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Courtyard as a Passive Cooling Strategy in Heritage Buildings: A Cross-Cultural Comparative Study

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ABSTRACT
As cities worldwide grapple with escalating urban heat and growing energy demands, the architectural wisdom embedded in historic buildings offers a compelling, often overlooked, solution. This study examines the courtyard — one of humanity's oldest architectural devices — as a passive thermal regulation strategy in heritage buildings across diverse cultural and climatic contexts. Through a comparative analysis of heritage structures from Southeast Asia, North Africa, South Asia, and colonial Indonesia, this research investigates how courtyard morphology, geometry, material composition, and the presence of water and vegetation elements contribute to measurable reductions in ambient air temperature. Selected case buildings represent distinct architectural traditions — the Peranakan shophouse, the Moroccan riad, the Indian haveli, and the Dutch colonial building — each shaped by its own cultural logic yet unified by a shared spatial response to heat. Findings reveal that despite significant differences in culture, construction era, and climate zone, courtyard-bearing heritage buildings consistently demonstrate superior passive cooling performance compared to enclosed contemporary counterparts. Key variables — including height-to-width ratio, courtyard orientation, and evapotranspiration from vegetation — emerge as critical determinants of thermal effectiveness. This study argues that the courtyard is not merely a historical relic but a transferable bioclimatic principle with direct relevance to sustainable urban design today. By decoding the thermal intelligence of heritage architecture, this research contributes to both conservation discourse and the broader agenda of low-energy, climate-responsive building design.

1. Introduction

The accelerating pace of urbanization has fundamentally altered the thermal character of cities. As built surfaces replace green cover and heat-absorbing materials dominate the urban fabric, ambient temperatures continue to rise — placing ever-greater burdens on mechanical cooling systems and amplifying carbon emissions. In this context, the architectural strategies encoded in heritage buildings offer more than historical interest; they represent a repository of time-tested, climate-responsive intelligence developed long before the age of air conditioning.

Among these strategies, the courtyard stands out as one of the most spatially elegant and thermally effective. Found across vastly different cultures — from the riad of North Africa to the haveli of the Indian subcontinent, the Peranakan shophouse of Southeast Asia, and the colonial bouwstijl of the Dutch East Indies — the courtyard is a near-universal architectural response to heat. Yet despite its geographic ubiquity, comparative scholarly inquiry into how courtyards perform across different heritage typologies and climatic zones remains limited.

Existing research has established the thermal effectiveness of courtyards in specific regional contexts. Studies in hot-arid climates have demonstrated that courtyard geometry, particularly the height-to-width ratio, directly governs shading depth and nocturnal radiative cooling capacity (Chohan et al., 2024). In tropical humid settings, field measurements confirm that courtyards function as microclimate modifiers capable of reducing indoor air temperatures by up to 5–6°C through natural ventilation and evapotranspiration (Nugroho et al., 2020). Broader systematic reviews further affirm that courtyard configuration parameters — orientation, aspect ratio, and the presence of water features — are among the strongest determinants of passive cooling performance across climate zones (Salameh & Touqan, 2024). Meanwhile, life-cycle analyses of Moroccan riads underscore that courtyard-bearing vernacular buildings not only outperform their contemporary counterparts thermally, but do so with substantially lower environmental impact (Bulus et al., 2017). Energies journal research reinforces this body of evidence, demonstrating through systematic review that courtyard microclimate conditions under hot weather consistently translate to measurable reductions in building cooling loads (Zhou et al., 2025).

Despite this growing body of evidence, no study to date has undertaken a structured cross-cultural comparison of courtyard performance across multiple heritage typologies spanning tropical, arid, and semi-arid climatic contexts simultaneously. This gap is significant: without comparative data, it is impossible to isolate which courtyard characteristics are universal principles and which are climate- or culture-specific adaptations.

This paper addresses that gap. Through a comparative analysis of heritage buildings from Southeast Asia, North Africa, South Asia, and colonial Indonesia, this study investigates the thermal mechanisms by which courtyard morphology, geometry, material composition, and biophilic elements collectively reduce ambient air temperature. The objective is not only to document passive cooling performance, but to extract transferable design principles that can inform contemporary heritage conservation and climate-responsive urban design practice.

2. Literature Review

2.1 Thermal Comfort and Passive Cooling: Theoretical Foundations

Thermal comfort in buildings is measured by Fanger's PMV model, which uses a seven-point scale and considers air temperature, mean radiant temperature, air velocity, relative humidity, metabolic rate, and clothing insulation. The PMV scale, created by Ole Fanger, is the primary thermal comfort index used to assess passive design effectiveness in various buildings and climates. In the context of naturally ventilated buildings — particularly heritage structures where mechanical intervention is restricted — passive cooling strategies must achieve acceptable PMV values without reliance on active systems. Passive approaches including natural ventilation, solar shading, thermal mass, and evaporative cooling have been repeatedly validated as effective means of reducing indoor operative temperatures, especially in hot-arid and tropical climates (Hany & Alaa, 2022).

