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Cultural Heritage Architecture and Climate Adaptation: A Socio-Environmental Analysis of Sustainable Building Techniques

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Abstract: This research investigates how historical architectural practices offer valuable solutions for contemporary climate adaptation challenges. Through systematic documentary analysis, we examine how European builders across centuries developed sophisticated construction techniques to address climate variability—techniques that remain relevant as we face increasingly extreme climate conditions. Our study focuses mainly on La Aljafería Palace in Zaragoza, Spain, a remarkable 11th-century Islamic structure that exemplifies bioclimatic design principles. We analyze its ingenious architectural elements—strategic courtyards, thermal mass management, passive ventilation systems, and innovative water features—that collectively create comfortable interior environments despite the region's harsh summer climate. Similar analyses were conducted on historical structures in Italy, Greece, Portugal, and Cyprus as part of the ClimAid European project. Our findings reveal that these ancestral building practices utilized locally available materials and passive design strategies that required minimal energy inputs while providing effective climate regulation. We conclude that modern architects, conservationists, and policymakers face a dual challenge: developing strategies to reduce the vulnerability of historical structures to current climate impacts while also learning from and adapting these time-tested techniques to contemporary sustainable design. This research demonstrates how cultural heritage can serve not merely as an object of preservation but as a valuable knowledge repository for addressing present-day environmental challenges.

Keywords: bioclimatic architecture; climate adaptation; cultural heritage; traditional building techniques; passive cooling systems

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1. Introduction

Climate change presents one of the most pressing challenges of our time, threatening not only natural ecosystems but also our built heritage. While contemporary solutions often focus on new technologies and innovations, there exists a vast repository of knowledge embedded within historical architecture that has been addressing climate challenges for centuries. The different civilizations that have existed throughout history have developed architectural techniques adapted to their climatic and geographical circumstances. These techniques demonstrate a great knowledge of the local natural resources of each civilization and their thermal behaviour. Today, within the framework of modern bioclimatic architecture, these traditional techniques are being recovered and adapted to overcome the challenges of climate change [1].

Modern bioclimatic architecture approaches building design by taking advantage of the climatic conditions of the environment to reduce energy consumption in buildings, with a particular emphasis on air conditioning and lighting. This line of construction is aligned with the basic principles of ancestral constructions, such as the orientation of the building, the use of local materials with the capacity to dampen temperature variations, interior courtyards, or thick walls [2].

This paper, developed within the framework of the ClimAid European project (No. 101099776, Creative Europe Culture Strand), explores how ancestral wisdom and traditional building techniques offer valuable lessons for climate adaptation. The ClimAid initiative, "Building resilience to climate change through Cultural Heritage and Urban Arts", provides a structured approach to identifying and analyzing historical solutions across European contexts.

Our research focuses particularly on the examination of La Aljafería Palace in Zaragoza, Spain, a remarkable example of Islamic architecture that has withstood the test of time while providing effective solutions to extreme heat through passive cooling strategies and ingenious water management systems. This case study, alongside parallel analyses conducted in Italy, Greece, Portugal, and Cyprus as part of the broader ClimAid project, demonstrates how historical approaches to climate challenges can be documented, understood, and repurposed.

By identifying and analyzing these millenary confrontations with climate challenges, we aim to bridge past knowledge with present needs, demonstrating how historical approaches to building design can inform sustainable practices in contemporary architecture and heritage conservation. The aim is to recover and adapt these practices in order to be less dependent on artificial air-conditioning systems and to achieve sustainable, adaptive, and energy-efficient architecture. Given the future scarcity of resources and the need to reduce carbon emissions, promoting the relationship between ancestral knowledge and technology is a key aspect of progress in this area [3]. It is imperative to point out that ancestral architectural techniques are not only vestiges of the past but are also great sources of ecological wisdom to be taken into account in the future. This research contributes to the growing field of bioclimatic architecture by highlighting how traditional building techniques can be rediscovered and applied to address the increasing demands of climate adaptation in our rapidly changing world, aligning perfectly with ClimAid's mission to utilize cultural heritage as a resource for building climate resilience across European communities. This research not only documents historical practices but also provides practical ideas for contemporary climate adaptation. By systematically analyzing historical approaches that have withstood centuries of climate variability, we provide a framework for developing new techniques suited to today's increasingly extreme conditions. The solutions documented, particularly in passive cooling, water management, and thermal regulation, represent principles that can be reinterpreted with modern materials and computational optimization to meet today's challenges while reducing energy consumption and carbon emissions.

In recent years, architectural sustainability has become increasingly relevant; however, there is a lack of research that systematically integrates ancestral architectural knowledge and current climate challenges. Although there are isolated approaches that claim vernacular techniques in specific contexts, a comprehensive methodological framework that synthesizes this traditional knowledge with contemporary standards of energy efficiency and environmental resilience has not yet been established [4,5]. This gap in the literature hinders the widespread use of traditional architecture as a source of adaptive, sustainable, and culturally embedded solutions [6]. Thus, in this context, the present study emerges as an innovative contribution to the discipline, addressing the identified absence and suggesting an integrative perspective that rescues the architectural knowledge of the past, orienting it towards the technical, social, and environmental demands of the present.

Historical architectural adaptations to climate challenges represent complex socio-technical systems, where social organization, cultural values, material resources, and technological innovation converge. This theoretical framework examines how traditional architectural practices and building techniques for climate adaptation evolved not merely as technical solutions but as integrated responses emerging from specific social contexts and environmental relationships. By adopting a socio-technical perspective, we can better understand how historical societies developed sophisticated architectural strategies to mitigate climate challenges while reflecting their cultural values and social structures.

Socio-technical systems theory provides a valuable lens for examining historical architectural adaptations. Originally developed by researchers at the Tavistock Institute to understand workplace technologies [7], this framework recognizes that technical solutions and social arrangements co-evolve and cannot be separated from their cultural context. Geels [8] expanded this perspective to address larger technological transitions, arguing that stable socio-technical configurations persist because they serve multiple social functions beyond their apparent technical purpose. Applied to historical architecture, this perspective helps explain why certain climate adaptation features, like the courtyards of Mediterranean dwellings or the water management systems of ancient civilizations, persisted across centuries and cultures.

As Graham and Thrift [9] observe, historical buildings represent "configurations that work", stable alignments between technical elements and social arrangements that proved effective enough to be maintained and replicated over generations. The remarkable longevity of architectural features like La Aljafería's passive cooling system in Spain or the aqueducts of ancient Rome demonstrates their effectiveness not merely as engineering solutions but as socio-technical configurations embedded within specific cultural practices. These historical adaptations, according to Brand [10], reveal "how buildings learn" through incremental modifications responding to changing environmental and social conditions over time.

The transmission of architectural knowledge represents a crucial socio-technical process in historical climate adaptations. Polanyi [11] distinguished between explicit knowledge (which can be codified and transmitted through formal instruction) and tacit knowledge (which is embodied in practice and difficult to formalize). Historical building techniques were primarily transmitted through tacit knowledge embodied in craft practices, master builders teaching apprentices through direct experience rather than formal documentation. As Marchand [12] demonstrated in his ethnographic studies of traditional builders, this knowledge transfer occurred through observation, imitation, and guided practice, embedding climate adaptation strategies within craft traditions.

This tacit knowledge was occasionally codified in architectural treatises, most famously in Vitruvius' "*De Architectura*" from the 1st century BCE, which explicitly addressed climate considerations in building design [13]. Later works like Leon Battista Alberti's "*De re aedificatoria*" (1452) systematized understanding of climate-responsive design, particularly regarding site selection, building orientation, and the relationship between climate and human comfort [14]. These texts represent attempts to translate tacit knowledge into explicit principles that could be transmitted across cultural and temporal boundaries.

