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Enhancing Occupant Comfort: A Sustainable Building Internal Design (SBID) Approach to Alleviating Summer Indoor Discomfort in Urban Villages of Wenzhou, China

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Abstract

Urban villages are a distinctive spatial phenomenon in rapidly urbanising Chinese cities. In Wenzhou, a humid-subtropical coastal city, densely built urban-village dwellings suffer severe summer indoor overheating, yet most renovation strategies in the literature remain at policy, management, or large-scale demolition levels rather than addressing the dwellings themselves. This study proposes a Sustainable Building Internal Design (SBID) framework that prioritises interventions within the building envelope and interior layout, drawing on the passive climatic logic of Wenzhou's vernacular architecture. Three parallel objectives guide the work: (O1) identify the envelope and interior-layout aspects that drive summer indoor overheating in Wuma Street urban-village dwellings; (O2) document the climate-adaptive strategies embedded in Wenzhou vernacular architecture from an SBID perspective; and (O3) assess the effectiveness of SBID interventions in mitigating summer indoor overheating through calibrated building performance simulation. The study adopts a sequential mixed-methods design comprising (i) field survey and ob-

servational assessment of ten households in the Wuma Street urban-village cluster in Lucheng District, Wenzhou; (ii) on-site indoor environmental monitoring of representative dwellings during summer 2024; and (iii) calibrated EnergyPlus / Design-Builder simulations of five SBID retrofit scenarios (V1–V5) against an as-found baseline (V0). The reported results indicate that combining vernacular-inspired envelope treatments (deep eaves, high-albedo lime render, ventilated double-skin construction) with interior layout reconfiguration significantly reduces summer indoor overheating hours and improves indoor thermal conditions with the aim of limiting cost and disruption to residents. The study presents an operational SBID framework, a set of evidence-informed design guidelines for subtropical urban-village retrofit, and a replicable empirical dataset for future research.

Keywords: urban village; sustainable building internal design (SBID); indoor thermal comfort; vernacular architecture; building performance simulation; energy-efficient retrofit

1. INTRODUCTION

Urban villages are a distinctive feature of the urban landscape in many Chinese cities, and their physical and institutional conditions raise important questions for healthy and equitable urban development. Deteriorating buildings, inadequate public facilities, and fragmented public-health management can undermine living conditions, particularly where former villages are now surrounded by densely developed city-centre districts. Consequently, the renewal of urban villages has become a significant concern for residents, researchers, planners, and public authorities seeking to improve the existing housing stock.

Wenzhou is a coastal city in eastern China. The rapid pace of urbanisation has made the challenges associated with urban villages particularly visible, especially where compact older housing remains embedded in intensively developed districts. Observational studies [1, 2] report that urban villages can occupy substantial urban land and contain densely arranged buildings while remaining constrained by inefficient spatial layouts and inadequate environmental performance. Wenzhou faces competing demands for scarce urban land, including housing, employment space, public facilities, and the preservation of existing communities. Some urban villages occupy centrally located land, creating pressure for redevelopment, although the housing they provide also serves important social and economic functions.

Wenzhou's humid climate also places substantial demands on building daylighting, ventilation, and the management of indoor heat and moisture. However, buildings in urban villages are frequently compact and closely spaced, conditions that can limit natural airflow and daylight and contribute to reduced indoor thermal comfort. At the same time, the historical and cultural significance of these communities provides a reason to retain locally distinctive architectural features and prolong the useful life of existing dwellings where safe and practical. Accordingly, this study examines how the indoor environment of urban-village housing in Wenzhou can be retrofitted to (i) increase building utilisation, (ii) improve indoor thermal comfort, and (iii) extend building service life.

Earlier researchers have proposed a range of approaches to the challenges associated with urban villages in Wenzhou. Most studies propose solving the problems at a macro level, including addressing residents' perceptions, improving the transparency of renovation work, coordinating multiple renovation models, and enhancing compensation mechanisms. Other studies address particular districts or counties in Wenzhou, developing recommendations grounded in local governance and housing conditions. Li, H. [3] specifically investigated the willingness of residents in urban villages in Lucheng District, Wenzhou, to participate in renovation, proposing that the government should focus on improving quality of life through people-centred urban-village renovations.

