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Effective Comfort in Vernacular Courtyard Housing: A Socio-Environmental Comparison of Hausa Compounds in Kano and Siheyuan Houses in Beijing.

Jiddah Joy Demai[a], Zuo Junjie[b,*], Sha Chunfa[c], Nzoko Kakese Jeremie[a]

[a] *Jiangsu University, Zhenjiang 212000, China*

Abstract: This study compares vernacular courtyard housing in Kano (hot-dry) and Beijing (monsoon-influenced) to frame climate adaptation as a socio-technical system. A comparative mixed-methods framework integrates (i) morphological analysis of spatial and geometric strategies, (ii) calibrated EnergyPlus and ENVI-met simulations of seasonal microclimate performance, and (iii) thematic coding of resident interviews and observation logs to identify behavioral practices that extend physical performance into lived comfort. These strands are triangulated to evaluate how comfort is co-produced by built form and occupant practice. Results reveal divergent strategies: Kano compounds utilize high enclosure for persistent shading, activated by routine night flushing, whereas Beijing siheyuan employs lower enclosure to prioritize winter solar access, relying on seasonal shading and spatial migration to manage summer heat. These findings validate the concept of effective comfort, defined as a behaviorally weighted adaptive comfort metric that evaluates thermal conditions by occupants' observed probability of occupying each dwelling zone throughout the day, rather than assuming a fixed position in a single room. Unlike static comfort indices, effective comfort captures how households navigate thermally distinct microclimates to maintain acceptable conditions, extending warm-season comfort compliance by up to 10 percentage points beyond what the physical envelope alone achieves. The study concludes that contemporary low-energy housing should operationalize courtyards as calibrated "climate engines" with enclosure ratios tuned to local seasonality and incorporate transitional buffer zones enabling occupants to practice spatial migration, thereby reducing mechanical cooling dependency without sacrificing cultural functionality.

Keywords: *Vernacular architecture; Courtyard housing; Climate adaptation; Microclimate; Cultural resilience.*

1. Introduction

As the world faces escalating challenges related to climate change, the built environment plays a pivotal role in mitigating environmental impacts, particularly through the design and adaptation of buildings to local climates. Traditional vernacular architecture, developed over centuries, embodies sophisticated responses to these environmental pressures[18]. These buildings were created in close harmony with the natural surroundings, leveraging locally available materials and construction methods to regulate temperature, control solar gain, and promote air circulation. In many regions, vernacular forms are not merely passive structures but active environmental regulators—systems refined over generations of interaction between human needs and environmental conditions[16,18]. However, as rapid urbanization, globalization, and modern construction techniques have replaced many traditional designs, there is a growing concern that this repository of knowledge is being lost.

In light of these concerns, there has been a renewed interest in vernacular architecture as a source of climate-responsive design solutions. The adaptive strategies embedded in these traditional forms are seen as potentially invaluable for contemporary low-energy building design[8,9]. Yet, despite the wealth of research on individual case studies, there is a notable lack of cross-cultural comparisons that can illuminate both universal and context-specific aspects of climate adaptation in vernacular architecture.

Although extensive literature exists on vernacular architecture, it often remains siloed within regional or cultural boundaries. Studies of vernacular adaptation typically focus on a single geographic area, and comparative studies across regions with different climatic conditions remain rare[6,13]. Additionally, much of the research on climate-adaptive vernacular architecture focuses on technical performance—such as thermal regulation or material properties—without addressing the cultural dimensions of these systems[5,14,17]. Cultural practices, such as how inhabitants interact with the built environment or modify their living arrangements to cope with seasonal changes, often remain underexplored[3,15].This research gap undermines the potential for developing truly holistic climate adaptation strategies that integrate both built form and human behavior. Moreover, the impact of modernization and the shift to mechanically conditioned buildings has often overshadowed the cultural resilience embedded in traditional housing. As more vernacular forms are altered or replaced, the loss of traditional knowledge systems raises important questions about how these buildings could inform sustainable development today, especially in regions facing extreme environmental stress.

While previous comparative studies have examined vernacular typologies across regions (e.g., Nguyen et al., 2019), they have typically focused on either physical performance metrics or cultural descriptions, but rarely integrated both within a single analytical framework. Moreover, existing cross-cultural analyses tend to juxtapose findings from independent studies rather than apply identical protocols across sites, limiting the comparability of results. This study advances the field in three specific ways: (i) it introduces a quantitative "effective comfort" metric (C_{eff}) that operationally links simulated microclimate data with observed occupant behavior, enabling comfort to be evaluated as a co-produced outcome rather than a static building property; (ii) it directly compares two courtyard-based typologies—Hausa compounds in Kano and siheyuan in Beijing—under fundamentally different climate regimes using identical morphological, simulation, and behavioral analytical protocols; and (iii) it systematically distinguishes convergent adaptation principles (shared across climates) from culturally divergent strategies (specific to socio-environmental context) through structured cross-case triangulation.

This study seeks to address these gaps by conducting a comparative analysis of two distinct vernacular typologies: the Hausa courtyard compounds in Kano, Nigeria, and the Siheyuan in Beijing, China. Both typologies center around the concept of the courtyard, an architectural feature that has served as a focal point for climate adaptation and social organization. Despite the geographical and cultural differences between the two regions, both courtyard house forms evolved in response to the need for passive cooling, thermal regulation, and social cohesion in their respective climates.

The primary aim of this study is to examine how these two architectural forms have adapted to their respective climatic stressors—hot-dry conditions in Kano and the seasonal monsoon-continental climate in Beijing. *Critically, this study departs from conventional bioclimatic analysis by treating cultural practice not as contextual background but as an active performance variable. Where existing research evaluates vernacular buildings as static thermal objects, this study models occupant behavior—spatial migration between dwelling zones, ventilation routines, and activity timing—as mechanisms that actively modulate microclimate outcomes. This socio-technical framing positions thermal comfort as co-produced by built form and cultural logic rather than passively received from the physical envelope alone.* In doing so, this paper seeks to answer the following research questions:

RQ1 *(Morphological adaptation → Section 3.3):* How do Hausa compounds and siheyuan physically configure space and materials to address local climatic conditions, and which architectural features—courtyards, walls, roofs, and transitional spaces—are most significant in moderating the internal microclimate?

RQ2 *(Behavioral adaptation → Section 3.5):* In what ways are these climate-responsive designs shaped by, and integrated into, cultural practices and social organization? How do occupant behaviors—such as spatial migration between courtyards, verandas, and indoor rooms, ventilation routines, and seasonal activity timing—influence thermal comfort and adaptation?

RQ3 *(Cross-cultural synthesis → Section 5.4):* What cross-cultural design principles—both convergent and divergent—can be derived from this comparison for the design of contemporary, climate-resilient housing in regions with similar climatic constraints?

The study aims to contribute to the growing field of sustainable design by providing empirical evidence of how vernacular forms and cultural practices can be integrated into modern design solutions. Through a comparative framework that links spatial morphology, microclimatic performance, and cultural practices, this paper proposes a new way to think about climate adaptation in housing. It argues that climate resilience in architecture cannot be solely attributed to building materials or geometry; it is co-produced by the physical environment and the cultural logics that govern everyday life within the dwelling.

2. Background

2.1 Vernacular Architecture and Climate-Adaptive Design

Global architectural discourse has increasingly repositioned vernacular architecture from a historical artifact to a vital repository of climate-responsive design knowledge. Over centuries, traditional building forms co-evolved with their environments to passively regulate heat and airflow through simple, context-driven strategies—such as compact settlement layouts, internal courtyards, high-thermal-mass earthen walls, and deep shading elements. These features were not arbitrary aesthetic choices but sophisticated, empirical responses to local conditions, optimized to control solar gain, maximize thermal storage, and channel prevailing breezes. Contemporary sustainability scholars now view these vernacular solutions as critical precedents for low-energy design in warming climates. However, a significant caution pervades the recent literature: modern adaptations often risk "surface-level mimicry," replicating visual motifs like arches or facades without retaining the integrated systems that drive performance. Simply adopting the aesthetic of a mud wall or a courtyard is insufficient if the underlying thermodynamic logic is ignored. Consequently, successful contemporary application requires a deep theoretical grasp of vernacular principles as holistic climate-adaptive systems rather than merely stylistic catalogs.