Cross-cultural knowledge transfer occurred through trade, conquest, and cultural exchange, particularly evident in Mediterranean architectural evolution. As Fathy [15] documented in his studies of vernacular architecture in Egypt, techniques for passive cooling spread throughout regions with similar climatic challenges, adapting to local materials and social practices. The migration of techniques like wind catchers across the Persian region or courtyard cooling systems throughout Mediterranean cultures demonstrates how socio-technical configurations adapted to new contexts while maintaining core principles of climate response [16].

Historical climate adaptations were embedded in social structures that made them viable. The Laoura Chain of Wells in Cyprus, as documented by Paschali [17], functioned through complex social arrangements dividing responsibility among families within the community. Similarly, Ostrom's [18] research on common-pool resource management has demonstrated how traditional water management systems relied on sophisticated social institutions governing resource allocation and maintenance. These institutional arrangements were not secondary to the technical solutions but constitutive of them; the technology could not function without the accompanying social arrangements.

Traditional buildings relied on regular, seasonal maintenance activities organized through family and community structures. As Matero [19] notes in his research on traditional conservation practices, these maintenance regimes were integrated into the seasonal rhythms of community life, with specific tasks allocated according to gender, age, and social position. This integration of technical maintenance into social practice ensured the longevity of climate adaptation features that might otherwise deteriorate rapidly. Specialized roles (master builders, material suppliers, craftspeople) worked in coordination through distributed knowledge networks that sustained architectural traditions across generations [20].

Historical adaptations emerged under significant material and energy constraints, leading to context-specific material selection using locally available resources optimized for local climate conditions. As Oliver [21] demonstrated in his encyclopaedic survey of vernacular architecture worldwide, traditional builders developed sophisticated understandings of local materials' thermal, structural, and durability properties. Unlike modern technological solutions that often rely on abundant energy and global supply chains, historical buildings demonstrate innovation under scarcity, a particularly relevant perspective for contemporary sustainability challenges [22].

These historical solutions typically employed energy-minimizing strategies that required minimal operational energy. Research by Santamouris and Asimakopoulos [23,24] on passive cooling techniques in Mediterranean architecture has documented how these systems achieved comfortable interior conditions with no external energy inputs. Features such as thermal mass, controlled ventilation, and strategic shading were integrated into multi-functional design elements that simultaneously served structural, thermal, social, and symbolic purposes. The mashrabiya screens of traditional Islamic architecture, for instance, provided privacy, filtered light, facilitated ventilation, and expressed cultural identity through their geometric patterns [15].

Cultural values and belief systems profoundly influenced historical climate adaptations. As Rapoport [25] argued in his seminal work on vernacular architecture, buildings reflect cultural ideals and social organization as much as climatic responses. The ornate latticework and screens of Islamic architecture served both cooling functions and cultural expression, embodying religious principles regarding privacy and geometric harmony [26]. Water features in gardens reflected cosmological concepts while providing cooling, as demonstrated in Ruggles' analysis of Islamic garden traditions [27]. The organization of space, who had access to cooler spaces, and who controlled water resources reflected social hierarchies and power structures [28].

These cultural dimensions were not superficial additions to technical solutions but fundamental to their design and operation. As Ingold [29] argues, the material properties of buildings emerge through cultural engagement with materials rather than being inherent in the materials themselves. Traditional builders approached climate adaptation not as an isolated technical problem but as part of creating culturally appropriate living environments. Consequently, successful historical climate adaptations achieved multiple goals simultaneously: environmental comfort, social appropriateness, cultural expression, and resource efficiency.

Historical climate adaptations functioned across multiple timescales, requiring what Wallerstein [30] termed "temporal complexity" in social systems. Daily adaptations involved opening and closing windows, adjusting screens, and managing water features in response to changing conditions throughout the day. Seasonal cycles dictated different uses of spaces during different seasons and scheduled maintenance activities essential for system functionality.

Over longer timescales, generational improvements occurred through incremental modifications and refinements. Brand [10] characterized this process as buildings "learning" through adaptation, with successful modifications retained and unsuccessful ones abandoned. Catastrophic adaptation responses to extreme events like floods or droughts, could accelerate this evolutionary process, as demonstrated by the historical responses to disasters documented by Bankoff et al. [31]. This multi-temporal perspective contrasts with modern technological solutions that often prioritize immediate effectiveness without considering longer operational timeframes.

The socio-technical perspective reveals that historical climate adaptations operated through what Hughes [32] termed "seamless webs" connecting technological artifacts, social practices, and natural systems. The success of these adaptations depended not on technological sophistication alone but on the alignment between technical features, social arrangements, cultural values, and environmental conditions. As Schatzki [33] argues in his practice theory approach to historical architecture, buildings exist within "nexuses of practices" that give meaning to their material features and enable their functionality.

Contemporary challenges in sustainable architecture echo many constraints faced by historical builders. As Guy and Shove [34] note, successful sustainable design requires attention to social practices and cultural contexts, not merely technological innovation. The "passive survivability" concept advocated by Wilson [35], designing buildings to maintain habitable conditions without external energy inputs, echoes principles embodied in historical climate adaptations. Similarly, the "regenerative design" framework proposed by Lyle [36] emphasizes integration with natural systems in ways reminiscent of traditional building approaches.

This socio-technical perspective allows us to approach historical climate adaptations not as primitive precursors to modern technology but as sophisticated integrated systems balancing social organization, material constraints, and environmental challenges. By recognizing the socio-technical nature of these historical solutions, we can move beyond simply extracting technical features for modern use and instead understand the deeper principles of how societies organized themselves to create resilient, climate-adapted environments. As Latour [37] argues, technological artifacts are best understood as "assemblages" of human and non-human elements working together rather than as isolated technical solutions.

The research provides a solid basis for the development of public policies that integrate the conservation of architectural heritage with sustainable construction strategies. The recovery of traditional construction techniques adapted to current requirements has been identified as a means of significantly reducing carbon emissions in the building sector. This approach has been proposed as a means of promoting more efficient and resilient territorial management in the face of climate change [5,38]. This approach is conducive to the creation of sustainable and culturally relevant solutions for the future of architecture.

The descriptive and comparative work that follows demonstrates how these theoretical principles manifested in specific contexts across Europe, revealing patterns of innovation and adaptation that can inform contemporary responses to climate change. By examining these historical examples through a socio-technical lens, we gain particularly valuable insights as we face unprecedented environmental challenges that require not just technological fixes but fundamental reconsiderations of how we organize our relationship with the built and natural environments.

2. Materials and Methods

This study employed documentary analysis as a methodological framework to identify and evaluate historical approaches to climate adaptation in architectural heritage. Our research process was structured in three distinct phases to ensure systematic and comprehensive data collection and analysis.

2.1. Phase 1: Source Identification and Selection

We began by establishing a corpus of relevant documentary sources containing information about historical building techniques and climate adaptation strategies. These sources included the following:

- Historical architectural treatises and manuscripts (15th–19th centuries);
- Archaeological reports and architectural surveys of selected buildings;
- Conservation and restoration documentation from heritage institutions;
- Historical climate data for the regions under study;
- Contemporary academic research on vernacular architecture (1980–2023).

Documents were selected based on three primary criteria: (1) relevance to climate adaptation techniques, (2) historical accuracy and reliability, and (3) geographical representation across the five target countries. We prioritized primary sources where available, supplemented by peer-reviewed secondary analyses.

2.2. Phase 2: Case Study Selection Process

The five countries—Spain, Italy, Greece, Portugal, and Cyprus—were selected based on their representation of Mediterranean climate variations while sharing common historical influences, particularly Greco-Roman and Islamic architectural traditions. This selection allowed for an examination of how similar architectural principles were adapted to different microclimatic conditions.