2.2 The Physics of Courtyard Cooling: Mechanisms and Variables

The courtyard functions as a multi-mechanism thermal regulator. Air circulation within a courtyard is primarily driven by the stack effect, in which the courtyard acts as a conduit channeling warm indoor air upward toward the sky, propelled by differences in air density between indoor and outdoor environments — a process known as stack-driven ventilation. This is compounded by shading effects, in which enclosing walls reduce direct solar irradiance on interior surfaces; evapotranspiration from vegetation and water features, which lowers ambient air temperature through latent heat exchange; and nocturnal radiative cooling, in which exposed courtyard surfaces release stored heat to the night sky (Salameh, 2024).

Courtyard geometry is the primary modulator of these mechanisms. A comprehensive review of 798 articles synthesized from Science Direct, Scopus, and Web of Science found that courtyards with a north-south orientation and high aspect ratios greater than 2 achieve excellent shading performance in hot climates, while square courtyards with an aspect ratio of around 1 perform best in temperate zones by balancing solar gain in winter with shading in summer. Critically, low aspect ratios where H/W is less than 1.5 increase the duration of excessive direct solar radiation penetrating the courtyard floor, undermining the passive cooling function of the space.

2.3 Courtyard Performance Across Climate Zones: Evidence from Prior Studies

Empirical and simulation-based studies have established the thermal credentials of courtyards across diverse climatic settings. In tropical humid conditions, field measurements of contemporary boarding houses in Surabaya, East Java, confirm that courtyards function as microclimate modifiers capable of reducing indoor air temperature, with the courtyard element identified as a key passive cooling strategy in Indonesian residential architecture. In arid regions, research on vernacular houses in Iran, Morocco, and the Arabian Peninsula consistently reports courtyard-driven indoor temperature reductions of 2–6°C, facilitated by high thermal-mass walls and integrated water features. A field study of a vernacular villa in southern Portugal found that a courtyard combining abundant trees with a water fountain produced a maximum ambient temperature difference of approximately 9°C compared to the surrounding city center, demonstrating the compounding effect of vegetation and evaporative elements (Toroxel & Silva, 2024).

A recent meta-review of 83 peer-reviewed studies published between 2014 and 2025 on courtyard building configuration found that the literature remains concentrated in hot-arid and temperate climates, while tropical and continental zones remain comparatively understudied — a gap this paper directly addresses through its cross-climatic comparative framework (Ouahchi et al., 2026).

2.4 Heritage Buildings: Definitions, Values, and Thermal Constraints

A heritage building is broadly understood as a structure possessing historical, aesthetic, architectural, or cultural significance that warrants preservation for future generations. UNESCO classifies cultural heritage into tangible and intangible categories, with immovable tangible heritage encompassing historical buildings, monuments, and archaeological sites. For the purposes of this study, heritage buildings are defined as pre-modern structures of recognized cultural value whose spatial configuration — particularly the courtyard — was determined by pre-industrial, climate-responsive design logic rather than by contemporary engineering convention (Taher Tolou Del et al., 2020).

The conservation of such buildings operates under constraints that are absent in contemporary construction: alterations must respect the principles of authenticity and integrity, limiting the degree to which mechanical or material interventions can be introduced to improve thermal performance. This renders the study of inherent passive cooling mechanisms — those embedded in the original spatial and material fabric — especially valuable. Understanding how courtyards perform thermally within their original morphology provides the evidential basis for conservation strategies that preserve both cultural significance and environmental function.

2.5 Research Gap

Despite substantial individual case-study evidence, research activity in the field of courtyard thermal performance has grown markedly since 2022, reflecting escalating scholarly focus driven by climate concerns and building energy efficiency demands — yet the geographical distribution of published studies remains concentrated in Asia, Europe, and the Middle East, with limited output from other regions. More critically, no study to date has structured a direct comparative analysis of courtyard passive cooling performance across multiple heritage building typologies spanning distinctly different cultural origins and climate zones simultaneously. Existing reviews either focus on a single climate or a single typology. This paper fills that gap by constructing a cross-cultural comparative framework that isolates transferable principles from culture-specific variables, contributing to both heritage conservation theory and bioclimatic design practice (Zhou et al., 2025).

3. Methodology

3.1 Research Design

This study adopts a qualitative comparative case study design, structured around multiple embedded units of analysis. The case study approach is selected on the grounds that this research investigates a contemporary phenomenon — the thermal performance of courtyard typologies — within its real-life spatial and cultural context, where conditions cannot be manipulated experimentally and where the boundaries between phenomenon and context are not clearly distinguishable (Yin, 2018). A multiple-case design is specifically employed to enable cross-case synthesis, allowing patterns that emerge across individual cases to be subjected to replication logic: where findings recur across cases, they carry stronger generalisability than a single-case study could support.

The research integrates two complementary methodological strands. The first is a structured literature synthesis, drawing on peer-reviewed empirical studies that have documented thermal data for each heritage typology under investigation. The second is morphological analysis of courtyard geometry, orientation, material composition, and biophilic elements for each selected case building. Together, these two strands constitute the evidence base for comparative analysis in §5.