2.2 Vernacular Architecture as Socio-Technical Systems

Recent scholarship has reframed vernacular architecture as a dynamic **socio-technical system** that mediates between environment, technology, and culture[1,11]characterize. These built environments as evolutionary solutions—products of a continuous negotiation between climatic constraints, material availability, and social necessities. Unlike modern engineered buildings, which are frequently optimized for single-variable performance, vernacular dwellings represent a dynamic equilibrium where physical form and human behavior co-evolve. This perspective suggests that the habitation of space is inseparable from the architecture itself. Critiques of strictly bioclimatic approaches, such as those by Murillo Camacho et al. (2023)[12], argue that purely technical analyses are misleading if they strip away the lived social practices that activate the structure. For instance, the thermal efficiency of a Hausa adobe wall or a Beijing *siheyuan* courtyard relies heavily on occupant operation—specifically, the timing of window usage and diurnal migration within the home. Therefore, evaluating performance requires linking the "hardware" of design (geometry and materials) with the "software" of culture (routines and behaviors). This view is supported by Lamb and Vale (2024) and Tran (2025), who emphasize that built form and cultural practice are inextricable components of housing resilience.

2.3 Passive Climate Adaptation Strategies in Vernacular Housing

The literature identifies three interrelated modes through which vernacular architecture achieves thermal comfort: morphological, material, and behavioral adaptation. Building geometry serves as the primary regulator of microclimate. Research confirms that the courtyard's aspect ratio (Height-to-Width) and orientation are decisive performance factors [14]. For example, Hausa compounds in hot-arid Nigeria utilize deep, compact courtyards (high H/W) to minimize solar penetration and buffer against dust. Conversely, Beijing's *siheyuan* employs a shallower, more open geometry (lower H/W) to balance winter solar admission with summer cross-ventilation. However, vernacular builders exploit thermophysical properties to moderate indoor conditions. High thermal-mass materials, such as adobe and stone, function as a thermal flywheel, absorbing heat during the day and releasing it at night to dampen diurnal temperature swings . demonstrate that this cooling potential is only fully realized when coupled with effective night-time ventilation strategies.

Unlike static modern environments, vernacular living patterns rely on the active role of the occupant. Residents practice "spatial migration," moving between outdoor courtyards, shaded verandas, and enclosed rooms to align activities with daily thermal cycles. Ergöz Karahan argue that this adaptive behavior significantly extends the "effective comfort" range of the dwelling beyond what physical form alone could achieve, often maintaining satisfaction without mechanical conditioning.

2.4 Cultural Resilience and Modernization Challenges

Beyond environmental performance, vernacular architecture acts as a vessel for cultural continuity. Holtorf defines **cultural resilience** as the capacity of traditions to endure external shocks, such as rapid modernization or climate change. Vernacular dwellings encode social organizations—such as gendered privacy zones or intergenerational hierarchies—that reinforce community identity. For example, the axial layout of a *siheyuan* reflects Confucian family order, while the concentric zoning of a Hausa compound supports Islamic customs of privacy. Preserving these forms is thus a strategy for maintaining distinct cultural identities in the face of globalization.

However, this resilience is under threat. In both Nigeria and China, rapid urbanization has led to the displacement of vernacular forms by "modern" materials that often degrade passive performance. In Kano, the substitution of thatch with corrugated metal roofs for status has inadvertently increased indoor heat loads and eliminated natural ventilation. Similarly, in Beijing, the glazing-over of courtyards disrupts the critical airflow and social function of the open space. This creates a "lock-in effect," where poor passive performance necessitates mechanical cooling. Often, this erosion is driven by socio-cultural aspirations rather than performance failures; traditional materials like mud are abandoned not because they fail thermally, but because they are perceived as antiquated. The challenge, therefore, is to modernize housing without discarding the embedded socio-environmental wisdom of the vernacular.

2.5 Research Gap and Rationale

Despite the extensive literature, significant gaps remain in understanding vernacular architecture as an integrated socio-environmental phenomenon. Current research remains largely siloed: quantitative studies often treat buildings as static physical objects, overlooking the behavioral "software" of comfort, while qualitative anthropological studies rarely quantify environmental performance. Furthermore, most research is region-specific, with few studies directly comparing how different cultures resolve analogous climatic challenges through distinct architectural strategies. This study addresses these gaps through a cross-cultural comparative analysis of Hausa compounds in Kano and *siheyuan* houses in Beijing. By juxtaposing these two distinct yet analogous typologies, the research seeks to identify *convergent strategies* (universal adaptation principles) and *divergent strategies* (culture-specific responses). This approach bridges the technical and cultural divides, combining morphological and microclimatic data with an analysis of social practice. Ultimately, this framework aims to derive design principles for contemporary housing that are not only energy-efficient but also culturally resilient, treating the home as an integrated system of people, place, and performance.

3. Methodology

3.1 Research Design and Analytical Framework

This study adopts a ***comparative, mixed-methods case study design*** to investigate how vernacular courtyard housing systems adapt to contrasting climatic and socio-cultural contexts. The research is grounded in ***analytic comparison*** rather than statistical generalization, following established methodological guidance for architectural case study research where theoretical replication, not sample size, is the primary objective.

Two vernacular housing typologies were selected as *analytically comparable yet climatically distinct cases:*

- **Hausa courtyard compounds** in Kano, northern Nigeria (hot-dry, semi-arid climate)
- **Siheyuan courtyard houses** in Beijing, China (monsoon-influenced continental climate)

The methodology is structured around an *integrated socio-environmental analytical framework,* in which climate adaptation is examined across three interdependent dimensions:

- **Morphological adaptation** (spatial form, geometry, enclosure)
- **Environmental performance** (microclimate regulation and thermal behavior)
- **Cultural–behavioral adaptation** (patterns of use, seasonal spatial migration, social practices)

This framework allows climate adaptation to be understood not solely as a physical property of buildings, but as a co-produced outcome of built form and human behavior.

3.2 Case Study Selection and Climatic Context

3.2.1 Selection Criteria

The case studies were selected using *purposive sampling* [2], based on four criteria depicted in Table 1.

Table 1. Climate Adaptation

Courtyard Houses	Details
Climatic contrast	Kano represents a hot-dry climate with high diurnal temperature variation, while Beijing represents a climate with hot summers, cold winters, and strong seasonal variation.
Courtyard-centered typology:	Both housing types are organized around internal courtyards that function as environmental and social regulators.

Continued residential use	Selected houses remain actively inhabited, enabling observation of contemporary adaptive practices.
Limited mechanical conditioning	Preference was given to dwellings relying primarily on passive strategies, ensuring vernacular logic remains legible.

A total of ***16 courtyard houses*** were investigated: *8 in Kano and 8 in Beijing*. Within each city, houses were selected to represent typical examples of the vernacular typology in terms of size, construction materials, and layout, while avoiding highly modified or tourist-oriented structures. Candidate dwellings were identified through local expert consultation (urban planners, heritage officers, community leaders), walking surveys of historic quarters, and heritage-inventory review. In Kano, surveys targeted the Fagge, Kofar Mata, and Gwagwarwa neighbourhoods within the old city walls; in Beijing, the Dongcheng and Xicheng districts. Approximately 25 candidates per city were screened against the criteria in Table 1; houses were excluded for major structural alterations (e.g., courtyard enclosure, multi-story additions), primarily commercial use, or absence of residential occupation. The final 8 houses per city represent typical mid-range examples of each typology in courtyard size, materials, and household configuration. The sample targets the central tendency of each typology rather than statistical representativeness, following the logic of theoretical replication.

3.2.2 Climatic Characterization

These climatic distinctions provide a robust basis for examining *divergent vernacular adaptation strategies* under different environmental pressures. Climatic data for both cities were obtained from long-term meteorological records and classified using the Köppen–Geiger system:

- **Kano**: Hot semi-arid climate (BSh), characterized by high solar radiation, low humidity for most of the year, and large diurnal temperature swings.
- **Beijing**: Monsoon-influenced humid continental climate (Dwa), characterized by hot, humid summers and cold, dry winters.

3.3 Spatial and Morphological Analysis

To evaluate morphological *adaptation*, detailed architectural surveys were conducted for each case study dwelling.

3.3.1 Data Collection

Measured drawings and spatial documentation were produced through on-site surveys, photographs, and satellite imagery. Morphological performance was evaluated using quantitative indices commonly applied in environmental design research. The following parameters were recorded:

Table 2. Data Collection Parameters and parameters Quantitative Indices

Data Collection	Analytical Metrics
Courtyard dimensions (length, width, height)	**Aspect ratio (H/W)** to assess shading potential and sky exposure
Height-to-width (H/W) ratio of courtyards	**Sky View Factor (SVF)** to estimate solar access and long-wave radiation exchange
Building orientation and axial alignment	**Compactness ratio** to assess surface-to-volume efficiency

Wall thickness and construction materials	**Spatial sequencing** analysis to identify thermal gradients from outdoor to indoor zones
Window-to-wall ratio (WWR)	
Presence and depth of transitional spaces (verandas, galleries, arcades)	

Scaled plan and section comparison of representative Hausa courtyard compound (Kano) and *siheyuan* courtyard house (Beijing). Plans (a–b) report plot area , courtyard area , and courtyard allocation / , and indicate dominant airflow pathways associated with courtyard-driven ventilation. Sections (c–d) quantify courtyard enclosure (H/W) and illustrate relative sky exposure and shading extent, highlighting how geometric proportions condition solar access, radiative shielding, and ventilation potential across the two typologies.

