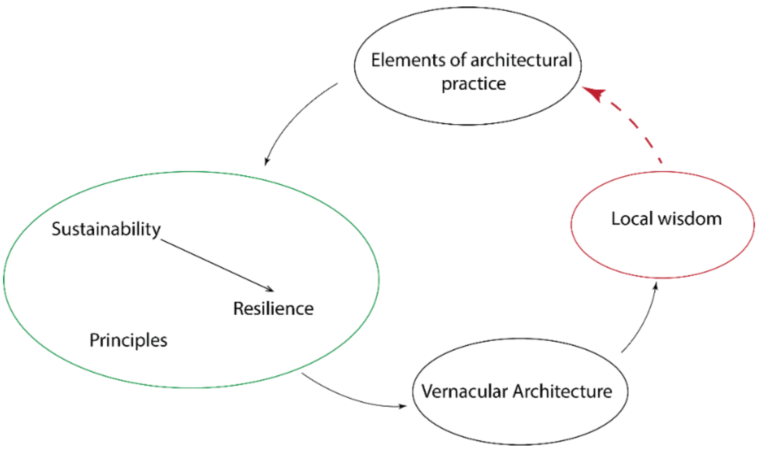

Fig. 17. Sustainability and Resilience in the Vernacular Architecture of Sana'a Old City
(Source: authors)

Lessons and Insights from the Discussion

The enduring intelligence embedded in Sana'a's vernacular architecture raises a critical question: can these traditional systems continue to perform efficiently under the pressure of climate change, and can contemporary design achieve a comparable contextual performance without resorting to superficial stylistic imitation?

Current scholarship increasingly suggests that climate change threatens the world's built cultural heritage (Antoniou et al., 2025), particularly its thermal performance (Sesana et al., 2021). Recent studies indicate a progressive degradation in the thermal performance of traditional buildings. For instance, (Li et al., 2026) found that passive cooling in tower buildings in Sana'a Old City will become ineffective under future climate scenarios. Similarly, (Kazim et al., 2021) reported that indoor temperatures in traditional stone architecture in Oman could exceed 40 ◦C under future conditions. Comparable declines in thermal performance have also been observed in earthen architecture in the Najed region (Alaioud et al., 2022). At the same time, contemporary designs often fail to match the contextual responsiveness of vernacular architecture as they prioritize rapid construction and are guided by divergent design philosophies. Modern buildings can achieve a comparable level of contextual efficiency, but typically at the high cost of contemporary sustainable materials, which remain inaccessible to low-income communities (Alaioud et al., 2022; Mahame et al., 2024).

Vernacular architecture alone cannot therefore adequately respond to the impacts of climate change, nor can contemporary architecture simply imitate them as nostalgic representations. Instead, a synergistic integration of a knowledge-rich vernacular system with modern technological advancements is required. The thematic analysis in this study proposes integrative strategies to enhance the sustainability and resilience of the built environment in Yemen and similar contexts broadly through an approach that combines traditional architecture knowledge with contemporary building science to improve building performance (Rizi et al., 2025). This approach aligns with the concept of Neo-Vernacular architecture or climate-responsive design, referring to the adaptation of traditional architectural knowledge through contemporary building science (Rizi et al., 2025). Such integration can enhance the user comfort and needs while improving energy efficiency and environmental sustainability (Markarian & Fazelpour, 2019), and may be operationalized through the same four domains identified in this study's thematic analysis :

Material and construction: This domain involves combining locally available, low-impact materials such as wood, lime, earth, burnt bricks, volcanic rocks, and stones with low-carbon contemporary structural innovations including recycled concrete, cooling Paint (PVDF-HFP), double glazing, green Concrete, recycled aggregates, and natural insulation materials. This hybridization can reduce carbon footprint, promote sustainable development, and provide high energy efficiency.

Climate-responsive design: This domain combines time-tested passive elements, including Mashrabiya, courtyards, wind catchers, and shading devices, with modern strategies such as latticed panels and photovoltaic (PV) cells integrated with a shading system. This requires careful consideration of climatic parameters, building orientation, and configuration of openings to optimize environmental performance.