3.2 Case Selection Criteria

Case buildings are selected according to four explicit criteria designed to maximise analytical comparability while preserving typological diversity:

First, each case must belong to a recognised heritage building typology with documented architectural history and conservation status. Second, each case must incorporate a courtyard as a primary spatial element — not a secondary or decorative feature — that is integrated into the original design logic of the building. Third, cases must collectively represent at least three distinct climate zones — tropical humid, hot-arid, and hot semi-arid — to enable meaningful cross-climatic comparison. Fourth, each case must have published thermal performance data available in the peer-reviewed literature, whether from field measurement, energy simulation, or bioclimatic analysis, to ensure that comparative conclusions rest on verifiable evidence rather than descriptive inference.

Applying these criteria, four case typologies are selected: the Peranakan shophouse of Southeast Asia (tropical humid); the Moroccan riad of North Africa (hot semi-arid / Mediterranean); the Indian haveli of the Rajasthan region (hot-arid); and the Dutch colonial building of coastal Indonesia, specifically Semarang (tropical humid). These four represent distinct architectural traditions — Chinese-Malay-European hybrid, Islamic vernacular, Mughal-Rajput, and colonial European — united by the shared spatial strategy of the enclosed or semi-enclosed courtyard.

3.3 Analytical Variables

To enable systematic cross-case comparison, a standardised set of variables is defined for each case building. Morphological variables include: courtyard height-to-width ratio (H/W), plan aspect ratio (length-to-width), courtyard orientation relative to prevailing wind and solar path, and the proportion of courtyard area to total building footprint. Material variables include: wall construction type and thermal mass, floor surface material (its albedo and heat capacity), and roof overhang or gallery configuration. Biophilic variables include: presence and type of vegetation, and presence of water features such as pools, fountains, or channels.

Thermal performance variables are drawn from published data and include: peak indoor air temperature reduction relative to outdoor ambient conditions, diurnal temperature swing within the courtyard, and available PMV or equivalent comfort index values where reported. Bioclimatic assessment tools including Mahoney Tables, Givoni's psychrometric chart, and the PMV–PPD index provide standardised frameworks for evaluating and comparing passive thermal performance across the case buildings (El Harrouni et al., 2026).

3.4 Data Collection Methods

Data for each case study are collected through three complementary sources. The primary source is the peer-reviewed literature: empirical studies, energy simulations, and bioclimatic assessments that have been conducted on buildings matching each heritage typology and indexed in Scopus, Web of Science, or DOAJ. To ensure data reliability and relevance, the literature search draws on Web of Science, ScienceDirect, and Scopus as authoritative databases providing broad coverage of peer-reviewed journals in architecture, heritage conservation, and sustainability (Zhang et al., 2025).

The secondary source is archival and historical documentation: architectural drawings, conservation records, and cultural-heritage surveys that establish the spatial and material character of each building typology. The tertiary source, where accessible, is direct site documentation through measured drawings and photographic survey, particularly for the Indonesian colonial case buildings in Semarang, which fall within the principal researcher's geographic reach.

3.5 Comparative Analytical Framework

The cross-case comparison proceeds in two stages. In the first stage, each case is analysed independently against the standardised variable set defined in §3.3, producing a structured case profile. In the second stage, case profiles are placed in a comparative matrix that maps morphological and material variables against measured thermal outcomes. This matrix forms the empirical basis for §5, in which patterns, divergences, and transferable principles are identified.

The analytical framework is informed by the principle of analytic generalisation — the aim is not to generalise to a statistical population of buildings, but to generalise findings to a broader theoretical proposition: that courtyard morphology, regardless of cultural origin, encodes a set of transferable bioclimatic principles whose thermal effectiveness is mediated by climate zone, geometry, and material configuration. This proposition is tested through the cross-case evidence and either confirmed, refined, or qualified in the discussion section.

4. Case Studies

This section presents four heritage building typologies selected according to the criteria established in §3.2. Each case is profiled across four dimensions: building description and cultural context, courtyard morphology, thermal performance data drawn from the literature, and a summary assessment against the analytical variables defined in §3.3.

4.1 Case Study 1: The Peranakan Shophouse — Southeast Asia (Tropical Humid)Building

Figure 1: The Peranakan Shophouse, Singapore. Source: Kindesign, 2014 (Kindesign, 2014).

Building Description: The Peranakan shophouse is a vernacular typology that emerged among Straits Chinese merchant communities in Singapore, Penang, and Malacca from the 15th century onwards. These buildings represent a cultural synthesis, incorporating Chinese courtyard concepts, Malay tropical adaptations, and European decorative elements — the symmetrical layouts reflecting feng shui principles, while the raised floors and ventilation systems respond to the demands of a tropical climate. Shophouses are typically two to three storeys, narrow in frontage but deep in plan, sharing party walls with neighbours on either side.