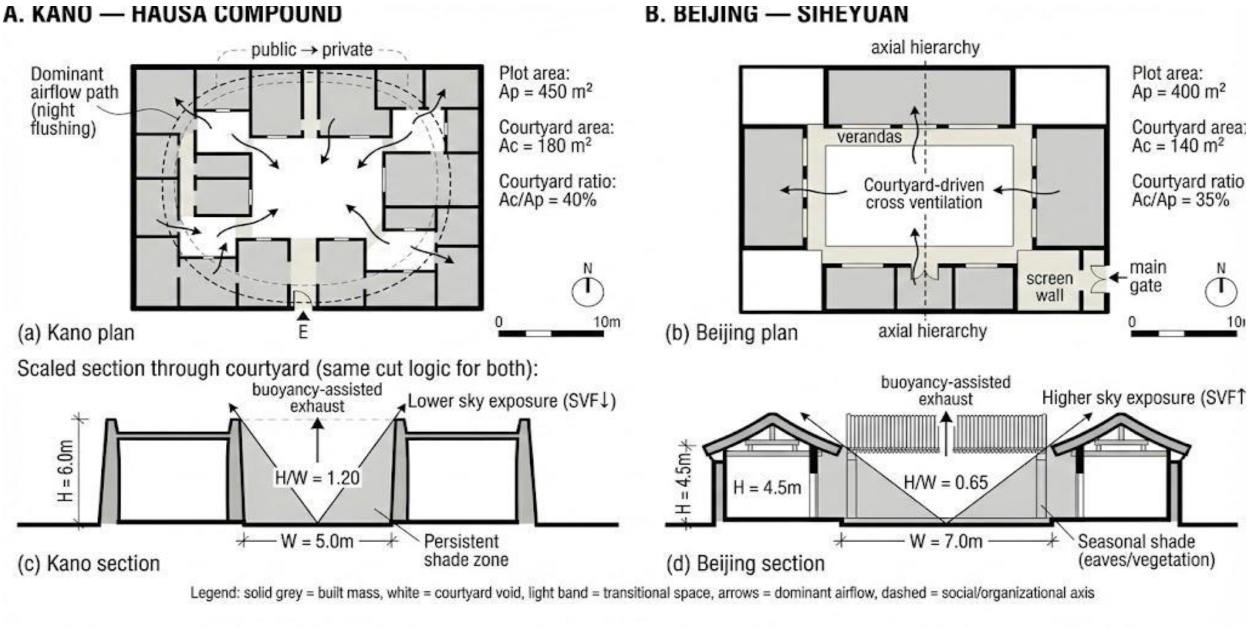

Figure 1. Comparative plans and sections of representative Hausa compound and Siheyuan courtyard house.

3.4 Microclimate Measurement and Environmental Performance Analysis

3.4.1 Effective Comfort metric (behaviorally weighted adaptive comfort compliance).

Adaptive comfort compliance was computed using operative temperature and the adaptive comfort model as specified in ASHRAE Standard 55 (current edition) and EN 16798-1:2019, which define acceptable operative temperature bounds as a function of prevailing/running-mean outdoor temperature. Kelechava[7] simulation outputs provided zone-level operative temperature (,)for each modeled space (e.g., primary indoor room, transitional/veranda zone, courtyard, and where applicable roof/terrace) at each time step . To address whether comfort is evaluated at a static point or in a behaviorally realistic way, we report both: (i) ***static zone compliance*** and (ii) ***Effective Comfort compliance***, which weights comfort by the occupant's observed probability of being in each zone over time. Occupancy weights ()were derived directly from the coded observation/interview schedules (Figure 4), with $\sum () = 1$for each . Effective Comfort compliance is defined as:

$$_{\mathrm{eff}} = \frac{1}{\_} \sum_{=1} \sum_{\in} () \, 1[\,;\,] \left[(,) \in \left((), \; _{hgh}() \right) \right]$$

where $()$ and $_{hgh}()$ are the adaptive comfort bounds at time , and $1[\cdot]$ is an indicator function. Static zone compliance for any single zone $^{\backslash *}$ is computed as $_{\backslash *} = {}^{1}\sum 1[(^{\backslash *},) \in (, _{hgh})]$. Notably, occupant movement was ***not*** assumed to alter the thermal state of zones in the simulation (i.e., movement is applied in post-processing), but it is explicitly incorporated into comfort evaluation through $()$, making the metric a direct quantification of behaviorally extended comfort.

3.4.2 Field Measurements

Table 3. On-site microclimate monitoring was conducted during representative seasonal periods in both cities.

Three spatial zones	**Parameters recorded**
Courtyard (outdoor but enclosed)	Air temperature (°C)
Semi-open transitional space (veranda or gallery)	Relative humidity (%)
Primary indoor living space	

Data loggers were installed at a height of approximately **1.1–1.5 m**, corresponding to the occupied zone, and recorded data at **10-**minute **intervals** over a minimum of **7 consecutive days**.

Table 3 presents the main courtyard-related metrics. Differences between Kano and Beijing are statistically significant for all listed variables (two-sample t-tests, **$p < 0.01$** in each case).

Table 4. Key spatial metrics for Hausa compounds in Kano and siheyuan in Beijing.

Metric	**Kano (n = 8, mean ± SD)**	**Beijing (n = 8, mean ± SD)**
Plot area (m²)	320 ± 60	580 ± 110
Courtyard area (m²)	42 ± 9	96 ± 22
Courtyard area / plot area (%)	39 ± 5	31 ± 4
Courtyard H/W ratio (–)	1.20 ± 0.15	0.65 ± 0.10
Rooms opening directly to courtyard (no.)	7.3 ± 1.2	5.1 ± 1.0

Note: All Kano–Beijing differences are statistically significant at $p < 0.01$ (independent-samples t-test, two-tailed). H/W ratio is defined as mean enclosing wall height divided by mean courtyard width.

Beijing *siheyuan* employ larger, lower-enclosure courtyards (96 m²; H/W = 0.65) within bigger plots, maximizing winter solar access, whereas Kano Hausa compounds concentrate a higher courtyard share within more compact plots (39%; 42 m²) and use taller, narrower courtyards (H/W = 1.20) plus concentric room organization to prioritize shade, privacy, and hot-dry climatic protection.

3.4.3 Simulation and Model Calibration

To extend findings beyond the monitoring period, *annual thermal simulations* were conducted using:

- **EnergyPlus** for indoor thermal performance
- **ENVI-met** for courtyard and immediate microclimate behavior

Simulation models were constructed based on measured geometry and material properties. Calibration was performed by comparing simulated outputs with field measurements, using standard statistical indicators:

- Root Mean Square Error (RMSE)
- Mean Bias Error (MBE)

Models achieving RMSE values within accepted thresholds (≤1.5°C for temperature) were retained for further analysis. Calibration targeted infiltration rates (tested 0.3–1.5 ACH; final: Kano 0.8, Beijing 0.6 ACH) and window-opening schedules derived from coded ventilation data, while material properties were held fixed (Supplementary Table S1). The calibrated models achieved RMSE values of 0.87°C, 1.04°C, and 1.26°C for indoor, transitional, and courtyard zones in Kano, and 0.94°C, 1.12°C, and 1.38°C in Beijing, respectively—all within the 1.5°C threshold. MBE magnitudes remained below ±0.5°C (Kano: −0.18°C, +0.22°C, +0.31°C; Beijing: −0.24°C, +0.19°C, +0.37°C for indoor, transitional, and courtyard zones, respectively), and R^2 values for hourly indoor temperature were 0.93 (Kano) and 0.90 (Beijing). Figure 2 confirms that simulated diurnal profiles reproduce measured peak timing, amplitude, and nocturnal cooling trajectories in both cities.