Spatial-functional design: Traditional family structure was predominantly based on the extended family system, in which multiple generations resided either within a single multi-story dwelling or across an entire residential block allocated to the extended family. Contemporary family structures have since shifted fundamentally, with the nuclear family emerging as a smaller, independent unit. Directly replicating the social, cultural, and spatial organization of the traditional house is therefore not feasible, as the requirements of contemporary life have evolved alongside new lifestyles and rhythms. Nevertheless, following the underlying logic of vernacular spatial organization can yield an adaptive spatial framework that accommodates the lifestyle, privacy, needs, and social rituals of the local community, while still meeting the modern functional requirements.

Architectural aesthetic: The reinterpretation of traditional forms through digital design tools enables a shift from imitation to abstraction. Parametric design, digital fabrication, and emerging technologies such as 3D printing allow traditional architectural elements such as ornamentation, patterns, and color systems to be translated into computational rules and generative models. This facilitates the production of diverse, performance-driven design solutions tailored to different building types and functional requirements. To support these four domains, advanced simulation and modelling tools, including building information modelling (BIM), Grasshopper, Climate Consultant, EnergyPlus, OpenFOAM, and computational fluid dynamics (CFD), can be employed to optimize performance in both new designs and the retrofitting of existing buildings, thereby contributing to affordable, durable, and sustainable housing solutions.

Recent studies further reinforce the potential of Neo-Vernacular approaches across each of these domains. In the context of Sana'a Old City, AlMaqremi and Abdou (2026) incorporated vernacular knowledge into modern retrofitting practices to restore climatic performance in contemporary housing, exemplifying the integration of climate-responsive design.

A dynamic energy model was developed in Design Builder, combining traditional design practices such as thermal insulation and Mashrabiyah with modern energy-efficient technologies, including double-glazing and high-efficiency LED lighting; this strategy achieves a 70.7 % reduction in annual electricity consumption, alongside significant savings in operational costs and CO_2 emissions. Similarly, combining local materials (bamboo, earth) with modern construction methods, fabrication, and modular systems can offer sustainable and culturally appropriate housing in Assam in north-east India (Barbhuiya et al., 2025). Furthermore, Alrashed, Asif et al. (2017) evaluated the performance of courtyards, Mushrabiyah, and adobe construction within Zero-energy housing models (ZEHs). Finding that Mushrabiyah reduced annual electricity demand by 4%, while Adobe construction achieved 6%, and had a limited positive role for the courtyards.

CONCLUSION

As noted in the literature review, most research on vernacular sustainability originates from Western Asia and Europe. While the Arabian Peninsula and Yemen in particular, remain markedly underrepresented in academic literature. This study addresses this geographical gap through a thematic analysis of vernacular architecture, sustainability, and resilience in the Old City of Sana'a. The findings demonstrate that the vernacular architecture of

Sana'a's Old City exhibits remarkable longevity and resilience, derived from four interrelated domains of local knowledge and practices in architecture. These four domains function together as a cohesive system that forms the architectural knowledge and practices. These domains function together as a cohesive system underlying the city's architecture, enabling it to self-regulate, adapt, and endure over time.

Sana'a Old City thus serves as a significant example of architectural intelligence and adaptability in achieving ecologically responsive, socially harmonious, and economically viable design, offering a model for integrating modern technology with local knowledge in contemporary architecture across developing-country contexts.
Climate- and context-specific testing nonetheless remains essential before any design strategy derived from this analysis is applied elsewhere.

This study moves beyond documentation to extraction: it emphasizes that lessons drawn from vernacular architecture can enhance the sustainability and resilience of contemporary architecture, both through experimental studies of vernacular elements and through the development of strategies that improve the comfort and functionality within contemporary applications. Further research from differing perspectives on vernacular architecture would also be valuable in exploring additional directions for its future development. By offering a new perspective on the vernacular architecture of Sana'a Old City, this study opens avenues for more detailed theoretical and practical inquiry. The primary limitation in this study is its qualitative scope, relying on thematic analysis of observational data, archival documents, and prior academic research. Future research should therefore extend this work through broader, quantitative measurement across all identified domains, in order to validate these insights for application in contemporary architecture, substantiate the effectiveness of vernacular design principles, and derive further insights based on experimental studies

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