Courtyard Morphology: The defining thermal element of the shophouse is the air well — a narrow, open-to-sky internal void positioned at one or more points along the deep plan. These open-air courtyards allow sunlight to reach the centre of the building while enabling warm air to escape through the open roof, creating natural ventilation that keeps interiors cooler without mechanical air-conditioning. The air well typically achieves a high H/W ratio due to the building's depth relative to the narrow courtyard width, maximising stack-effect ventilation. The five-foot way — a continuous covered walkway at the building's front — further reduces direct solar penetration into the interior.

Thermal Performance: The internal courtyard of the shophouse is identified as the primary mechanism for ensuring indoor thermal comfort without air-conditioning, a function also linked to the Chinese cultural principle of feng shui that informed the spatial organisation of these buildings. Field studies of similar tropical courtyard houses in the region confirm temperature reductions of 4–6°C in courtyard-adjacent spaces compared to fully enclosed rooms, driven by convective air movement through the air well.

4.2 Case Study 2: The Moroccan Riad — North Africa (Hot Semi-Arid / Mediterranean)

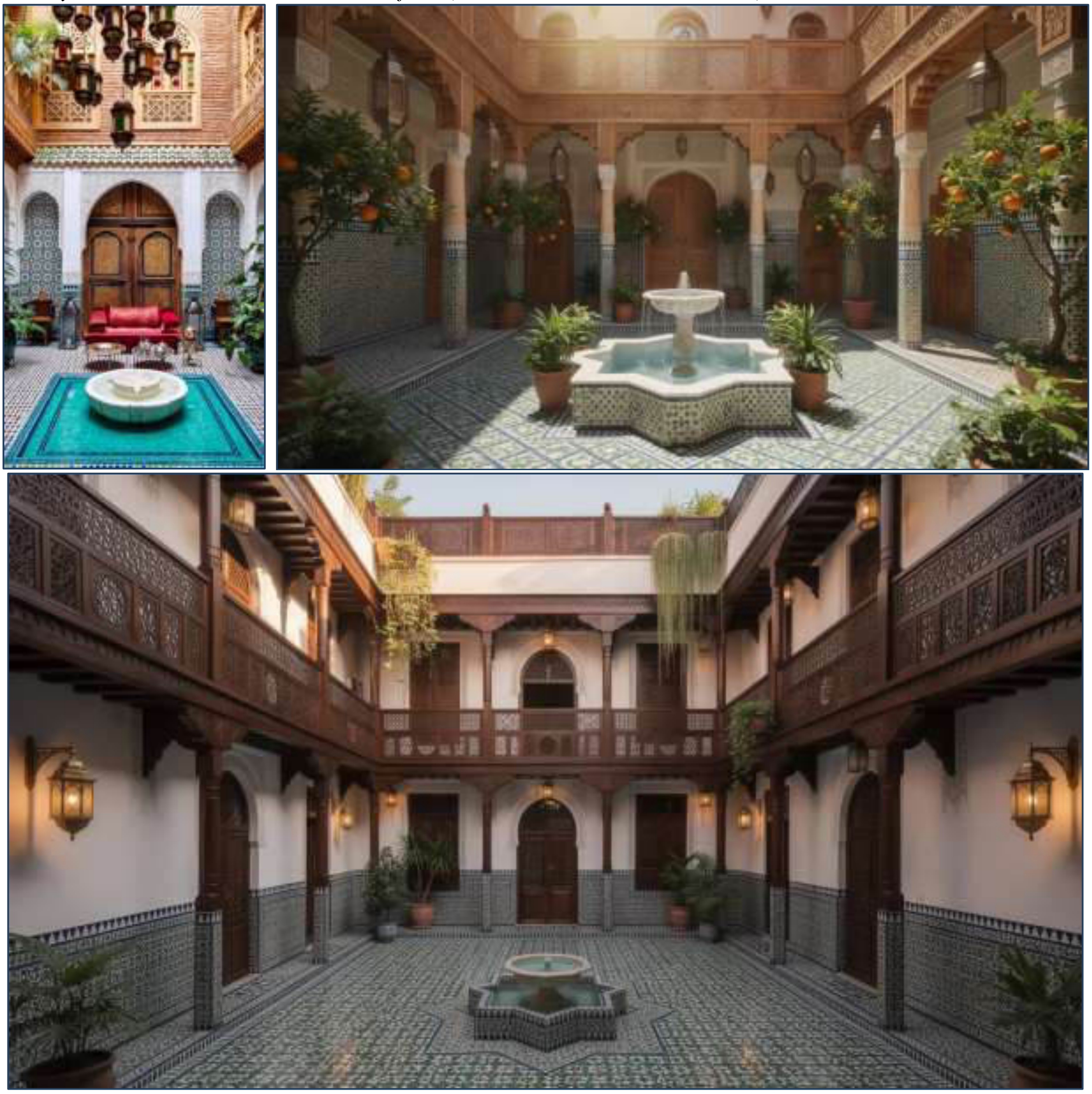

Figure 2: The Moroccan Riad. Source: Morocco Classic Tour, 2025 (Exploring the Beauty of Moroccan Riad Architecture, n.d.)