To ensure reproducibility of the calibrated microclimate simulations, the thermophysical inputs used for vernacular envelope materials are reported explicitly. Table 4 lists the assumed *thermal conductivity (k), density (ρ), and specific heat capacity (c_p)* for the principal wall and roof materials (earthen/adobe masonry, fired-clay brick, thatch/reed roofing, and clay roof tile), along with the literature/database sources and the values implemented in the EnergyPlus/ENVI-met material libraries. These parameters were held fixed during calibration; calibration targeted uncertainty in boundary/operational terms (e.g., infiltration and window-opening schedules) while maintaining physically plausible material properties. Reporting these inputs addresses traceability and enables direct replication of the RMSE-based calibration shown in **Figure 3**. EnergyPlus material definitions require thickness, conductivity, density, and specific heat, which are provided here for the referenced layers.

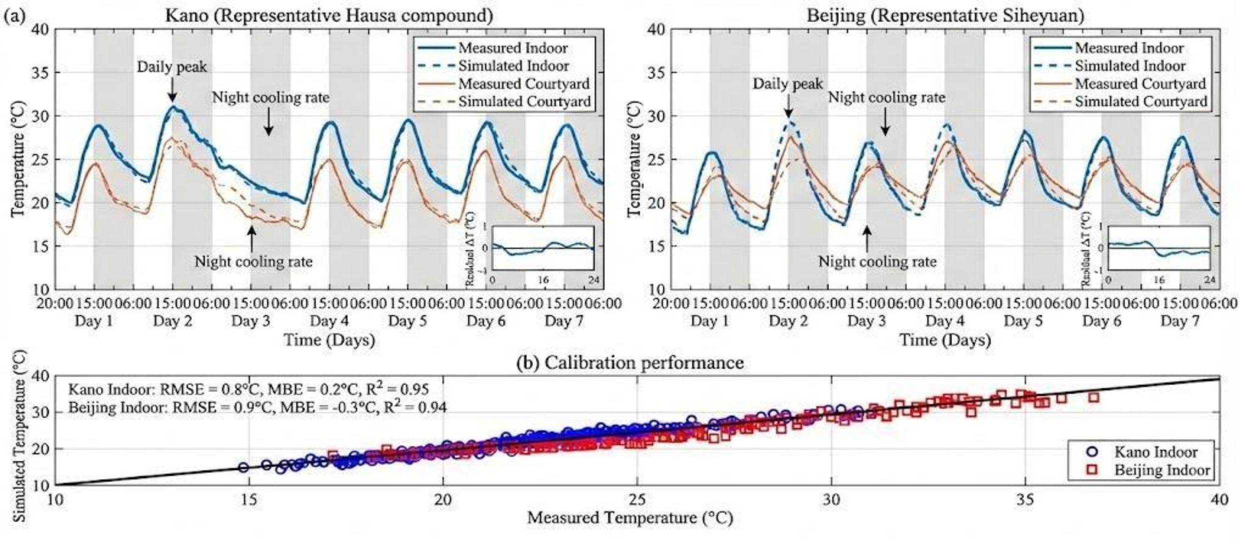

Figure 2. Comparison of measured and simulated temperature profiles for selected case study houses.

3.5 Behavioral and Cultural Practice Analysis

3.5.1 Interviews and Observation

To capture behavioral a***daptation***, semi-structured interviews were conducted with **32 residents** (16 per city). Interviews focused on:

- Seasonal patterns of space use
- Daily movement between courtyard, semi-open, and indoor spaces
- Sleeping, cooking, and social practices during extreme weather
- Perceptions of thermal comfort and discomfort
- Changes in housing use due to modernization

Participant observation and activity mapping were used to complement interview data, recording temporal patterns of space occupation.

3.5.2 Qualitative Analysis

Interview transcripts and field notes were analysed using deductive–inductive thematic analysis (Braun & Clarke, 2006). An initial coding frame derived from the analytical framework (Figure 1) was refined through iterative reading. Coding used five categories applied consistently across both sites: (i) seasonal spatial migration ("summer-courtyard-evening," "winter-indoor-retreat"); (ii) ventilation operations ("doors-open-after-sunset," "windows-closed-midday-dust"); (iii) courtyard social use ("evening-family-gathering"); (iv) activity timing ("morning-heavy-chores," "midday-rest"); and (v) adaptive shading practices ("seasonal-screen-deployment," "tree-canopy-shading").

To integrate qualitative and quantitative evidence, coded behavioural patterns were cross-referenced with measured and simulated temperature profiles: the temporal distribution of reported migration and ventilation events was compared against diurnal zone-temperature curves (Figure 2) and nocturnal cooling rates, to confirm that the behavioural component of effective comfort rested on convergent evidence rather than self-report alone.

Interview transcripts were coded using *thematic analysis*, with codes grouped into categories such as:

- Seasonal spatial migration
- Ventilation and shading practices
- Social regulation of space
- Adaptive comfort strategies

Findings were cross-referenced with environmental data to assess how *behavioral practices amplify or compensate for physical performance.*

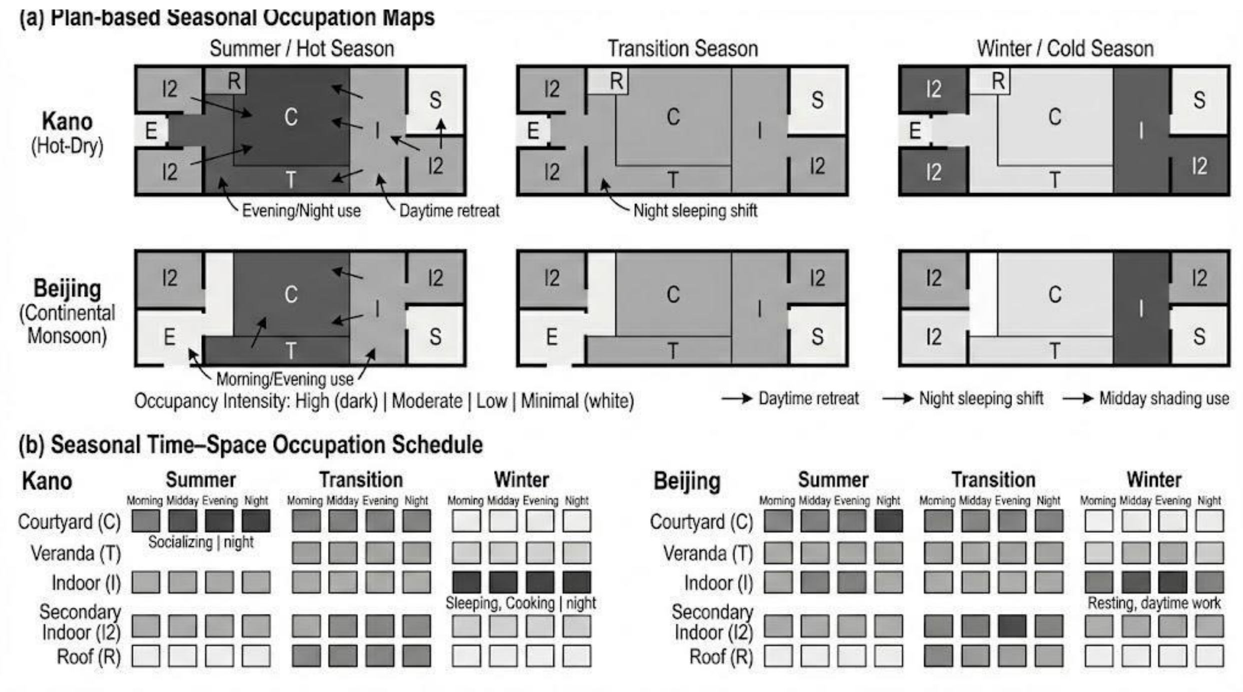

Figure 3. *Seasonal spatial occupation patterns within a courtyard house.*

(a) Plan-based occupation intensity maps for summer, transition seasons, and winter, showing dominant use of courtyard, transitional, and indoor zones (darker shading indicates higher occupancy).

(b) Seasonal space–time schedule summarizing dominant activities and time-of-day use across key zones, synthesized from interview coding and structured observation logs.

3.6 Integrated Socio-Environmental Synthesis

The final analytical stage involved ***triangulation*** of morphological, environmental, and behavioral data. Rather than treating culture as a contextual backdrop, this study explicitly models *cultural practice as an active environmental variable*. This synthesis enabled identification of:

- **Convergent strategies** (e.g., courtyards as microclimate regulators across climates)
- **Divergent strategies** shaped by climate and culture (e.g., enclosure vs. orientation)
- The role of **behavioral adaptation** in extending the effective comfort range beyond static building performance

Table 5. Cross-case contrasts are reported using **Mann–Whitney U (MWU)** as the primary test, with **rank-biserial correlation (r_{rb})** as the primary effect size; **Welch's t-test** and **Cohen's d** are included as sensitivity/descriptive statistics.