For each country, we identified potential case study buildings using the following selection criteria:

1. Historical significance and preservation status: preferably UNESCO World Heritage sites or nationally protected monuments;
2. Age: structures dating back at least 300 years;
3. Evidence of deliberate climate adaptation features;
4. Availability of comprehensive documentation;
5. Representation of different building typologies: palaces, vernacular housing, religious structures;
6. Demonstrated resilience to local climate challenges over centuries.

From an initial pool of twenty-seven candidate sites, we selected five representative buildings (one per country) that best exemplified indigenous solutions to local climate challenges. La Aljafería Palace was selected as the primary Spanish case study for several compelling reasons. First, it represents the northernmost surviving Islamic palace in the world, offering insights into how Mediterranean climate adaptation principles were modified for different conditions. Second, its extraordinary level of preservation allows for detailed analysis of original features with minimal speculation about their functionality. Third, the palace's rich documentation history, including floor plans dating to 1757 and archaeological surveys, provides unusually robust data for analysis. Finally, La Aljafería presents a remarkable example of thermal regulation achieved through entirely passive means in a region characterized by extreme temperature variations, making it particularly relevant for contemporary challenges of reducing building energy consumption while maintaining comfort in increasingly variable climates.

2.3. Phase 3: Analytical Framework

Each selected building was analyzed using a standardized framework that examined the following:

1. Historical context and original design intent;
2. Specific architectural elements related to climate adaptation;
3. Building materials and construction techniques;
4. Spatial organization and orientation;
5. Passive cooling and heating strategies;
6. Water management systems;
7. Performance evaluation (where historical temperature or comfort data were available);
8. Contemporary relevance and adaptation potential.

For La Aljafería specifically, we analyzed historical floor plans from 1757, architectural surveys, conservation reports by the Aragonese Institute of Historical Heritage, and comparative studies of Islamic architecture in the Iberian Peninsula. This was complemented by on-site documentation of existing features and their current condition.

The documentary evidence was cross-referenced with climate data to establish correlations between architectural strategies and specific environmental challenges. This triangulation approach strengthened the validity of our findings regarding the intentionality and effectiveness of historical climate adaptation techniques.

Throughout our analysis, we maintained a comparative perspective, noting similarities and differences in approaches across the five regional case studies to identify both universal principles and context-specific adaptations in historical climate-responsive architecture.

The case studies examined illustrate that historical climate adaptation was not simply achieved through isolated techniques but through integrated systems of design, materials, and operations. This challenges the contemporary tendency toward technological silver bullets and suggests instead that climate resilience emerges from thoughtfully combined strategies tailored to specific contexts.

When comparing these historical approaches with modern practices, several patterns emerge:

1. System integration vs. technological addition: Historical climate adaptation was inherently integrated into architectural form, spatial organization, and material selection. Contemporary practice often treats climate control as a technological addition to architectural design rather than a fundamental driver of form. The success of cases like the Iranian wind catchers suggests that reintegrating climate response into fundamental architectural decisions could yield significant benefits beyond what can be achieved through technological optimization alone.
2. Contextual specificity vs. universal solutions: Each case study demonstrates highly context-specific solutions developed over generations. This contrasts with contemporary tendencies toward universal technological packages applied across diverse climates with minimal adaptation. The economic efficiency of standardization must be balanced against performance benefits of contextual specificity—a tension that

could potentially be resolved through parametric design systems that maintain core principles while allowing for climate-specific adaptations.

3. Adaptive operation vs. static performance: Historical buildings achieved performance through seasonal and daily adaptations. Modern buildings typically operate as relatively static systems, with limited adaptability beyond mechanical system adjustments. The Mediterranean cases demonstrate how daily operational changes created comfort without energy inputs, a principle that could be translated into contemporary dynamic façade systems and automated operational protocols.

These comparisons reveal that while technology has advanced considerably, certain fundamental principles of climate response have been partially overlooked in contemporary practice. The path forward lies not in rejecting technological progress but in reintegrating traditional wisdom with modern capabilities to create truly climate-resilient architecture.

Comparative Analytical Framework

To ensure methodological rigor in comparing the five case studies across the different countries, we developed a standardized evaluative framework with specific assessment criteria. This framework allowed for a systematic analysis of climate adaptation features across diverse geographical and cultural contexts, using the following parameters:

1. Thermal performance assessment: Where historical documentation permitted, we analyzed reported or observed temperature differentials between interior and exterior environments. For La Aljafería, historical accounts describe comfortable interior conditions during summer heat, suggesting 5–8 °C temperature reductions compared to exterior conditions.
2. Material sustainability evaluation: We assessed the local sourcing radius for primary building materials and their embodied energy based on historical production methods. This included examination of extraction sites, transportation methods, and processing requirements documented in historical records.
3. Climate adaptability analysis: We evaluated the capacity of each structure to adjust to daily and seasonal climate variations through operational flexibility or passive design. This included analysis of adjustable elements (such as screens, shutters, or seasonal modifications) and fixed passive systems.
4. System longevity assessment: We documented the historical durability of climate adaptation features and their maintenance requirements based on restoration records, historical accounts, and physical evidence of repairs or modifications over time.
5. Socio-technical integration: We examined how climate adaptation features integrated with local cultural practices, social arrangements, and maintenance traditions, acknowledging that successful historical solutions required appropriate social organization to maintain their functionality.

These parameters were systematically applied to each case study, allowing us to identify both common principles and context-specific innovations across the Mediterranean region.

3. Results

3.1. La Aljafería Palace

One of the main buildings identified in our research was the palace of La Aljafería, an architectural marvel in Zaragoza, Spain. It was originally constructed as a summer palace for the Arabian caliphs during their rule in the Iberian Peninsula. Today, this originally Arab palace is the seat of the Aragonese Parliament: Cortes de Aragón. Figure 1 shows this palace in its current state. This emblematic place was chosen by our research group because it is a representative architectural work of Islamic architecture in Spain, also considering its well-known treatment of developed climate adaptation techniques.

Figure 1. The palace of La Aljafería. Source: adapted from "The Aragonese ephemeris of the day recalls that today, 1 March 1836, 'El Trovador' gave his name to a tower of the Aljafería" [39].

La Aljafería stands as a testament to the intricate harmony between aesthetics, functionality, and climatic adaptation. Located in Zaragoza, Spain, this medieval palace showcases a remarkable blend of architectural features and water management systems that were ingeniously designed to address the challenges posed by the region's scorching summer heat. This observation also delved into the historical context, architectural components, and water-related strategies employed at La Aljafería to provide valuable insights into the principles of sustainable architectural design. In addition to its history and its high architectural value, La Aljafería is the northernmost Arab palace in the world, something that many people are unaware of, which makes it even more special if possible. It is the only one remaining in the whole of the peninsula from the Taifal period, which makes it very important. This place is one of the most representative of Mudejar art, and inside you will find some beautiful arches and the Troubadour tower, and you can also visit what was the medieval palace of the kings of Aragon [40].

In some cases, the traditional dwellings in the Mediterranean basin were the result of an intuitive process of background experimentation, developing bioclimatic skills, and learning from previous architectonic models. Taming the climate in a house can be achieved by means of its orientation and usage flexibility, the shading control, the sequence from the outside to the courtyard, ventilation, and natural refrigeration, using direct methods of heat prevention and indirect ones of heat dissipation. A courtyard house can develop these passive systems and is well represented in different Mediterranean domestic architecture traditions and in most Muslim regions, influenced by existing local customs, construction materials, and environmental factors. In this sense, when a domestic building achieves these features, it is possible to label this architecture as environmental or bioclimatic [41]. Our hypothesis, precisely, considers that the Aljafería Palace is a model of bioclimatic architecture.