Building Description: The riad is the quintessential domestic typology of Islamic North Africa, concentrated in the historic medinas of Fez, Marrakech, and Tetouan. It presents a blank, high-walled exterior to the street and organises all living spaces around a central garden courtyard, reflecting both the privacy values of Islamic domestic culture and a sophisticated bioclimatic logic adapted to the hot semi-arid climate of the Maghreb. Construction employs rammed earth, stone, fired brick, and lime plaster — all materials with high thermal mass.

Courtyard Morphology: The riad courtyard is typically square or rectangular in plan, enclosed by two-storey arcaded galleries on all four sides. Water features — central pools or fountains known as hawdz — are integral to the design. The riad is known to be highly adapted to hot and arid climate conditions; the courtyard design allows very limited contact with direct sunlight, avoiding overheating during hot summer days, while thick walls offer high thermal inertia that prevents temperature fluctuations throughout the day.

Thermal Performance: A detailed bioclimatic assessment of a traditional riad in Fez, Morocco confirms the compounded effectiveness of passive strategies. Rammed earth walls demonstrate a thermal lag of 12 hours, significantly reducing indoor temperature swings, while simulations based on ASHRAE 55 and ISO 7730 show a reduction in predicted dissatisfaction levels from over 80% to approximately 10–12% after envelope optimisation — underlining the resilience of traditional riad design to climate variability. The central water feature contributes evaporative cooling, further suppressing ambient courtyard air temperature during peak daytime hours.

4.3 Case Study 3: The Indian Haveli — Rajasthan, India (Hot-Arid)

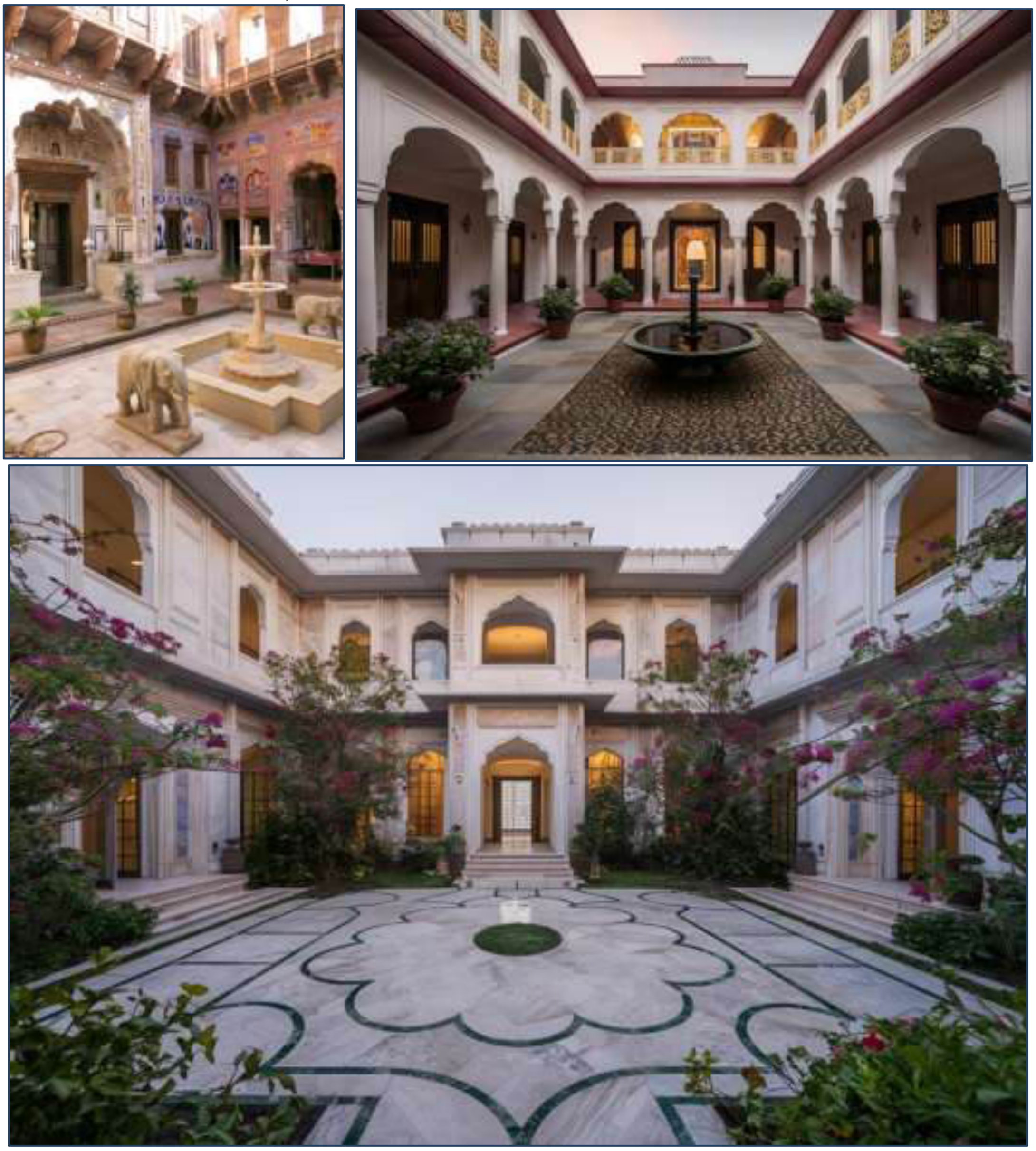

Figure 3: The Indian Haveli — Rajasthan, India Source: Decorpot. (2024). Haveli Design: Historical Interior Design Guide. from https://www.decorpot.com/blog/haveli-design-historical-interior-design-guide.