In short, the proposals for the renovation of urban villages in Wenzhou mainly focus on (i) strengthening and supplementing policies and systems under government leadership, and (ii) improving social security for residents at the management level so that villagers can take the initiative to renovate. Such governance-oriented strategies can require lengthy negotiations and substantial institutional coordination, which may delay improvements to residents' daily living conditions. By contrast, this study starts with renovation at the scale of the urban-village dwelling, leveraging vernacular architecture to address local climate change and exploring ways to improve the indoor thermal environment without demolition.

Wenzhou's residential building stock reflects successive responses to social, demographic, and climatic change. Historic private dwellings preserved from the late Imperial and early Republican periods—exemplified by Yongjia Furong Village and Taishun Ancient Village (approximately 1644–1949; Figure 1)—embody a passive climatic-adaptive logic that has been refined over centuries of hot-humid summers (Figure 2). After the founding of New China, growing household sizes drove the incremental replacement of single-storey bungalows by 3–6-storey self-built urban-village dwellings, which today house much of the city's migrant and working-class population (Figure 3). Although these urban-village dwellings respond to the same humid-subtropical climate (Köppen Cfa) as their vernacular predecessors, their envelope construction, materials, and interior layout have largely discarded the passive climatic logic of the older stock. This combination of historical continuity and contemporary discontinuity motivates the present study: rather than treating vernacular architecture as decorative heritage, this study re-reads it as a functional repository of climate-responsive strategies that are directly transferable into modern urban-village retrofit. This framing underpins the three objectives introduced in Section 1.2 and the three corresponding research questions presented in Section 1.3.

Small, multi-storey residential buildings met Wenzhou's needs during earlier phases of urban development, but many of these structures now present conflicting demands for housing affordability, urban renewal, and contemporary environmental performance. Their continued occupation makes practical, low-disruption improvements particularly important. Urban villages are settlements absorbed into expanding Chinese cities, appearing in both suburban districts and central urban areas [4]. They are surrounded by skyscrapers, transportation infrastructure, and other modern urban structures. Urban villages are a unique phenomenon in China's urbanisation process [5]. In this article, the term 'urban village' refers specifically to settlements located within the established urban centre rather than to rural villages beyond the city boundary.



Figure 1. Yongjia Furong Village and Taishun Ancient Village (source: online photographs; original photographer and permissions to be confirmed)



Figure 2. Wenzhou vernacular buildings from the late Imperial and early Republican periods, photographed by the authors on site (August 2023; left)

On the one hand, the problem of urban villages has seriously affected the appearance of modern cities and the quality of life for residents. On the other hand, some urban villages are located in bustling city centres, providing residents with convenient access to urban amenities. The visual and spatial character of a city reflects elements of its development history and can also communicate a distinctive cultural identity [6]. However, demolishing and reconstructing these residences requires the government to pay substantial compensation to residents, and the approval procedures are extremely difficult

[7]. Demolition-led redevelopment on the current scale is a particularly dominant mode of urban transformation in China, owing to the dual land-ownership structure (urban vs. rural collective) and to the ambiguous tenure regime of urban villages [8, 9].



Figure 3. Wenzhou urban-village dwelling, photographed by the authors on site (August 2023; right)

The urban-village problem occurs not only in Wenzhou but also poses a hidden danger in many first- and second-tier areas in China, where urbanisation is developing rapidly and housing prices are high. Issues such as public security and fire protection in urban villages are major safety concerns for the government [10]. The central locations of many urban-village buildings offer substantial accessibility advantages. For developers, demolition or renovation can bring substantial economic benefits [11]. From a social perspective, urban villages are part of the historical heritage of urban construction and development and hold significant preservation value [12]. However, for residents, urban villages are a contradictory existence: while they are surrounded by convenient public facilities, the old buildings have begun to exhibit safety problems [13], such as stairs in disrepair and damaged building façades.

Observational studies [1, 2, 14] report that urban-village residences exhibit many unsustainable architectural features from two perspectives: building conditions and resident behaviour. First, the indoor equipment in urban-village housing is aging and outdated, and cannot adapt to modern intelligent systems such as fresh-air and energy-saving systems that improve indoor air quality. Moreover, the lack of a unified management organisation in urban villages means that installing this equipment requires government personnel to consult each household, creating a huge workload and coordination difficulties.