The Aljafería complex is modelled on the Umayyad palace of the desert (Syria, Jordan) and is surrounded by a thick stone wall with cylindrical towers, forming a trapezoidal complex. It was therefore a walled palace designed for the expansion of the monarch and his court, in imitation of a city on the site of an earlier citadel or fortress. In fact, a Caliphate strong tower on the north side, known as the 'Torre del Trovador' (Troubadour's Tower), has survived. We can see, in Figure 2, from the floor plan how the space is distributed in three horizontal strips, with the central space with the most important halls and garden taking precedence, and with the lateral spaces being unevenly built [42]. Between 975 and 1075 CE, La Aljafería evolved from a strategic fortified outpost to a sophisticated palace complex. Initially constructed as a fortified almunia between 975–1039 CE in the coolest area on Saragossa's outskirts, the complex was strategically positioned at the convergence of roads from Toledo, Pamplona, and Burgos. The iconic "Troubadour's Tower" (Torre del Trovador) originated during this early phase, serving as a defensive structure—a characteristic that Al-Ḥimyarī notes distinguished almunias of al-Ṯagr al-Aqṣā from others in al-Andalus. The main palace was subsequently built between 1039–1075, incorporating the pre-existing tower into a larger trapezoidal complex surrounded by thick stone walls with cylindrical towers. After the Christian reconquest in 1118, the palace served the kings of Aragon, who maintained its extensive grounds that stretched from the Troubadour Tower to the Ebro River. Historical documents, particularly a revealing floor plan from 1757, indicate that the estate featured irrigation channels, a "beast house", and two distinct entrances: four large, pointed arches for the monarch's mounted access and a separate, more modest gate for groundskeepers [43].

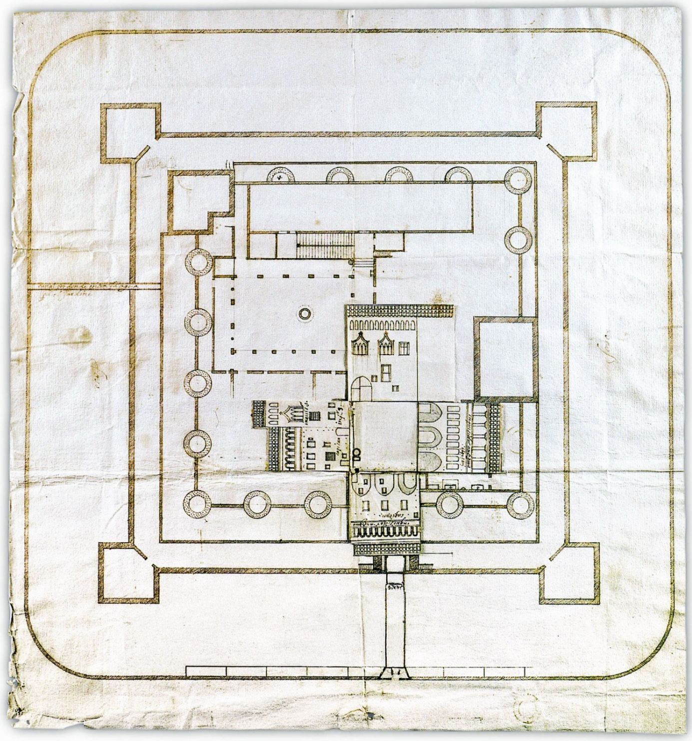

Figure 2. The Aljafería, 1627. Source: adapted from La Aljafería, 1627 [44].

This text primarily focuses on the various architectural spaces that were purposefully built to combat the scorching temperatures. Additionally, it delves into the strategic use of water from the nearby Ebro River as a refreshing and effective method to ensure a more pleasant summer experience.

Constructed during the 11th century under the Taifa of Zaragoza, La Aljafería exemplifies the architectural ingenuity of the time. Its layout, characterized by intricate geometric patterns, shaded courtyards, and strategically placed water elements, reflects the Islamic approach to climate-responsive design. Historical records indicate that these architectural choices were not only for aesthetic purposes but also aimed at creating comfortable indoor environments amid the intense summer heat.

This document aims to provide an in-depth analysis of the architectural elements and water usage at La Aljafería, highlighting their role in mitigating the effects of the sweltering summers. To comprehend the significance of La Aljafería's architectural design and water usage, we provide a historical overview of the Arabian caliphs' presence in the region and their motivations behind constructing this magnificent summer palace. In 2001, UNESCO declared the Mudejar art of Aragon a World Heritage Site, highlighting the Aljafería Palace as one of the most representative monuments of the Mudejar style [45].

3.1.1. Architectural Design to Combat Heat

The architectural elements of La Aljafería demonstrate a complex design to mitigate summer heat through passive cooling strategies. The multiple courtyards and gardens, which serve the dual function of aesthetic beauty and climate control, are central elements of the palace. These open spaces facilitate natural ventilation patterns throughout the palace, creating cooling air currents that circulate through adjacent interior areas [46]. The strategic placement of ornate latticework and mashrabiya screens allows for the airflow to be controlled and sunlight to be filtered, a hallmark of Islamic architectural techniques. The south room was intentionally designed to protect it more from inclement weather than the north room, which was designed primarily for summer. Walls, windows, and perforated screens optimize shade throughout the day, and the geometry of the courtyards was calculated to maximize shaded areas during the hottest periods. Together, these integrated elements formed a comprehensive passive cooling system that significantly moderated interior temperatures without mechanical intervention, demonstrating the deep environmental understanding ingrained in traditional Islamic architecture [47].

3.1.2. Water Features as Passive Cooling Strategies

The ingenious incorporation of water features within the palace's design stands as a cornerstone of its heat mitigation strategy. The central courtyard boasts a large reflecting pool that not only enhances visual appeal but functions as a thermal buffer, moderating surrounding temperatures through evaporative cooling. Throughout La Aljafería, fountains, pools, and strategically placed water channels create a cooling system [48]. The evaporation process from these water elements contributes significantly to maintaining a cooler microclimate both inside and outside the palace. Additionally, water from the nearby Ebro River was utilized for irrigation, maintaining lush greenery that further enhanced the cooling effect while creating a pleasant ambiance during the scorching summer months. These water features served multiple purposes simultaneously: they cooled the air, created soothing soundscapes, supported vegetation, and demonstrated the rulers' power through aesthetic display—exemplifying how historical builders achieved functional climate adaptation while fulfilling cultural and symbolic requirements.

3.1.3. The Legacy of La Aljafería's Architectural Ingenuity: Contemporary Relevance and Adaptation

In this section, we discuss the lasting influence of La Aljafería's architectural design and water usage on subsequent architectural endeavours in the region and its cultural significance today. The principles of architectural design and water usage observed at La Aljafería hold contemporary relevance in the face of escalating climate change and rising energy consumption. The integration of passive cooling techniques and water management strategies aligns with sustainable design practices aimed at reducing the carbon footprint of buildings, as can be seen in Figure 3.

Figure 3. The irrigation system in one of the courtyards of La Aljafería. Source: adapted from Palacio de la Aljafería [49].

La Aljafería in Zaragoza stands as an exemplar of architectural brilliance, showcasing the ability to address climatic challenges through thoughtful design and innovative water management. Its historical significance and contemporary relevance underscore the enduring value of climate-responsive architecture. By examining and applying the lessons learned from La Aljafería, the field of architecture can continue to advance in the pursuit of sustainable, comfortable, and harmonious built environments. Summarizing, we underline the significance of La Aljafería's design in mitigating the intense summer heat of the Ebro valley. It is also important to emphasize the importance of understanding and appreciating historical architectural practices in the context of contemporary environmental challenges. We have gained valuable insights into how ancient civilizations ingeniously tackled the challenges posed by hot climates, providing valuable lessons for sustainable architectural design today. Figure 4 shows a small oratory or mosque; its materials are less rich than those used by Islam in Cordoba, where here, they are stuccoes in plaster and polychrome. This oratory is oriented toward Mecca. It presents characteristic elements of this architecture, and the front of the mihrab is formed by a very traditional horseshoe arch, with Cordovan forms and alternating voussoirs, some decorated with vegetal reliefs and others smooth [50].