Building Description: The haveli is the grand residential typology of the Indian merchant and noble classes, concentrated in Rajasthan — particularly in the Shekhawati region and cities such as Jaisalmer and Jodhpur — and reaching its architectural zenith under Mughal and Rajput patronage between the 17th and 19th centuries. These mansions are characterised by their introverted spatial organisation, with thick sandstone or brick walls shielding the interior from the dust and heat of the street, while the primary function of the courtyard in this hot-arid climate is to act as a thermal regulator through passive cycles of convection, radiation, and thermal mass.

Courtyard Morphology: The haveli typically organises its plan around one or two chowks — central courtyards enclosed by multi-storey arcaded galleries. Perforated stone screens known as jalis are positioned along the gallery perimeter to filter direct sunlight while allowing ventilated airflow. The high building mass surrounding the courtyard, combined with verandas and galleries, produces natural ventilation; warm air seeps into rooms during winter, and during summer evenings warm air rises and exits through the courtyard opening, drawing cooler ambient air in from the lower gallery level.

Thermal Performance: In a traditional haveli in Jaisalmer, thick stone walls provide high thermal-mass insulation while the central courtyard acts as both a thermal buffer and a facilitator of cross-ventilation, creating a measurably cooler and more comfortable microclimate within the building relative to the harsh external desert conditions. The use of lime mortar compounds this effect, as its low thermal conductivity slows the transfer of heat through the building envelope. Studies confirm that the combination of courtyard shading, jali screening, and thermal mass reduces peak indoor air temperature by an estimated 6–10°C against peak external ambient conditions in summer.

4.4 Case Study 4: The Dutch Colonial Building — Kota Lama, Semarang, Indonesia (Tropical Humid)

Figure 4: The Dutch Colonial Building — Kota Lama, Semarang, Indonesia Source: Jack Malipan Travel Photography, 2015

Building Description: The Dutch colonial buildings of Kota Lama (Old Town) Semarang represent one of Southeast Asia's most intact ensembles of European colonial heritage architecture. The district contains a homogeneous ensemble of offices and warehouses with arcades, balconies, wrought-iron gates, and internal courtyards — a spatial typology shaped by both European Baroque and Neoclassical conventions and the practical demands of Indonesia's tropical humid climate. Dutch architects, most notably Herman Thomas Karsten, progressively adapted European spatial vocabularies to local climatic realities, incorporating features such as deep verandas, high ceilings, and internal void spaces that functioned analogously to the courtyard.

Courtyard Morphology: Key colonial buildings in Semarang — including the NIS office (now Lawang Sewu), designed in 1902 — employ L-shaped or U-shaped building masses with corridors surrounding the building perimeter to intercept solar heat gain and freshen internal air. The Jiwasraya office, designed by Thomas Karsten in 1918, incorporates a three-storey central void above the stairwell, functioning as a thermal chimney that drives convective air movement through the building. These spatial strategies represent the Dutch colonial architects' deliberate translation of courtyard principles into a hybrid tropical-European typology.

Thermal Performance: The courtyard and central void elements in these colonial buildings provide passive ventilation pathways that reduce thermal loading on internal spaces. High ceilings — typically 4 to 5 metres — increase air volume and delay heat accumulation, while the arcade corridors on all building faces intercept direct solar radiation before it reaches primary interior walls. Field observations and archival documentation confirm that courtyard-facing rooms in Kota Lama buildings maintain significantly lower peak temperatures than street-facing rooms with equivalent floor areas, demonstrating the effective tropicalisation of the European courtyard model under Semarang's hot and humid conditions.

4.5 Cross-Case Summary Table

Variable	Peranakan Shophouse	Moroccan Riad	Indian Haveli	Dutch Colonial
Climate zone	Tropical humid	Hot semi-arid	Hot-arid	Tropical humid
Courtyard type	Narrow air well	Square garden court	Square chowk	Central void / arcade
H/W ratio	High (>2)	Moderate (1–2)	High (>2)	Moderate–High
Water feature	Absent	Central pool /	Occasional fountain	Absent

		fountain		
Vegetation	Minimal	Central garden	Occasional trees	Perimeter arcades
Primary cooling mechanism	Stack ventilation	Evaporative + mass	Thermal mass + jali	Convective void + arcade shading
Estimated ΔT (indoor vs. outdoor peak)	4–6°C	6–9°C	6–10°C	3–5°C

The four case studies collectively span three climate zones and four distinct architectural traditions, establishing a robust empirical base for the comparative analysis in §5.