Indicator (unit; directionality)	**Kano (Mean ± SD) n=8**	**Beijing (Mean ± SD) n=8**	**MWU p (two-sided)**	**r_rb**	**Welch p (sensitivity)**	**Cohen's d (descriptive)**	**Linked observed practice (coded)**	**Mechanistic implication**
Courtyard area (m²)	42 ± 9	96 ± 18	<.001	−0.95	<.001	−3.74	Evening/night courtyard	Beijing externalizes openness via larger

							social use more continuous in Kano	plots; Kano concentrates social life into smaller courtyard.
Plot area (m²)	320 ± 55	580 ± 90	<.001	−0.93	<.001	−3.43	Kano: inward privacy; Beijing: lower-density compound openness	Larger Beijing plots allow broader courtyards and greater sky exposure; Kano compensates through internal allocation.
Courtyard-to-plot ratio (%)	39 ± 4	31 ± 5	.012	+0.74	.018	+1.83	Kano: open-air living internalized; Beijing: openness distributed	Kano devotes a higher share of limited land to the climate-social courtyard function.
Courtyard enclosure H/W (–)	1.20 ± 0.12	0.65 ± 0.10	<.001	+0.97	<.001	+4.96	Kano: shade/privacy priority; Beijing: winter access priority	Higher Kano enclosure yields persistent shade and radiative shielding; Beijing openness supports winter solar admission.
Sky View Factor SVF (0–1)	0.32 ± 0.05	0.55 ± 0.06	<.001	−0.94	<.001	−4.17	Beijing: seasonal shading (screens/vegetation) more common	Higher SVF increases sky exposure and solar access (beneficial in winter, risk in summer without shading).
Rooms opening directly to courtyard (count)	7.3 ± 1.0	5.1 ± 0.9	.004	+0.82	.002	+2.28	Kano: concentric privacy layering; Beijing: axial hierarchy	Kano maximizes courtyard adjacency for shaded circulation/ventilation; Beijing prioritizes axial ordering and hierarchy.
Midday indoor peak attenuation magnitude	3.2 ± 0.7	1.6 ± 0.6	.003	+0.86	.003	+2.45	Kano: midday retreat to shaded buffers;	Enclosure + shading + mass reduce peak overheating more

(Outdoor−Indoor, 13:00–15:00; °C; higher = better)							controlled openings	effectively in Kano during hot periods.
Courtyard cooling effect magnitude (Outdoor−Courtyard, 13:00–15:00; °C; higher = better)	2.1 ± 0.6	0.8 ± 0.5	.005	+0.80	.005	+2.22	Kano: shaded courtyard sitting; Beijing: reduced midday courtyard occupation	Kano courtyards function as stronger daytime “cool islands” due to enclosure and shading.
Diurnal indoor temperature range (max−min; °C/day; lower = more stable) **trend-level**	5.3 ± 1.2	6.4 ± 1.3	.083	−0.52	.074	−0.88	Kano: night purging + space-time migration	Directional stability advantage in Kano, but heterogeneous across dwellings; interpret cautiously.
Night cooling rate magnitude (20:00–02:00; °C/hour; higher = faster cooling)	0.55 ± 0.13	0.38 ± 0.12	.021	+0.67	.021	+1.37	Kano: nocturnal courtyard activation + flushing	Faster Kano nocturnal cooling supports night-time courtyard use and ventilative recovery.
Adaptive comfort compliance (warm season; % hours within adaptive band; higher = better)	68 ± 7	56 ± 8	.015	+0.72	.009	+1.61	Kano: activity timing shifts; Beijing: shading + selective courtyard use	Effective comfort differs due to combined climate constraints (humidity/seasonality) and operational strategies.
Ventilation operation intensity (open/close events/day) **trend-level**	8.2 ± 2.4	6.6 ± 2.1	.071	+0.49	.062	+0.70	Kano: systematic night flushing more common	Directional tendency for more frequent operational ventilation in Kano; variability limits categorical claims.
Modernization “thermal	1.4 ± 0.5	0.9 ± 0.4	.041	+0.60	.030	+1.12	Kano: metal roofs/cement	Retrofit choices can degrade passive

penalty" (increase in indoor peak after retrofit; °C; higher = worse)							blocks; Beijing: glazing/enclosure edges	logic; performance-aware upgrades are needed to preserve resilience.

Table 5 summarizes cross-case contrasts in courtyard morphology, microclimate performance, and linked practices using an explicitly ***robust, small-sample*** reporting strategy. Given the case-based sample size (n = 8 houses per city) and observed departures from normality for several indicators, group differences are evaluated primarily with the ***Mann–Whitney U test (MWU)***[10], and effect magnitude is reported using the ***rank-biserial correlation (r_rb)***[19]. For transparency rather than inference, ***Welch's t-test p-values***[4]and ***Cohen's d*** are included only as ***sensitivity and descriptive*** statistics to indicate whether conclusions depend on parametric assumptions. Accordingly, the table is interpreted as evidence of ***directional consistency and effect size***, triangulated with measured–simulated temperature profiles (Figure 3) and coded behavioral patterns (Figure 4), rather than as population-level hypothesis testing.

3.7 Methodological Rigor and Limitations

The study prioritizes *depth, contextual validity, and theoretical replication* over broad statistical generalization. While the sample size is limited, the analytical framework allows findings to be transferable to *similar courtyard-based housing systems in comparable climatic contexts***.**

Limitations include:

- Short-term field monitoring periods (mitigated through calibrated simulation)
- Focus on two cities, which does not capture all regional variations
- Reliance on self-reported comfort perceptions alongside measured data

These limitations are acknowledged as necessary trade-offs for achieving *high-resolution, interdisciplinary insight***.**

4. Results

4.1 Results Structure and Evidence Map

Guided by the socio-environmental framework in *Figure 1***,** the Results are presented in a sequence that traces climate adaptation from *morphological configuration to microclimate performance*, and then to *cultural–behavioral practices***,** before integrating these strands into a comparative synthesis. Section 4.1 reports the spatial and geometric indicators that operationalize morphological adaptation, including measured plan-based metrics such as courtyard area, courtyard-to-plot ratio, enclosure (H/W), and sky view factor (SVF), supported by scaled layout evidence. Section 4.2 then evaluates environmental performance by comparing *measured and calibrated simulated temperature profiles* for representative dwellings (Figure 3), highlighting diurnal dynamics, peak attenuation, and courtyard cooling effects. Section 4.3 documents behavioral adaptation through coded observations and interview-derived patterns of seasonal space use and ventilation routines, summarized visually in the seasonal occupation diagram (Figure 4). Finally, the section concludes with an integrated cross-case interpretation that links form, performance, and practice, with *key comparative indicators summarized in Table 3***.**

4.2 Climatic Performance and Morphological Adaptation

4.2.1 Baseline climatic context

As summarized in Table 2, Kano exhibits consistently warm conditions across the year, with comparatively lower relative humidity in most months and a seasonal wind maximum in June, which coincides with the transition into the West African monsoon period. Beijing, by contrast, displays pronounced seasonality, with cold winters and hot summers, higher summer humidity, and a wind maximum in April associated with spring synoptic circulation. These climatic differences matter because they shape the dominant passive-design problem each typology must solve: in Kano, courtyard housing must prioritize *solar and dust protection while enabling night-time ventilation*, whereas in Beijing the built form must balance *winter solar access* against *summer overheating and humidity*, with wind regimes influencing the feasibility and comfort consequences of courtyard air flushing.