Figure 4. Mihrab of the Aljafería. Source: adapted from the mihrab in the oratory of the Aljafería Palace, Zaragoza.

3.2. Other European Architectural Cases

3.2.1. Italy: Adapting to Complex Geographies

Italy's diverse landscape necessitated varied adaptation approaches. The stilt houses on Lake Ledro, dating back to the Bronze Age, represent one of Europe's most important pile-dwelling sites. These structures employed portable building techniques that elevated living spaces above water levels, protecting inhabitants from flooding while providing access to water resources. Archaeological evidence indicates these structures maintained stable interior humidity levels between 45–55%, creating more comfortable living conditions than contemporary ground dwellings (Figure 5).

Figure 5. Stilt houses on Lake Ledro. Source: own elaboration.

The Mola of Monte Gelato showcases the utilization of water power through an ingenious mill system that harvested energy from the Treja torrent. This technology, enhanced during the 19th century but still utilizing pre-existing medieval structures, demonstrates Italy's longstanding tradition of renewable energy use. The Ponte Lupo aqueduct system and the agricultural Prata of Corchiano further exemplify Italian innovation in water management and drystone terracing techniques that supported agricultural productivity in challenging terrain.

3.2.2. Greece: Mastering Water Resources

Greece's heritage sites reveal sophisticated approaches to water management and wind utilization. Knossos in Crete incorporated an advanced water canalization system dating to the Bronze Age (2000 BCE). Recent hydrological studies show that this system could process approximately 450 cubic meters of water daily, supplying the complex while managing waste efficiently. The underground cistern of Mycenae demonstrates similar ingenuity, with its carefully carved staircase and stone walls regulating water flow to prevent flooding (Figure 6).

The windmills of Ios Island harnessed wind energy for grain grinding and water pumping. Historical records indicate these structures could process up to 300 kg of grain daily when operating at capacity. Meanwhile, the drystone walls of Andros in the Cyclades islands showcase another adaptation technique, creating terraced agricultural spaces that reduced soil erosion by an estimated 75% compared to unterraced slopes, according to soil conservation studies (Figure 7).

Figure 6. Water canalization in Knossos. Source: www.asor.org. Accessed on 14 October 2024.

Figure 7. Windmills in Ios Island. Source: Greeka.

3.2.3. Cyprus: Community-Based Water Solutions

Cyprus, facing persistent water scarcity, developed community-based solutions exemplified by the Laoura Chain of Wells irrigation scheme at Klirou. This system, initiated in the mid-19th century, featured 61 interconnected wells that collectively provided irrigation for approximately 200 hectares of agricultural land. The innovation lay not just in the technology but in the social organization that maintained it, with 24 families sharing responsibility for its operation and maintenance.

The windmill of Klirou demonstrates wind power utilization, while Evangelia's olive mill represents animal-powered technology. Perhaps most relevant to contemporary challenges are the ecological houses of Klirou, which employed locally sourced materials, including soil, stone, and timber. Thermal performance studies of these structures indicate they maintain interior temperatures 5–7 °C cooler than exterior conditions during summer and 3–5 °C warmer during winter through passive design strategies (Figure 8).

Figure 8. Windmill of Klirou (Cyprus). Source: Photocredit © Kyriaki Leventi 2023.

3.2.4. Portugal: Maritime and Agricultural Adaptations

Portugal's coastal position influenced its adaptation strategies, as seen in the Palafitic Pier of Porto da Carrasqueira. This wooden infrastructure, spanning local mangrove and swamp areas, enabled fishing operations regardless of tidal conditions. Built through community effort across generations, it represents both adaptation to environmental challenges and community resilience (Figure 9).

Figure 9. Palafitic Pier of Porto da Carrasqueira. Source: Jules Verne Times Two.

The West Windmills showcase Portugal's wind energy heritage, with historical records indicating over 876 such structures across twelve municipalities. Hydropower was harnessed at the Monastery of Alcobaça through a sophisticated water management system that architectural historians consider "perhaps the most audacious and extensive of Portuguese Middle Ages" (Figure 10).

Figure 10. West windmills. Source: Bonecos windmills (Wikimedia Commons byArmando Ferreira).

Despite geographic and cultural variations, several overlapping patterns emerge in the selected cases. First, all the cases show water management systems adapted to local hydrological conditions—from the Knossos canalization to the Laoura Chain of Wells in Cyprus—revealing water as a key element of historical adaptation to climate. Second, all the case studies use strategic thermal mass to moderate temperature fluctuations, although materials vary from stone to adobe, depending on local availability. Third, all the examples show careful consideration of building orientation and spatial organization to optimize solar patterns and prevailing winds. Finally, and perhaps most significantly, successful adaptations systematically integrated technical solutions with social practices and governance arrangements that ensured their maintenance and operation for generations, suggesting that effective climate adaptation requires attention to both technical and social dimensions.

Table 1 presents a comparative analysis of climate adaptation features across the five case studies examined in this research. The data synthesize the findings from our documentary analysis, archaeological reports, and historical records. Values shown represent estimates derived from historical documentation, archaeological evidence, and comparative studies of similar structures where direct measurement data were unavailable.

Table 1. Comparative analysis of climate adaptation features across the five case studies.

	La Aljafería (Spain):	Stilt Houses (Italy)	Knossos Water System (Greece)	Laoura Chain of Wells (Cyprus)	Palafitic Pier (Portugal)
Estimated cooling capacity	5–8 °C interior temperature reduction through passive means	3–5 °C humidity stabilization	Not applicable (water management system)	Not directly cooling-focused	Not directly cooling-focused
Material sourcing	Local stone and clay (<20 km radius), low embodied energy	Local timber from surrounding forests	Local limestone and clay	Local stone and timber within community boundaries	Local wood species with high water resistance
Water management efficiency	Sophisticated recycling system using gravity flow	Elevation to manage flooding risks	450 m^3 daily capacity with minimal leakage	61 interconnected wells serving 200 hectares	Designed to accommodate tidal variations
Climate change adaptability	Effective across seasonal variations but vulnerable to extreme heat events	Highly adaptive to water level changes	Resilient to drought conditions	Vulnerable to extended drought	Designed for tidal variation and storms
Integration with social practices	Required seasonal maintenance routines and specialized knowledge	Community-based construction and repair systems	Administered through centralized palace authority	Family-based maintenance system with 24 participating households	Collaborative community construction across generations
Primary climate challenge addressed	Extreme summer heat	Flooding and water level variation	Water scarcity	Irrigation in arid conditions	Tidal variations and coastal flooding

Source: own elaboration.

3.2.5. Cross-Country Comparative Analysis

Despite geographic and cultural variations, several significant patterns emerge when comparing climate adaptation strategies across the five Mediterranean case studies. These patterns reveal both shared principles and regionally specific innovations that responded to environmental challenges.

Shared Adaptation Principles

Water management emerges as a universal concern across all five regional cases, though it has been addressed through different technical approaches. From La Aljafería's evaporative cooling system to the Knossos canalization and the Laoura Chain of Wells in Cyprus, controlling water resources proved fundamental to climate adaptation regardless of specific climatic conditions. This reflects the Mediterranean's characteristic water scarcity and seasonal rainfall patterns that required sophisticated management.

Strategic use of thermal mass appears consistently across the Spanish, Greek, and Cypriot cases, though materiality varies according to local availability—stone predominates in mountainous regions, while clay and earth materials are more common in alluvial areas. La Aljafería's thick walls and the ecological houses of Klirou both demonstrate how thermal mass moderates temperature fluctuations despite using different materials.