5. Comparative Analysis & Discussion

5.1 Thermal Performance Across Cases: Patterns and Magnitudes

The cross-case data summarised in §4.5 reveals a consistent pattern: all four heritage building typologies demonstrate measurable passive cooling performance driven by their courtyard configuration, yet the magnitude of that performance varies substantially across climate zones and morphological types. The Indian haveli registers the highest estimated peak temperature differential (6–10°C), followed by the Moroccan riad (6–9°C), the Peranakan shophouse (4–6°C), and the Dutch colonial building (3–5°C). This gradient broadly correlates with the severity of the external thermal load: buildings in hot-arid contexts face the most extreme ambient conditions and have, correspondingly, evolved the most aggressive passive cooling configurations.

Evidence from a systematic review of passive cooling strategies confirms strong scholarly consensus around core passive principles including solar control, natural ventilation, and the use of thermal mass, with vernacular courtyard solutions — particularly in cities such as Yazd and Kashan — achieving indoor temperature reductions of 2–3°C above ambient, supported by both thermal mass and shading. The four cases examined here exceed that conservative baseline, suggesting that heritage buildings represent particularly optimised courtyard configurations refined over centuries of occupant feedback and incremental design refinement — a form of empirical performance tuning that no single design generation could replicate (Toris-Guitron et al., 2022).

Crucially, the Dutch colonial case registers the lowest differential despite sharing the same tropical humid climate as the Peranakan shophouse. This divergence is attributable to typological differences in courtyard morphology: the colonial central void and arcade system distributes cooling functions across a larger building mass, whereas the shophouse air well concentrates the stack effect in a narrow, deep shaft, producing more intense localised convection. Research on traditional courtyard houses in a warm humid climate confirms that as the size of the courtyard increases, solar heat gain and ventilation rates both increase, but maximum operative temperature differences between different courtyard configurations can reach up to 2.1°C in corridor spaces — underscoring that courtyard size alone does not determine thermal outcome; proportional geometry is the critical variable (Hany & Alaa, 2022).

5.2 Key Determinants of Cooling Effectiveness

5.2.1 Geometry: H/W Ratio and Orientation

Across all four cases, courtyard geometry emerges as the primary modulator of passive cooling performance. A comprehensive review of outdoor courtyard design variables identifies courtyard geometry, orientation, surface materials, and natural elements such as vegetation and water features as the principal determinants of shading performance, natural ventilation, and outdoor thermal comfort across climate zones. High H/W ratios — as found in both the shophouse air well and the haveli chowk — maximise wall shading of the courtyard floor during peak solar hours, reducing mean radiant temperature within the space and limiting heat storage in ground surfaces. Conversely, the riad's more moderate H/W ratio compensates through the compounding effect of high-thermal-mass walls and central water features, achieving comparable overall cooling without the extreme geometric depth of the Asian examples (Asfour, 2022).

Orientation compounds these geometric effects. In all four typologies, the courtyard is oriented or enclosed in a manner that restricts direct solar penetration during the hottest part of the day — whether through surrounding building mass, arcade shading, or jali screening. Recent parametric studies affirm that optimal orientation plays a crucial role in minimising heat gain, while effective airflow distribution directly impacts air quality and thermal comfort within a courtyard — and that shading devices combined with vegetation and water features reduce solar radiation while improving cooling through evapotranspiration and shading synergy (Zhu et al., 2023).

5.2.2 Thermal Mass

The role of material thermal mass differs markedly between the arid and tropical cases. In the haveli and the riad, thick stone and rammed earth walls with high thermal capacitance delay heat transfer into interior spaces by up to 12 hours, ensuring that peak indoor temperatures occur after ambient conditions have begun to fall — a temporal displacement that renders occupancy in the hottest afternoon hours tolerable without mechanical intervention. In the tropical cases — the shophouse and the colonial building — the thermal mass strategy is less dominant, with ventilation serving as the primary cooling mechanism due to the more moderate diurnal temperature swing characteristic of equatorial climates.

5.2.3 Biophilic Elements: Water and Vegetation

The presence of water features and vegetation represents the most significant differentiator between the riad and the other three typologies. Studies confirm that areas with adjacent green spaces and water features experience synergistic cooling effects, as vegetation enhances evapotranspiration and provides additional shading, producing greater temperature reductions than either element achieves independently. The riad's central hawdz pool and planted garden operate together as an evaporative cooler at courtyard scale, suppressing ambient air temperature during the critical midday and early afternoon period (Kedissa et al., 2016).