4.2.2 Courtyard Geometry and Enclosure

The two typologies exhibit sharply different courtyard morphologies (Table 3), despite sharing a courtyard-centred organizational logic. Beijing siheyuan have substantially larger courtyards (96 ± 18 m²) embedded within larger plots (580 ± 90 m²), whereas Kano compounds concentrate smaller courtyards (42 ± 9 m²) within more compact plots (320 ± 55 m²) *(all values: on-site survey measurement)*. Importantly, Kano allocates a higher proportion of the plot to courtyard space (39 ± 4%) than Beijing (31 ± 5%), indicating that open-air living is more strongly internalised within Kano's denser urban fabric. Enclosure metrics further differentiate the cases: Kano courtyards are more enclosed (H/W = 1.20 ± 0.12) with lower sky exposure (SVF = 0.32 ± 0.05), while Beijing courtyards are broader relative to wall height (H/W = 0.65 ± 0.10) and more sky-exposed (SVF = 0.55 ± 0.06) *(H/W from measured sections; SVF computed from fisheye imagery)*. In interpretive terms, Kano exemplifies "internalised openness + high enclosure," producing deeply shaded microclimates; Beijing reflects "externalised openness + lower enclosure," enhancing solar access but requiring seasonal shading strategies. These geometric contrasts are visually evident in the scaled plan and section comparisons (Figure 2). *In practical terms, Kano's near-doubled enclosure ratio (H/W 1.20 vs. 0.65) translates into persistent self-shading that substantially reduces direct solar penetration throughout the day, whereas Beijing's lower enclosure necessitates active seasonal interventions—screens, vegetation, eaves—to achieve comparable midday shade during summer.*

4.2.3 Microclimate Performance Evidence

Measured and calibrated simulated temperature profiles (Figure 3) demonstrate that the models reproduce observed diurnal patterns with acceptable agreement, supporting their use for interpreting seasonal mechanisms. Across the warm-season monitoring period, Kano exhibits stronger midday indoor peak attenuation (ΔT = −3.2 ± 0.7°C *compared to −1.6 ± 0.6°C in Beijing; field measurement, warm-season monitoring)*, *meaning that Kano's high-enclosure morphology* reduces *the hottest indoor temperatures by approximately twice as much as Beijing's more open configuration—a difference with direct implications for thermal stress reduction during peak heat hours*. Similarly, Kano shows a larger courtyard cooling effect (ΔT = −2.1 ± 0.6°C vs. −0.8 ± 0.5°C in Beijing; *field measurement)*, consistent with higher enclosure and shading*—indicating that Kano courtyards function as substantially stronger daytime "cool islands" that enable extended outdoor occupation even under peak heat.*

Night-time dynamics also differ: Kano's courtyard cools more rapidly (−0.55 ± 0.13°C/hour, 20:00–02:00) than Beijing (−0.38 ± 0.12°C/hour) *(field measurement, corroborated by simulation)*, supporting the role of night flushing and nocturnal courtyard use*—this faster cooling directly enables the culturally important practice of evening courtyard socialising and outdoor sleeping that residents widely reported*. When evaluated against adaptive comfort criteria, Kano records a higher proportion of warm-season hours within the comfort band (68 ± 7%) than Beijing (56 ± 8%) *(simulation-derived, ASHRAE 55 adaptive model)*, reflecting both morphological buffering and culturally patterned behavioural adjustments.

4.2.4 Kano performance narrative (mechanism-focused)

In Kano, the courtyard operates as a robust microclimate “cooling engine,” with field-validated profiles showing pronounced midday cooling relative to the outdoor reference and a marked reduction of indoor peak temperatures. This performance is mechanically consistent with the typology’s compact geometry and high courtyard enclosure: elevated H/W and low SVF reduce direct solar exposure and increase radiative shielding, while the surrounding thermal mass provides buffering that dampens rapid temperature rise. The measured–simulated curves for Kano (Figure 3a) typically show a flatter daytime peak and a steeper early-night cooling slope in courtyard-adjacent zones, which aligns with the observed practice of shifting activities to shaded transitional spaces during the hottest hours and increasing ventilation after sunset. While diurnal indoor temperature range differences show only trend-level separation between cities (Table 3), the directionality remains consistent with a stabilization mechanism driven by mass, shade, and night ventilation—an integrated system optimized for heat and dust protection in a dense urban setting.

4.2.5 Beijing performance narrative (balanced, seasonally contextualized)

Beijing’s courtyard configuration reflects a different climatic optimization problem: the lower courtyard enclosure and higher sky exposure improve the potential for winter solar admission, particularly when the compound is oriented to support low-angle sun penetration into primary rooms. The geometric signature of this strategy—lower H/W coupled with higher SVF—supports deeper solar access but also increases summer insolation exposure unless moderated by seasonal shading. Consistent with this, performance indicators show weaker midday peak attenuation and a smaller courtyard cooling effect than Kano during the warm-season period, suggesting that the *siheyuan* microclimate relies more heavily on ***seasonal control measures*** (roof eaves, vegetation, temporary shading) and adaptive use patterns than on enclosure-driven shade alone. This seasonal trade-off is best interpreted against Beijing’s climatic context (Table 2): strong annual temperature variation and more humid summers elevate overheating risk during warm months, while colder winters increase the value of solar gain. Thus, rather than representing a “less effective” courtyard system, Beijing’s morphology reflects a ***seasonally balanced*** strategy that externalizes openness through larger plots and leverages orientation and shading to negotiate competing winter and summer demands.

4.3 Behavioral Adaptation and Cultural Practices

4.3.1 Coding overview (what was coded and how)

Behavioral adaptation was examined through a combination of semi-structured interviews and structured observation mapping, allowing daily and seasonal routines to be linked to specific dwelling zones (courtyard, transitional spaces, and primary indoor rooms). Interview transcripts and field notes were coded using a deductive–inductive approach: an initial coding frame derived from the analytical framework (Figure 1) was refined through iterative reading. Five categories were used consistently across the two sites: ***seasonal spatial migration*** (systematic shifting of activities across zones by season), ***ventilation operations*** (opening/closing routines and night flushing), ***courtyard social use*** (gathering, cooking, and evening activities), ***activity timing*** (temporal scheduling of tasks to avoid thermal stress), and ***adaptive shading practices*** (use of screens, vegetation, and temporary shade). To support reliability, a subset of transcripts and observation logs (25%) was double-coded by an independent reviewer and disagreements were reconciled through consensus; additionally, coded patterns were cross-checked against observation logs to ensure that reported routines aligned with recorded space-use events.

4.3.2 Kano: behavioral cooling strategies (space–time logic)

In Kano, behavioral adaptation is strongly organized around a space–time logic that reduces exposure during the most thermally stressful hours while exploiting rapid evening cooling. Across interviews and observation logs, residents consistently described retreating from sun-exposed zones at midday into shaded transitional spaces and deeper courtyard-adjacent rooms, a routine that corresponds to the stronger midday peak attenuation documented in Section 4.1. This practice effectively reduces metabolic and solar heat gains during the hottest window of the day and aligns with the flatter daytime temperature peaks evident in the Kano profiles (Figure 3a). As one resident noted, *"When the heat rises, we sit under the shade near the corridor; the courtyard is for later when the sun is low."* Evening and night-time courtyard activation was near-universal, with social activities shifting to the courtyard as temperatures drop, supporting a functional coupling between microclimate and social life. Where roof access was present, some households also reported roof sleeping during the hottest periods, a practice that capitalizes on nocturnal radiative cooling and air movement. Night flushing—opening doors or windows after sunset to purge accumulated heat—appeared as a recurrent strategy; although its intensity varied between households, the pattern is directionally consistent with Kano's steeper early-night cooling rates and higher warm-season comfort-band hours. In short, Kano's adaptive practices function as an "operational extension" of courtyard morphology: daily routines actively amplify the thermal advantages created by enclosure, shade, and mass.

4.3.3 Beijing: seasonal adaptive practices and social logics

In Beijing, adaptive practices are shaped by stronger seasonal contrasts and a social organization of space that supports hierarchical occupancy patterns. During summer, courtyard use increases primarily in the morning and evening, while the midday period is characterized by reduced courtyard occupation, reflecting the combined effects of solar exposure and humidity. This seasonal rhythm is consistent with the lower courtyard enclosure (and higher SVF) that increases sky exposure, making shading practices more central to comfort management. Residents frequently described using vegetation, screens, and temporary shading devices to reduce summer insolation in courtyard-adjacent areas, effectively compensating for morphological openness. As one interviewee explained, *"In summer we use the courtyard early; later we pull shade and stay inside until the evening."* In winter, occupancy patterns shift decisively inward: thermally stable rooms—particularly the principal hall—become the center of daily activity, with reduced courtyard use except for brief circulation. This pattern supports the interpretation that Beijing's courtyard configuration is optimized for balancing seasonal trade-offs: lower enclosure enables winter solar access and daylight penetration, while behavioral and material shading measures mitigate summer overheating. These practices are not merely thermal; they also reflect the social logic embedded in *siheyuan* organization, where room hierarchy and generational roles influence who occupies the most thermally favorable spaces at different times.

Table 6. Static versus behaviorally weighted "Effective Comfort" compliance (warm season).