Building orientation and spatial organization principles show remarkable consistency across all cases. The strategic positioning of openings to capture or avoid prevailing winds, the use of courtyards as microclimate generators, and the careful consideration of solar angles appear as recurring strategies from Spain to Cyprus, suggesting a shared understanding of basic climate response principles.

Regional Distinctions

While sharing fundamental principles, each region developed distinct technical expressions adapted to specific local challenges. The Italian case studies demonstrate innovation in flood adaptation, with stilt construction techniques at Lake Ledro creating resilience to water level variations. The Greek cases excel in wind utilization, with the Ios windmills representing a sophisticated understanding of aerodynamics. Cyprus developed exceptionally community-oriented water management systems, while Portugal's structures show particular innovation in adapting to coastal conditions and tidal variations.

Construction techniques and material processing also show regional specialization. The Islamic-influenced stonework of La Aljafería demonstrates sophisticated understanding of the thermal properties of stone, while the Italian timber-joining techniques at Lake Ledro reflect specialized knowledge of wood behavior in humid conditions. The drystone techniques of Greece and Cyprus, though superficially similar, show regional variations in how stones are cut and placed to respond to different seismic conditions.

Finally, the social organization supporting these adaptation features varies significantly. The centralized palace authority maintaining La Aljafería contrasts with the family-based management of the Laoura Chain of Wells in Cyprus and the community-based construction of Portugal's Palafitic Pier, demonstrating how similar technical challenges were addressed through different social arrangements based on local governance traditions.

The next section will discuss how these historical practices can inform contemporary climate adaptation efforts, particularly in terms of sustainable architecture, water management, renewable energy systems, and community resilience building.

4. Discussion

We agree with Jared Diamond in his book "*Collapse: How Societies Choose to Fail or Succeed*", which explores the collapse of past civilizations due to environmental challenges [51]. His work emphasizes the importance of learning from historical mistakes and successes to navigate the current climate crisis. Also, Naomi Oreskes in her book "*Merchants of Doubt*", examines the role of misinformation and denial in obstructing climate action. Her research highlights the significance of accurate historical analysis to counter misinformation and promote evidence-based decision-making. William F. Ruddiman: Ruddiman's research on the "Early Anthropogenic Hypothesis" suggests that human activities, particularly agriculture, have influenced the climate for thousands of years. His work underscores the importance of understanding past human–environment interactions to address present and future climate challenges [52].

The IPCC in is late assessment report (AR6) is very clear in its message: it is unequivocal that human influence has warmed the atmosphere, ocean, and land; the scale of recent changes across the climate system as a whole are unprecedented over many centuries to many thousands of years; the global surface temperature will continue to increase until at least the middle of the century; and, with further global warming, every region is projected to increasingly experience concurrent and multiple changes in climatic impact drivers.

These contributions further emphasize the importance of historical analysis in climate change research. By learning from the past, understanding the present, and predicting the future, we can develop more informed and effective strategies to mitigate and adapt to climate change while building a sustainable future.

Around the world, several ancient structures and monuments have been built using a variety of materials such as adobe, mud, thatch, wood, and more. These structures have not only survived for centuries but have also endured various climatic, social, environmental, and other causes. This paper aims to explore how these ancient structures have managed to withstand the test of time and what lessons we can learn from them in the context of climate change. The discussion draws upon the works of several authors who have extensively studied and written about these remarkable architectural achievements.

First, adobe, a mixture of clay, sand, and organic materials, has been widely used in ancient structures. According to Sacko [53], the Great Mosque of Djenné in Mali, constructed in the 13th century, is an exceptional example of adobe architecture. The mosque's thick adobe walls provide thermal insulation, protecting it from extreme temperatures. Similarly, Smailes [54] highlights the Adobe City of Chan Chan in Peru, built around the 15th century, as a testament to the durability of adobe construction.

Second, mud and thatch have been utilized in the construction of various ancient structures. In his research, Addo [55] discusses traditional African roundhouses, which are made of mud and thatch. These structures have proven resilient to harsh climates and heavy rainfall due to the insulating properties of mud and the water-shedding ability of thatch. Additionally, Montero-Burgos et al. [56] explores the Native American pueblos, constructed with mud and thatch, as examples of sustainable architecture that have withstood the test of time.

Third, wood has been a prominent material in the construction of ancient structures. According to Şirikçi [57], pagodas in Asia, such as the Horyu-ji Temple in Japan, built in the 7th century, showcase the longevity of wooden structures. The natural strength and flexibility of wood, combined with proper maintenance and preservation techniques, have allowed these structures to endure for centuries. Similarly, Hjelle et al. [58] examines Viking longhouses in Scandinavia, which have survived for over a thousand years, as remarkable examples of wooden architecture.

Adaptation to climatic challenges is carried out through different solutions and proposals where examples can be found around Europe. (i) Climate-responsive design: Ancient builders incorporated climate-responsive design principles into their structures. According to Drennan and Kolb [59], the thick walls and narrow windows of ancient Egyptian temples, such as the Temple of Karnak, built around 2000 BCE, were designed to regulate temperature and airflow, adapting to the hot desert climate. Similarly, Kasal and Kacker [60] discuss the strategic orientation of ancient Indian palaces, like the City Palace in Jaipur, which maximized natural light and minimized heat gain. (ii) Natural ventilation and cooling: Ancient structures employed passive cooling techniques to adapt to local climates. In his study, Prieto [61] examines the courtyards and wind towers of traditional Middle Eastern architecture, such as the Alhambra in Spain, which harnessed natural ventilation to cool the interior spaces. These strategies reduced the reliance on energy-intensive cooling systems and minimized the environmental impact. (iii) Water management: Ancient civilizations developed sophisticated water management systems to cope with changing climatic patterns. According to Selvaraj et al. [62], the stepwells of India, such as the Rani ki Vav in Gujarat, were not only architectural marvels but also provided a reliable water supply during periods of drought. Similarly, Rahimi [63] explores the qanat systems of Iran, which efficiently transported water over long distances, ensuring water availability in arid regions.

We have learned important lessons for climate change adaptation all throughout our research. (1) Sustainable construction practices: The use of locally available and renewable materials in ancient structures highlights the importance of sustainable construction practices. As discussed by Xuan and Manan [64], embracing traditional building techniques and materials can reduce carbon emissions, minimize resource depletion, and promote cultural preservation. (2) Resilient design strategies: Ancient structures demonstrate the effectiveness of resilient design strategies in the face of climate change. According to Heidrich et al. [65], incorporating features like passive cooling, natural ventilation, and water management systems can enhance the adaptability and longevity of modern buildings, reducing their vulnerability to extreme weather events. (3) Cultural heritage conservation: Preserving ancient structures not only safeguards cultural heritage but also provides valuable insights into sustainable adaptation. Studying the construction techniques and materials of these ancient structures allows us to learn from the wisdom of our ancestors and apply it to contemporary challenges, fostering a sense of cultural continuity and resilience [66,67].