Second, the reported window-to-wall ratios (WWRs) differ by orientation, and some façades have insufficient opening areas whereas others exceed the stated design limits (Table 1). These discrepancies complicate the balance between daylight, natural ventilation, solar heat gain, and energy performance. In Wenzhou's humid climate, inadequate ventilation can permit moisture to accumulate indoors, potentially aggravating dampness and increasing the deterioration risk for electrical fittings and finishes. WWR alone, however, does not determine ventilation effectiveness because opening type, operability, prevailing winds, and room layout also matter. Additionally, surveys conducted by Yi et al. [1] and Wei et al. [14] found that some residents did not prioritise window lighting and ventilation. This is mainly because the buildings

are closely spaced, so opening windows or drawing curtains compromises privacy, and some windows provide inadequate lighting. Insufficient windows for natural lighting and ventilation hinder the regulation of the indoor thermal environment and air quality, especially in response to climate change.

Table 1. Orientation-specific window-to-wall ratios reported for Wenzhou urban-village dwellings

Building orientation	Specified WWR limit	Observed WWR range
East-facing	< 0.25	21–25%
South-facing	< 0.45	11–25%
West-facing	< 0.25	36–40%
North-facing	< 0.40	6–15%

Thirdly, the unsustainability of indoor urban-village environments affects the behaviour and habits of residents. Storage provision is insufficient in many urban-village houses (Figure 4). Where usable indoor floor area is approximately 60 m², limited built-in storage often causes belongings to occupy circulation and living areas. The accumulation of household items obstructs residents' circulation routes and interferes with the intended use of the available rooms [15]. Furthermore, some earlier interior designs relied on rigid, standardised layouts (Figure 4) and did not consider the usage habits and needs of different residents. For example, the bathroom design lacks partitioning, preventing family members from carrying out separate bathroom activities at the same time (e.g., when one person is brushing their teeth, another cannot use the toilet). Additionally, the potentially unnecessary partition between the bedroom and the balcony not only occupies indoor space but also affects natural lighting and ventilation [16].



Figure 4. Interior of typical Wenzhou urban-village dwelling, showing storage shortage and formulaic internal layout, photographed by the authors on site (August 2023)

1.1. THE SUSTAINABLE BUILDING INTERNAL DESIGN (SBID) CONCEPT

To address the unsustainable building problems outlined above, this study introduces the concept of Sustainable Building Internal Design (SBID). SBID applies the principles of sustainable development to internal architectural design: minimising environmental impact, conserving resources, and maximising the health and well-being of occupants [17–19].

Drawing on the recent literature, SBID is operationalised into six measurable design dimensions that influence indoor thermal conditions, as synthesised below:

(i) Building envelope shading devices. External shading can reduce unwanted solar gains during hot periods, particularly where the orientation and form of adjacent buildings expose windows or walls to intense sunlight. Guo et al. provide evidence that opaque shading of external walls can be an effective overheating-mitigation strategy for urban-village housing in subtropical China [2]. The suitability of horizontal overhangs, screens, and local shading elements depends on the sun path, window position, and the need to retain useful daylight and natural ventilation.

(ii) Window-to-wall ratio (WWR). The window-to-wall ratio affects several outcomes simultaneously, including daylight availability, cross-ventilation potential, solar gain, and cooling demand. Chi et al. examine orientation-dependent WWR optimisation for traditional dwellings in Zhejiang Province, using daylight, air-temperature, and air-velocity criteria rather

than applying one universal target [20]. For Wenzhou urban-village retrofits, the appropriate WWR should therefore be determined separately for each façade, together with opening geometry, shading, and the surrounding building density.

(iii) Building envelope orientation. The direction of exposed façades and openings affects both incident solar radiation and opportunities for ventilation. The orientation-sensitive analysis by Chi et al. suggests that the performance of a particular glazing area cannot be evaluated independently of orientation [20]. Where the building's overall orientation cannot be changed, SBID can still improve the arrangement of operable windows and internal airflow paths, while taking account of neighbouring buildings that may obstruct incoming breezes.

(iv) Building envelope materials. Wall, roof, and glazing properties influence heat transfer, internal surface temperatures, and the capacity of the dwelling to moderate short-term outdoor temperature fluctuations. Fernando et al. describe the technical opportunities and practical challenges of sustainable façade systems, while Guo et al. examine the sensitivity of overheating to building construction and retrofit measures [2, 18]. Insulation, ventilated layers, and glazing upgrades should be considered in conjunction with moisture control and the existing structural condition.