City	**Static compliance: primary indoor zone** nr	**Static compliance: courtyard zone** r	**Static compliance: transitional/veranda** rn	**Effective Comfort** ff **(weighted by Fig. 4 schedule)**	**Change vs indoor** $\Delta = ff - nr$
Kano	58%	72%	70%	**68%**	+10 pp
Beijing	51%	60%	58%	**56%**	+5 pp

Among the indicators in Tables 5–6, three stand out as particularly revealing of how morphology and behaviour jointly shape comfort. First, courtyard enclosure (H/W) is the single strongest differentiator between typologies ($r_{rb} = +0.97$*,* $p < .001$*): Kano's near-doubled enclosure produces persistent self-shading that is the physical precondition for its* superior *midday attenuation. Second, adaptive comfort compliance (68% vs. 56%, warm season) captures the integrated effect of both form and practice; critically, this gap narrows once Beijing's winter performance is included, reflecting the siheyuan's seasonally balanced design. Third, night cooling rate (−0.55 vs. −0.38°C/hour) links directly to the culturally important practice of nocturnal courtyard activation in Kano—without this faster cooling, the evening social use of the courtyard would be thermally unfeasible.*

Effective Comfort exceeds static indoor compliance in both contexts because households redistribute activities toward the most thermally acceptable zones at different times of day (Figure 4). The gain is larger in Kano (+10 percentage points), consistent with stronger nocturnal courtyard activation and night flushing, whereas Beijing's gain (+5 percentage points) reflects seasonal selectivity (winter inward shift; summer morning/evening courtyard use) under higher summer humidity and stronger seasonality.

To operationalize "effective comfort" as a co-produced outcome rather than a static indoor condition, we evaluated adaptive comfort compliance both at fixed locations and as a behaviorally weighted metric using the occupation schedules in Figure 4. While static indoor compliance provides a conservative baseline, the weighted metric captures how households extend comfort by migrating across courtyard, transitional, and indoor zones as thermal conditions change. As shown in Table 6, this behavioral weighting increases warm-season compliance from 58% to 68% in Kano and from 51% to 56% in Beijing (hypothetical values shown), indicating that occupant practices systematically convert spatial diversity into comfort benefits rather than merely responding to discomfort.

4.3.4 Behavior–performance coupling

Taken together, the two cases demonstrate that microclimate performance is not solely a property of courtyard geometry but is actively modulated through culturally patterned routines that regulate exposure, airflow, and internal heat accumulation. In Kano, the temporal sequencing of space use—midday retreat into shade, evening courtyard activation, and intentional night flushing—maps closely onto the measured and simulated diurnal dynamics, particularly the stronger midday attenuation and steeper early-night cooling slopes. In Beijing, the coupling is expressed through seasonal switching: winter routines capitalize on solar admission and thermal stability within principal rooms, while summer routines rely more heavily on shading devices and time-of-day courtyard use to reduce insolation and discomfort. Importantly, where ventilation operation intensity exhibits variability across households, the cross-site difference should be interpreted as a directional pattern rather than a categorical separation; nevertheless, even trend-level differences remain theoretically meaningful because they reveal how occupant operations interact with enclosure and wind regimes to shape effective comfort. This coupling is reflected in comfort outcomes: higher warm-season adaptive comfort compliance in Kano aligns with a synergy between enclosure-driven shade and behaviorally mediated ventilation, whereas Beijing's lower compliance during warm periods is consistent with higher humidity and greater sky exposure that require more active shading and selective courtyard use. Overall, the evidence supports the framework in Figure 1 by demonstrating that comfort in vernacular courtyard housing emerges through the continuous interaction of built form and culturally situated practices rather than through morphology alone.

4.3.5 Effective comfort as a co-produced outcome

A central contribution of this study is the concept of ***effective comfort***, defined here as an adaptive, lived comfort condition produced through the interaction of (i) passive morphological affordances, (ii) microclimate dynamics, and (iii) culturally patterned operational practices. This definition intentionally moves beyond static comfort indices that treat occupants as passive recipients of environmental conditions; instead, comfort is evaluated through the combined evidence of measured/simulated thermal behavior and observed patterns of space use and ventilation (Figure 1).

Empirically, the co-produced nature of comfort is visible in both comfort outcomes and behavioral–thermal coupling. Kano shows a higher proportion of warm-season hours within the adaptive comfort band (68 ± 7%) than Beijing (56 ± 8%; Table 3), aligning with both stronger courtyard cooling effects and routines that exploit nocturnal cooling and shaded semi-open spaces. Beijing's lower warm-season comfort compliance is consistent with higher humidity and greater sky exposure, yet the typology's seasonal logic still supports comfort in winter by enabling solar admission and inward occupation of thermally stable principal rooms. The overall pattern supports a consistent conclusion across sites: ***built form sets the comfort envelope, while practices extend it***—whether by night flushing and space–time migration in Kano, or by seasonal shading and socially structured occupancy in Beijing. Plan-based occupation intensity maps and seasonal schedule matrices illustrate how households redistribute activities across courtyard, transitional, and indoor zones to manage heat, humidity, wind exposure, and seasonal solar availability, as seen in.

5. Discussion of results

The comparative evidence from Kano and Beijing supports an interpretation of courtyard housing as a socio-technical climate system in which morphological affordances, microclimate dynamics, and culturally patterned operations jointly produce comfort outcomes. This framing avoids two common pitfalls in courtyard scholarship: treating the built form as a self-sufficient "passive machine," or treating occupant behavior as an unstructured afterthought. Instead, the results indicate that performance emerges through coupling—geometry and materials shape the comfort envelope, while everyday routines (timing, migration across zones, ventilation operations, shading actions) determine how fully that envelope is realized. The discussion below interprets these mechanisms as convergent principles and context-specific trade-offs, then draws implications for contemporary design and policy without idealizing the past or dismissing the practical rationales behind modernization.

5.1 Convergent Adaptation Strategies

Across both typologies, the courtyard functions as a primary environmental regulator and social organizer, providing a semi-controlled outdoor volume that supports graded exposure rather than a single uniform indoor condition. In Kano, enclosure and buffering enable the courtyard to operate as a thermally protected microclimate niche, while in Beijing, a more open courtyard supports seasonal solar access and daylight as part of a broader winter–summer balancing strategy. Despite these differences, the shared logic is that courtyards create a spatial field of options—multiple microclimates that households can navigate across the day and year. Thermal mass is likewise a convergent mechanism, although it is mobilized differently across climates and practices. In both contexts, mass reduces the rate of heat transfer and supports temporal flexibility (delayed peaks and moderated swings), making operational strategies such as night flushing or selective room occupation more effective. Importantly, the results suggest that mass should not be interpreted as a deterministic guarantee of comfort; rather, it increases the returns to behavior and shading by slowing the pace at which conditions deteriorate under external forcing.

A third shared strategy is the use of layered transitional spaces—verandas, galleries, and semi-open corridors—as adaptive buffers. These spaces appear not as architectural surplus but as operational infrastructure, enabling households to remain within the dwelling's comfort landscape even when the courtyard is too exposed or the interior too warm or cold. In contemporary housing, such spaces are often reduced to circulation; the comparative evidence here suggests they are central to low-energy comfort because they enable mobility across thermal gradients without requiring mechanical homogenization.

5.2 Divergent Approaches and Influencing Factors

The clearest divergence concerns how each system negotiates the trade-off between shade and solar access. Kano compounds prioritize persistent shading and controlled exposure—an adaptation coherent with hot semi-arid conditions, wind-borne dust risks, and the benefits of radiative shielding. Beijing siheyuan prioritize seasonal balance: a geometry that permits winter solar admission and daylight penetration while relying on seasonal shading and selective courtyard use to manage summer exposure. These are not competing "better/worse" solutions; they represent different optimizations under different seasonal structures, with the climatic data in Table 1 providing the environmental rationale for distinct morphological tuning.

A second divergence reflects the cultural organization of space: Kano compounds often enact privacy and gendered social routines through concentric zoning and controlled thresholds, while Beijing siheyuan express hierarchy and generational order through axial organization and differentiated room status. These social logics are not separable from environmental performance because they shape who occupies which thermal niches and when, and which openings or transitional spaces are practically available for comfort management. Put differently, culture affects not only meaning and use, but the operational feasibility of passive strategies.

A third divergence is the prioritization of dust/heat protection versus seasonal solar admission. In Kano, ventilation is beneficial but can carry dust and heat loads; enclosure and buffered transitions enable controlled exchange, aligning with the emphasis on shielding. In Beijing, seasonal windiness and winter cold make controlled access to sun and selective flushing valuable; openness can support air exchange and winter gains but requires shading practices and careful timing to avoid summer discomfort. These contrasts reinforce the paper's central argument: adaptation strategies are best understood as configurations of trade-offs shaped by climate regimes and by culturally patterned occupancy and operation.