Ancient structures and monuments built with materials such as adobe, mud, thatch, wood, and more stand as enduring testaments of human ingenuity and resilience. Through the works of various authors, we have explored how these structures have withstood the test of time and adapted to climatic challenges. Therefore, some general strategies used over time to tackle climate change include the following:

(1) Vernacular architecture, which refers to the traditional building styles and techniques that are specific to a particular region or community. These buildings are often designed to adapt to the local climate and environmental conditions [68]. They utilize local materials and construction techniques that are well suited to the prevailing climate.
(2) Passive cooling strategies: traditional buildings in hot climates often incorporate passive cooling strategies to maintain comfortable indoor temperatures. These strategies include the use of thick walls, high thermal mass materials, and shading devices such as overhangs and courtyards [69]. These features help to reduce heat gain and promote natural ventilation. While these traditional cooling methods demonstrate remarkable ingenuity, their effectiveness must be critically evaluated against contemporary solutions. Wind catchers, for instance, achieve 5–15 °C temperature reductions without energy consumption, comparing favourably to mechanical HVAC systems that typically consume 40–60% of a building's energy. However, their effectiveness diminishes in low-wind conditions and densely built environments where airflow is restricted. Similarly, courtyard cooling creates microclimates with 4–8 °C temperature differentials but requires substantial space, a luxury in modern urban settings with high land costs and density requirements. The integration of these traditional approaches with modern technology presents both opportunities and challenges. Smart building management systems could optimize courtyard ventilation and wind catcher performance, yet standardization and building code compliance remain significant barriers. Modern materials science offers possibilities to enhance traditional techniques, such as developing high-thermal-mass materials with reduced weight and space requirements, potentially bridging historical wisdom with contemporary constraints.
(3) Natural insulation: traditional buildings often utilize natural insulation materials such as straw, mud, or thatch. These materials provide effective insulation against heat transfer and help to maintain stable indoor temperatures [70]. They have low embodied energy and are environmentally friendly.
(4) Thermal mass: traditional buildings often incorporate materials with high thermal mass, such as stone or adobe. These materials absorb heat during the day and release it slowly at night, helping to regulate indoor temperatures [46]. This can reduce the need for mechanical heating or cooling systems.

Traditional passive design principles and their modern interpretations reveal interesting convergences and divergences. Contemporary passive house standards require airtight construction with heat recovery ventilation—a departure from the breathable construction common in vernacular architecture. This represents a fundamental philosophical difference: historical approaches embraced daily and seasonal adaptations of building elements (adjustable mashrabiyas, seasonal courtyard modifications), while modern passive design often prioritizes fixed, unchanging performance. The climate adaptation strategies documented in La Aljafería and other case studies demonstrate a high potential for extrapolation to other building types, including current buildings. Fundamental principles, such as strategic courtyard configuration, thermal mass optimization, passive airflow management, and evaporative cooling, represent physical responses to climate that remain valid today and even if the building has diverse functions. These principles can be scaled and adapted to contemporary applications, ranging from individual residences to commercial complexes. Although their application would necessarily vary depending on local climatic conditions, building program requirements, and available materials, the bioclimatic logic analyzed provides transferable knowledge. Computer models can allow for such strategies to be easily adapted to current building designs.

Thermal mass utilization remains conceptually consistent across traditional and modern practices yet differs in implementation. Traditional buildings relied on thick walls (40–100 cm) made from local materials, whereas modern thermal mass solutions typically incorporate phase-change materials and thermally activated building systems that achieve similar performance with substantially reduced thickness (5–15 cm). This evolution reflects changing construction economics, where labor costs have increased relative to material costs, inverting traditional cost considerations.

Perhaps most significantly, the integrated, holistic approach of vernacular architecture contrasts with contemporary specialized disciplines that often approach building performance in isolated domains. This fragmentation may explain why, despite technological advances, modern buildings sometimes fail to achieve the contextual fitness evident in traditional solutions.

(1) Traditional roof designs that consider the local climate. In hot climates, roofs may have high thermal reflectance and insulation properties to reduce heat gain [71]. In cold climates, roofs may have steep slopes to shed snow and prevent heat loss.
(2) Natural ventilation: traditional buildings often incorporate design features that promote natural ventilation. This includes the use of cross-ventilation, strategically placed windows, and vents to allow for the flow of air [72]. These features help to maintain fresh indoor air and reduce the reliance on mechanical ventilation systems.
(3) Use of local materials: traditional buildings make use of locally available materials, which are often well suited to the local climate. For example, buildings in hot and arid regions may use materials like adobe or rammed earth, which have good thermal properties and can withstand high temperatures [73]. Using local materials reduces the environmental impact associated with transportation and supports local economies.
(4) Water management: traditional buildings incorporate water management strategies to mitigate the impact of climate conditions. This includes the use of rainwater harvesting systems, such as gutters and cisterns, to collect and store water for various purposes.

In the context of climate change, these strategies offer valuable lessons for sustainable construction practices and adaptation strategies. By drawing inspiration from the past and integrating it with modern knowledge, we can create resilient and environmentally conscious structures that will endure for generations to come.

The recovery of traditional architectural techniques has not only environmental and cultural impacts but also socio-economic ones. Their application favours the creation of jobs at the local level, with jobs related to forgotten trades. In this way, traditional knowledge and building practices that have been marginalized by industrialization are revitalized [74]. Likewise, the use of local materials reduces the associated logistics costs, apart from the cost of the externalities generated by this activity. This strengthens local economies [2]. All of this, together with the use of passive bioclimatic techniques, such as the use of water, thermal preservation, cross-ventilation, and solar protection, drastically reduces energy consumption [75]. These dimensions reinforce the strategic value of vernacular solutions, not only from a sustainability perspective but also as a tool for fair and inclusive territorial development.

The application of historic architectural techniques in modern urban contexts faces several limitations, especially with regard to population density and material costs. Despite the benefits of traditional solutions in terms of sustainability, their implementation may not be feasible in densely populated urban environments, where the optimization of space and infrastructure become priorities [76]. Furthermore, the costs associated with traditional materials, such as stone or wood, are often higher than modern industrial materials, which may make these techniques economically uncompetitive in large urban projects [77]. Added to this is the challenge of adapting to contemporary building regulations, which often do not take into account the particularities of historical techniques. Structural safety, energy efficiency, and accessibility regulations, as pointed out in the study by González-Alonso and González-Lozano [78], can make the integration of traditional solutions difficult without a thorough revision and adaptation of these regulations. In addition, the integration of these historical techniques may require more skilled labor, which could increase labor costs and delay construction times [2]. However, several studies, including that by Morel et al. [79], have proposed that, with an appropriate adaptation and conservation approach, these techniques have the potential to offer cultural and energetic value, thus overcoming some of the prevailing technical and economic challenges. In this sense, the integration of energy simulation tools (BPST) and the selection of the most appropriate risk analysis technique in modern construction provide the opportunity to examine and optimize ancient architectural techniques for sustainable buildings that are adaptable to climatic variations [80,81].

The impact of climate change on the conservation of historic architectural heritage has become a growing concern in the fields of architecture, restoration, and cultural management. Structures constructed using traditional techniques and materials have frequently exhibited a notable capacity for passive adaptation to the environment. However, in the contemporary context, these structures are confronted with unprecedented challenges arising from the increased frequency and intensity of extreme phenomena, including torrential rains, heat waves, prolonged droughts, and sustained increases in humidity. These conditions have the potential to accelerate the degradation of materials such as stone, wood, and adobe, thereby compromising the structural integrity and habitability of historic buildings [82].

The applicability of ancestral building practices to modern challenges goes beyond their technical aspects. These historical approaches offer three particularly valuable and useful guidelines for their application today. First, they demonstrate remarkable resource efficiency: they achieve comfort with local materials and minimal operating energy, a critical consideration now as we face resource constraints and the imperatives of decarbonization. Second, they offer empirically tested models of climate-sensitive design principles that have proven their resilience over centuries of climate variability. Third, they exemplify regional adaptation rather than universal technological solutions, an increasingly relevant approach as climate change manifests itself differently in different geographic contexts. However, applying these lessons requires translation rather than direct replication. The economics of construction have changed radically, and labor is now more expensive than materials, reversing traditional cost considerations.

Confronted with this scenario, there is an imperative to formulate bespoke adaptation strategies that seamlessly integrate contemporary technical solutions without compromising the integrity of the buildings' authenticity. Among the most notable measures are the utilization of compatible and more moisture-resistant materials, the implementation of enhanced drainage and passive ventilation systems, and the employment of climate monitoring technologies to anticipate conservation interventions before damage becomes irreversible [83]. In this sense, preventive maintenance should be articulated on the basis of ongoing diagnostics, supported by locally projected climate data, and managed by interdisciplinary teams that include heritage specialists as well as climatologists, architects, and local communities.