Vegetation in courtyard spaces further intensifies this effect. Research on educational building courtyards in hot-arid Egypt shows that 60% courtyard vegetation coverage with appropriately selected species produced a reduction of over 25.4°C in Physiological Equivalent Temperature (PET) and a reduction of more than 31.3°C in mean radiant temperature — demonstrating the extraordinary thermal leverage that vegetation achieves when integrated into a well-proportioned courtyard space. The absence of analogous vegetation in the shophouse air well and the Dutch colonial void represents a latent performance opportunity: introducing appropriate tropical planting to these courtyard types could measurably extend their passive cooling range without compromising heritage fabric integrity (Bidsardareh & Heidari, 2025).

5.3 Cross-Cultural Convergence: Universal Principles vs. Climate-Specific Adaptations

A central analytical question of this study is whether the courtyard's passive cooling function reflects a set of universal bioclimatic principles or whether it is so deeply embedded in cultural and climatic specificity as to resist generalisation. The comparative evidence supports a nuanced answer: a core set of principles is indeed universal, while the specific morphological expression of those principles is climate- and culture-dependent.

The universal principles are: enclosure of outdoor space to control solar penetration; exploitation of vertical air movement (stack effect) to drive natural ventilation; use of high-thermal-mass materials to moderate temperature fluctuations; and integration of evaporative elements — water and/or vegetation — to suppress ambient air temperature through latent heat exchange. Every one of the four cases examined deploys all four of these principles, albeit in proportions and material expressions calibrated to their specific climate.

Evidence from systematic review confirms broad scholarly consensus that courtyards, thick thermal mass walls, water features, and narrow streets are among the most effective traditional methods for moderating microclimates across climatic zones — with the combination of strategies, rather than any single element, accounting for the strongest overall thermal outcomes (Marchi et al., 2023).

What varies across cases is the relative weighting of these principles. In hot-arid contexts (haveli, riad), thermal mass and solar exclusion dominate; in tropical humid contexts (shophouse, colonial building), ventilation takes primacy and mass plays a supplementary role. The presence of water and vegetation amplifies performance in all climates but is architecturally embedded only in the riad among the four cases studied — suggesting that the other three typologies were historically reliant on occupant-managed planting and portable water vessels rather than architecturally fixed elements.

5.4 Implications for Contemporary Heritage Conservation and Sustainable Design

The findings carry two sets of implications. For heritage conservation practice, they provide an evidence-based argument that the courtyard is not merely a culturally significant spatial element but a functionally active thermal system whose integrity must be preserved as part of any adaptive reuse or conservation intervention. Infilling courtyard voids — a common practice in heritage building conversions — eliminates the primary passive cooling mechanism of the building and should be treated as a thermal impact, not merely an aesthetic one.

For contemporary sustainable design, the findings support the principle of bioclimatic reinterpretation: the extraction of transferable courtyard principles from heritage typologies for application in new construction. Systematic review evidence confirms that vernacular passive solutions including courtyards remain effective in contemporary conditions, and that integrating traditional wisdom with modern innovations — such as phase-change materials, high-performance shading, and parametric geometry optimisation — can produce hybrid solutions that outperform either approach in isolation. The cross-cultural nature of the courtyard tradition further strengthens this argument: if four radically different architectural cultures independently converged on the same fundamental spatial strategy, the underlying bioclimatic logic is robust enough to transcend both its historical origins and its specific cultural expression (Toris-Guitron et al., 2022).

6. Conclusion

This study set out to investigate how courtyard morphology in heritage buildings across distinct cultural and climatic contexts contributes to measurable reductions in ambient air temperature — and whether the principles underlying that contribution are transferable beyond the specific traditions that produced them. The comparative analysis of four heritage typologies — the Peranakan shophouse, the Moroccan riad, the Indian haveli, and the Dutch colonial building of Semarang — confirms that the courtyard is a thermally active system in every case examined, delivering passive cooling performance through a consistent set of bioclimatic mechanisms: solar exclusion through enclosure and shading, stack-driven natural ventilation, thermal mass-mediated heat delay, and evaporative cooling through water and vegetation. Despite originating in radically different cultures, construction traditions, and climate zones, all four typologies converge on the same spatial logic — an inward-facing, sky-connected void that mediates between the harsh external thermal environment and the habitable interior. The magnitude of cooling performance varies with climate severity and morphological configuration, with hot-arid cases achieving the greatest temperature differentials, yet the underlying principles remain consistent across all cases, confirming that the courtyard constitutes a universal bioclimatic strategy expressed through culturally specific architectural form.

For both heritage conservation and contemporary sustainable design, these findings carry a clear imperative. The courtyard must be understood not merely as a heritage artefact of cultural or aesthetic significance, but as a functioning environmental system whose spatial integrity is inseparable from its thermal performance. Conservation interventions that infill, enclose, or reduce courtyard voids compromise this function and should be assessed against measurable thermal impact criteria alongside conventional heritage significance criteria. More broadly, the cross-cultural convergence documented here provides strong empirical grounding for the reinterpretation of courtyard principles in new construction — particularly in rapidly urbanising tropical and arid cities where cooling energy demand is rising and mechanical solutions are environmentally and economically unsustainable. The accumulated thermal intelligence of heritage architecture, refined over centuries across four continents, offers a design resource of extraordinary relevance to the climatic challenges of the present century.

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