(v) Building envelope colour. The solar absorptance of an exposed finish affects the amount of radiation absorbed by a façade or roof. Alpuche et al. used EnergyPlus simulations to examine the influence of external surface absorptance on the thermal performance of affordable housing [21]. Although that study concerns a warm-dry Mexican climate, the physical importance of solar absorptance provides a rationale for testing lighter, higher-albedo finishes in Wenzhou, subject to local climatic assessment.

(vi) Interior layout. Spatial arrangements affect movement, daylight penetration, privacy, and the continuity of potential airflow paths between external openings. Wei et al. combine residents' perceptions with building performance simulation when evaluating urban-village rental spaces, illustrating the value of considering functional requirements alongside environmental conditions [14]. Flexible partitions, improved storage integration, and the removal of unnecessary interior obstructions can therefore be examined as low-disruption design measures rather than assumed to deliver a fixed thermal benefit.

Together, these six dimensions inform the SBID retrofit scenarios (V1–V5) modelled in this study.

SBID is positioned as a vernacular-rooted, occupant-centric framework that is distinct from, but complementary to, four adjacent paradigms. (i) Relative to green building, which emphasises overall environmental performance across the whole life cycle [22], SBID is restricted to the dwelling interior and is therefore implementable without disturbing the urban fabric. (ii) Relative to Passive House [23], which targets strict airtightness and energy thresholds, SBID accepts the existing envelope of urban-village dwellings and optimises climatic response through internal measures. (iii) Relative to nearly zero-energy buildings (NZEB), which require high-performance envelopes and active systems, SBID is deliberately low-tech and replicable at low cost. (iv) Relative to bioclimatic design [24], SBID inherits the site-specific climatic-response logic but focuses on internal design rather than master-plan siting.

These dimensions demarcate SBID from purely technological efficiency-oriented frameworks and align it with the user-centred, climate-responsive philosophies of Fathy [25], Vale & Vale [26], and the vernacular-architecture tradition documented by Oliver [27].

Meanwhile, according to the 2023 Sustainable Development Goals (SDGs) Report released by the United Nations, progress on Sustainable Development Goal 11 (Sustainable Cities and Communities) has been weak and insufficient, manifested in the increase in the number of people living in slums and slum-like environments, especially in many small cities and towns. Wenzhou is no exception. The issues in Wenzhou's urban villages have hindered the sustainability of cities and communities. Therefore, it is urgent to address the problem of unsustainable buildings in Wenzhou's urban villages.

Building on the arguments above, this study selects Wenzhou's urban-village houses and residents as its object of inquiry. It seeks inspiration from the climate-adaptive logic of Wenzhou vernacular architecture and translates that logic into the Sustainable Building Internal Design (SBID) framework, providing transferable design guidance for cities confronting similar urban-village challenges. SBID is operationalised into six measurable design dimensions—envelope shading devices, window-to-wall ratio (WWR), envelope orientation, envelope materials, envelope colour, and interior layout—each of which is mapped to one or more of the three research questions (Section 1.3) and tested through the V0–V5 simulation campaign (Section 3.3).

To avoid scope ambiguity with the paper's title, this study explicitly states that SBID prioritises internal design interventions; envelope modifications (e.g., shallow overhangs, lime re-rendering of external walls) are adopted only as supporting measures where strictly necessary. This internal-first, envelope-supporting distinction is applied consistently throughout the remainder of the paper, including the research questions (Section 1.3), the simulation scenarios (Section 2.1), and the discussion of effectiveness (Section 3.3).

Existing research on urban villages in Wenzhou—and in comparable first- and second-tier Chinese cities—can be grouped into four broad streams, each addressing a different dimension of the urban-village problem. The first stream addresses physical-safety concerns [28], highlighting that high building density, cluttered public spaces, and the use of

outdated building materials that do not meet current fire-safety standards increase risk for residents. The second stream addresses security concerns [29, 30], noting that urban villages, as settlements for transient populations, lack public facilities and management systems, which are associated with higher crime rates. The third stream addresses public-health concerns [31, 32], observing that public spaces are generally poorly maintained and lack adequate waste-management infrastructure. The fourth stream addresses energy and environmental concerns [33, 34], documenting insufficient lighting and ventilation in densely built urban-village dwellings.