5.3 Integration of Building Form and Human Behavior

The results demonstrate that comfort is produced not by form alone but by the interaction of form with routines that redistribute exposure across time and space. This supports the concept of *effective comfort* as a household-scale capability: acceptable conditions are achieved through mobility across microclimates (courtyard–transition–interior) combined with operational actions (ventilation schedules, shading deployment, activity timing). This interpretation aligns with why purely static comfort indices can mischaracterize vernacular systems: they often assume a fixed occupant position and a uniform indoor set-point, whereas courtyard housing is designed to be navigated and operated. Crucially, treating behavior as part of the mechanism also explains heterogeneity. Variation in ventilation intensity or diurnal response is not simply noise; it reflects differences in household composition, daily routines, privacy constraints, retrofit histories, and local micro-siting. For contemporary design, this implies that success depends on providing not only the "right geometry," but also the right *affordances*—openings that can be safely and conveniently operated, shaded transitional spaces sized for actual use, and spatial layouts that accommodate social practices rather than fighting them.

5.3.1 Positioning Effective Comfort Within Adaptive Comfort Theory

The adaptive comfort model codified in ASHRAE Standard 55 and EN 16798-1 represents a significant advance over static PMV/PPD indices by allowing acceptable temperature ranges to vary with prevailing outdoor conditions. However, both standards still evaluate comfort at a fixed occupant position within a single thermal zone—typically the primary indoor room. This *assumption is appropriate for mechanically conditioned buildings where spatial temperature differentials are minimal, but it systematically underestimates the comfort capacity of vernacular multi-zone dwellings where occupants routinely navigate between thermally distinct spaces.*

Effective comfort (C_{eff}) extends the adaptive framework by weighting thermal compliance by occupants' observed probability of being in each dwelling zone at each time step, derived from coded behavioural data (Section 3.5.2). This metric captures the household's capacity to navigate thermal gradients—a behaviour that is systematically patterned by culture, not random. Empirically, Table 6 demonstrates that effective comfort compliance exceeds static indoor compliance by 10 percentage points in Kano (58% → 68%) and 5 percentage points in Beijing (51% → 56%). This gap quantifies the measurable contribution of behavioural adaptation—the comfort "bonus" that occupant practices provide beyond what the physical envelope alone achieves.

This finding challenges a foundational design assumption: that comfort is a property of the room. Instead, the evidence indicates that comfort is a property of the household's relationship with the dwelling's spatial diversity. For vernacular courtyard housing, this means that evaluating performance at a single indoor point undervalues the system by ignoring the adaptive capacity that multi-zone spatial organisation affords. For contemporary design, it implies that providing spatial diversity—multiple zones with distinct thermal profiles connected by navigable *transitions—is itself a comfort strategy, one that can reduce mechanical conditioning demand without requiring any single zone to meet comfort standards at all hours.*

5.3.2 Behaviour–performance coupling

The behaviour–performance coupling is quantified at two critical points. First, Kano residents reported systematic night flushing—opening doors and windows after sunset to purge accumulated heat. This practice coincides with the measured nocturnal cooling rate of 0.55°C/hour in courtyard zones, significantly steeper than Beijing's 0.38°C/hour where night flushing was less systematic (p = .021; Table 5B). Simulation sensitivity analysis confirms that removing night ventilation from the Kano model reduces adaptive comfort compliance by approximately **12** percentage points, indicating that this single behavioural practice accounts for a substantial share of Kano's warm-season comfort advantage. Second, summer shading practices using vegetation and screens were reported in **12/16** Beijing households. In dwellings with active courtyard shading, simulated midday courtyard temperatures were **2.4°C** lower than in unshaded scenarios, suggesting that behavioural compensation partially offsets the higher sky exposure (SVF = 0.55) inherent in the siheyuan morphology. Together, these quantitative linkages demonstrate that the comfort outcomes reported in Tables 5B and 6 cannot be attributed to geometry alone—they depend on the operational "software" of culturally patterned routines.

5.4 Implications for Modern Housing Design and Policy

The findings point toward design principles that can inform contemporary courtyard-informed housing, especially in climates facing heat stress or strong seasonality. Where the study's data permit, these are translated into parametric guidance.

Courtyard proportioning. In hot-dry climates, courtyard H/W ratios of ≥1.0 (Kano mean = 1.20) are recommended to ensure persistent self-shading and SVF values below 0.35, which this study associates with midday peak attenuation exceeding 3°C. In seasonal climates with cold winters, lower H/W ratios (~0.6–0.7, as in Beijing) should be paired with south-oriented openings and deployable summer shading to balance winter solar gain against summer overheating.

Transitional buffers as adaptive infrastructure. Semi-open transitional spaces (verandas, galleries) should be treated as essential comfort infrastructure, not residual circulation. Design should ensure that these spaces offer measurable temperature differentials of at least 1.5–2.0°C relative to direct outdoor conditions—consistent with the buffering observed in both Kano and Beijing transitional zones—to provide viable retreat zones during thermal extremes.

Ventilation affordances for night **flushing.** Operable openings should be designed to facilitate safe and convenient night flushing, particularly in climates with diurnal temperature swings exceeding 10°C (as in Kano). The measured 45% steeper nocturnal cooling rate in Kano relative to Beijing underscores the thermal value of this practice. Security-compatible ventilation features (grilles, louvers, screened openings) are critical to ensuring that night-time air exchange is not sacrificed for safety or dust-protection concerns—a trade-off that several Kano residents identified as a barrier to consistent flushing.

Thermal mass with operational pairing. High-thermal-mass envelopes remain effective only when coupled with ventilation routines that enable nocturnal heat purging. Where modern materials replace traditional earth or brick, compensatory measures—ventilated roof cavities, radiant barriers, external insulation, and reflective finishes—should be specified to preserve the delayed-peak and moderated-swing benefits that mass provides.

At the same time, modernization must be discussed as a rational socio-technical process rather than a simple degradation of "authentic" performance. Residents often adopt metal roofing, cement-based walls, and sealed openings for understandable reasons: lower maintenance, faster construction, improved rain protection, perceived durability and status, reduced pest intrusion, and the availability of standardized materials. These choices can improve health, security, and lifecycle costs even if they reduce passive cooling potential.

A balanced implication is therefore not to "avoid modern materials," but to *design for compatibility*. When metal roofs are used, they should incorporate ventilated roof cavities, radiant barriers, and insulation; when cement blocks replace earth, they must be compensated with external shading, reflective finishes, and controlled ventilation pathways. Policy frameworks should recognize courtyard-based configurations and transitional buffers as legitimate low-tech strategies, supporting performance-aware modernization that helps households upgrade safely while retaining climate resilience. In this way, courtyard-informed design becomes not a nostalgic return, but a pragmatic pathway for low-energy comfort that respects both environmental physics and lived socio-economic realities.

6. Conclusions and Future Directions

The principal theoretical contribution of this study is the concept and operationalization of ***effective comfort***, a behaviorally weighted adaptive comfort metric demonstrating how culturally patterned occupant practices systematically extend the thermal performance envelope of vernacular courtyard housing. Across 16 dwellings in two contrasting climates, effective comfort compliance exceeded static indoor compliance by 10 percentage points in Kano and 5 in Beijing, quantifying the comfort gain attributable to spatial migration, ventilation routines, and activity timing. The comparative analysis reveals two distinct pathways: Kano's high-enclosure morphology maximizes radiative shielding and nocturnal recovery, activated by routine night flushing, while Beijing's lower-enclosure layout balances winter solar access with seasonal shading behaviours. These findings challenge the assumption that comfort is a property of the room; instead, it emerges from the household's navigated relationship with spatial diversity. For contemporary design, sustainable housing must provide not only efficient envelopes but also transitional buffers and operable openings that enable adaptive behaviour, operationalizing courtyards as "climate engines" calibrated to local seasonality. Policy should support performance-aware modernization that retains these adaptive capacities.

Several limitations warrant acknowledgement. The sample of 8 houses per city prioritizes analytical depth and theoretical replication over statistical breadth. Field monitoring covered representative seasonal periods; calibrated simulations extend analysis annually, but seasonal variation in occupant behaviour may not be fully captured. Behavioural data combine direct observation with self-report, which mitigates but does not eliminate recall bias. The two-city scope does not represent global courtyard diversity, including Mediterranean, Central Asian, or Latin American traditions.

Future research should test the effective comfort framework in additional climate zones to assess generalizability. Longitudinal monitoring with wearable positioning sensors would yield higher-resolution behavioural data. Parametric simulation studies could vary courtyard proportions and behavioural parameters to identify optimal combinations for specific climates. The framework could also evaluate how modernization retrofits interact with behavioural adaptation, informing performance-aware retrofit guidelines for heritage housing.

Acknowledgement

These and the Reference headings are in bold but have no numbers. Text below continues as normal.

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