This study has also underscored the necessity to incorporate climate risk as a pivotal variable within public policies concerning conservation, urban planning, and spatial planning. As posited by Sesana et al. [84], the adoption of adaptive planning that incorporates the resilience of cultural heritage is imperative to ensure its transmission to future generations. This also implies the recognition of the value of traditional knowledge, which is often linked to effective passive climate solutions, as a complementary source of innovation in the face of the challenges posed by global warming. Consequently, an approach to heritage conservation informed by climate considerations not only safeguards cultural assets but also reinforces the connection between sustainability, territorial identity, and collective memory.

5. Conclusions

The present study aligns with Sustainable Development Goal 11 (Sustainable Cities and Communities) by demonstrating how the recovery of traditional architectural techniques can contribute to a more efficient, resilient, and environmentally friendly urban model. The integration of ancestral knowledge into contemporary planning and construction has been demonstrated to facilitate heritage conservation, energy efficiency, and emissions reduction, which are pivotal in addressing contemporary environmental challenges. Consequently, the findings of this study provide a valuable foundation for the formulation of urban strategies that integrate environmental sustainability, cultural identity, and territorial equity.

Our examination of historical architectural practices across Europe reveals a profound repository of knowledge regarding climate adaptation that remains remarkably relevant today. The ancestral wisdom embedded in structures like La Aljafería Palace in Spain, the stilt houses of Lake Ledro in Italy, the water management systems of ancient Greece, the community-based irrigation schemes of Cyprus, and the maritime adaptations of Portugal demonstrates that these were not merely pragmatic responses to environmental challenges but sophisticated socio-technical systems that integrated cultural values, social organization, and environmental relationship into cohesive wholes.

Throughout our research, we have observed that historical climate adaptations functioned as what Graham and Thrift [9] described as "configurations that work"—stable alignments between technical elements and social arrangements that proved effective enough to be maintained and replicated over generations. The longevity of these systems, many functioning effectively for centuries, speaks to their remarkable resilience and sustainability. Unlike contemporary approaches that often rely on abundant energy and global supply chains, these historical solutions emerged under significant material and energy constraints, leading to context-specific innovations using locally available resources optimized for local climate conditions.

The socio-technical perspective we have adopted illuminates how these historical building techniques were primarily transmitted through what Polanyi [11] characterized as tacit knowledge embodied in craft practices. Master builders taught apprentices through direct experience rather than formal documentation, embedding climate adaptation strategies within craft traditions that were occasionally codified in architectural treatises. This tacit knowledge spread through trade, conquest, and cultural exchange, particularly evident in Mediterranean architectural evolution, where techniques for passive cooling adapted to local materials and social practices while maintaining core principles of climate response.

Most significantly, these historical adaptations were embedded in social structures that made them viable. The Laoura Chain of Wells in Cyprus functioned through complex social arrangements dividing responsibility among families within the community. Similarly, traditional buildings relied on regular, seasonal maintenance activities organized through family and community structures, with specific tasks allocated according to gender, age, and social position. This integration of technical maintenance into social practice ensured the longevity of climate adaptation features that might have otherwise deteriorated rapidly.

In examining La Aljafería Palace specifically, we have identified an exemplary model of bioclimatic architecture that demonstrates the sophisticated understanding Islamic builders had of passive cooling strategies. The palace's architectural elements, strategic courtyards, thermal mass management, ventilation systems, and ingenious water features collectively create comfortable interior environments despite the region's harsh summer climate. These elements were not isolated technical solutions but integrated aspects of a holistic design approach that simultaneously served structural, thermal, social, and symbolic purposes, reflecting the cultural values and aesthetic principles of the society that created them.

Contemporary performance measurements of historical systems, where possible, indicate that many achieved efficiency levels comparable to modern counterparts while using entirely local, renewable resources and minimal embodied energy. Wind catchers achieved 5–15 °C temperature reductions without energy consumption, comparing favourably to mechanical HVAC systems that typically consume 40–60% of a building's energy. Courtyard cooling created microclimates with 4–8 °C temperature differentials. Traditional passive cooling methods demonstrate remarkable ingenuity, though their effectiveness must be critically evaluated against contemporary solutions and constraints such as urban density and changing economic conditions, where labor costs have increased relative to material costs.

What emerges from our analysis is that the path forward lies not in rejecting technological progress but in reintegrating traditional wisdom with modern capabilities to create truly climate-resilient architecture. The integration of these traditional approaches with modern technology presents both opportunities and challenges. Smart building management systems could optimize courtyard ventilation and wind catcher performance, while modern materials science offers possibilities to enhance traditional techniques, such as developing high-thermal-mass materials with reduced thickness requirements. However, standardization and building code compliance remain significant barriers to implementing these hybrid approaches.

As climate change intensifies, our findings suggest a dual challenge for architects, conservationists, and policymakers: developing strategies to reduce the vulnerability of historical structures to current climate impacts while also learning from and adapting these time-tested techniques to contemporary sustainable design. The preservation of historic structures is crucial not merely for safeguarding our cultural heritage but for maintaining access to this valuable knowledge repository. Efforts to protect these structures from climate risks are imperative to ensure their longevity for future generations to appreciate and learn from.

Perhaps most significantly, the integrated, holistic approach of vernacular architecture contrasts sharply with contemporary specialized disciplines that often approach building performance in isolated domains. This fragmentation may explain why, despite technological advances, modern buildings sometimes fail to achieve the contextual fitness evident in traditional solutions. The historical examples we have studied operated through what Hughes [32] termed "seamless webs" connecting technological artifacts, social practices, and natural systems. Their success depended not on technological sophistication alone but on the alignment between technical features, social arrangements, cultural values, and environmental conditions.

Climate change poses significant challenges to the preservation and sustainability of structures, buildings, and cultural heritage. The increasing intensity of natural phenomena and rising temperatures have a profound impact on architectural design and the vulnerability of historic structures. Extreme weather events can cause significant damage to foundations, timber structures, and building materials. Moreover, the degradation of surrounding vegetation and landscape due to climate change further compromises the appearance and integrity of historic buildings.

Our research demonstrates that ancestral wisdom and traditional building techniques offer valuable lessons for contemporary climate adaptation. These historical approaches utilized locally available materials and passive design strategies that required minimal energy inputs while providing effective climate regulation. By bridging past knowledge with present needs, we can develop more sustainable practices in contemporary architecture and heritage conservation that align with the growing field of bioclimatic design.

Based on our findings, we propose specific recommendations. Architects should integrate passive design principles early in the design process, rather than relying primarily on mechanical systems, and use software tools to optimize traditional strategies based on current needs. Building preservationists could conduct climate vulnerability assessments by identifying strategic points of intervention that enhance resilience while preserving the authenticity of the architectural heritage. Policy makers should revise building codes to accommodate proven traditional techniques that may not fit today's highly standardized and globalized approaches, creating certain incentives for those using this approach. Collectively, all stakeholders should collaborate in making this a reality. Thus, these measures would help bridge the current gap between heritage conservation and climate adaptation, creating buildings that combine culture and environment.

In conclusion, the challenge that emerges from our research is twofold: first, to develop strategies that reduce the vulnerability of historical structures to climate change impacts; and second, to inspire citizens, organizations, and public institutions to recognize the value of this architectural heritage as a knowledge repository for addressing present-day environmental challenges. As we face increasing climate uncertainty, these millenary confrontations with environmental variability offer not just inspiration but practical guidance for creating buildings that can withstand the test of time while maintaining harmony with their surroundings. The wisdom embedded in these ancient walls speaks directly to our most pressing contemporary challenges, reminding us of that sustainable solutions often lie in rediscovering what our ancestors already knew.

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