More specifically, the second category involves security issues [29, 30], emphasising that urban villages, as settlements for transient populations, lack public facilities and management systems, leading to high crime rates.

In parallel, the third category involves public-health issues [31, 32], noting that public spaces in urban villages are generally poorly maintained and lack adequate waste-management facilities.

Finally, the fourth category addresses energy and environmental issues [33, 34], focusing on the lack of adequate lighting and ventilation in densely built urban villages, leading to energy and environmental concerns.

These four streams share a common orientation: they investigate urban-village issues primarily at the societal or district scale, with comparatively little attention given to the residential dwellings themselves as a unit of analysis. In recent years, scholars have begun to document the phenomenon of summer indoor overheating in urban-village dwellings [1, 2, 14], and computer simulations have confirmed that buildings in subtropical monsoon climates do indeed suffer from indoor overheating. However, compared with the volume of work on policy, security, public health, and macro-scale energy issues, research on indoor overheating in urban villages during summer remains limited—both in terms of the causes that drive it at the dwelling scale and in terms of the design solutions that can alleviate it.

Urban-village architecture—the focus of the present study’s renovation effort—presents an interconnected set of challenges, including high building density, aging façades, poor indoor environmental quality, risk of indoor overheating, inadequate infrastructure, and safety hazards [2, 35]. Researchers have responded to these challenges from two complementary angles: (i) policy and management responses that operate at the city or district scale, and (ii) architectural-design and planning responses that operate at the building or unit scale. The present study belongs to the second stream but goes beyond purely technological retrofit by drawing on vernacular climatic logic to inform internal design.

Sustainable-design concepts have emerged as a promising response to the architectural challenges of urban-village dwellings. Yudhistira [35] proposed a modular, scalable building system that incorporates local natural materials to address hazards associated with insufficient structural strength. Guo et al. [2] suggested adding exterior-wall shading to mitigate the risk of indoor overheating in urban-village buildings from a sustainable-development perspective. However, only a limited number of studies have shown that solutions grounded in sustainable-design concepts can improve the underlying issues of urban-village architecture, and the application of sustainable internal design to these buildings remains particularly underdeveloped.

Building renovation is recognised as a method to extend the lifespan of structures and is commonly applied to existing buildings. In the context of urban-village buildings, renovation efforts primarily focus on enhancing structural safety by updating plumbing, adding fire-safety equipment, and reinforcing exterior walls [36, 37]. Particularly, Yang [36] suggested reinforcing and refurbishing the exterior walls of Suzhou’s urban-village buildings and repainting the façades to improve their overall architectural appearance.

Another focus is on renovating the communal facilities within these buildings [38, 39], aiming to provide a safer, more convenient, and comfortable living environment for urban-village residents, with particular attention to the safety and accessibility for the elderly. Specifically, Wei [38] proposed safety and age-friendly renovations in the communal spaces of Guangzhou’s urban villages, suggesting that installing barrier-free infrastructure not only ensures safe and harmonious movement but also promotes mental and emotional well-being.

Despite these advances, only a few researchers have highlighted the need to address indoor overheating during summer in urban villages [2, 14]. Wei et al. [14], for example, argue from the perspective of tenant satisfaction and well-being that the thermal performance and lighting conditions of urban villages do not meet relevant standards and urgently need upgrading. Yet design solutions specifically aimed at alleviating indoor discomfort in urban villages during summer remain limited and fragmented, and few of the proposed measures are framed as Sustainable Building Internal Design.

Following the above arguments, this study addresses three research gaps: (i) there is insufficient dwelling-scale evidence on the envelope and interior-layout aspects that drive summer indoor overheating in urban-village housing; (ii) although Wenzhou’s vernacular architecture embodies a coherent set of passive climatic-adaptive strategies, these strategies have rarely been documented in a form directly transferable into contemporary urban-village retrofit; and (iii) the effectiveness of sustainable-design interventions targeting indoor overheating in urban-village housing has rarely been quantified through calibrated building performance simulation. Based on these three gaps, the study pursues three parallel objectives—O1 (envelope and interior-layout aspects), O2 (vernacular climatic-adaptive strategies), and O3 (simulation-based effectiveness verification)—articulated and translated into three corresponding research questions. Wenzhou’s hot-summer / warm-winter humid-subtropical climate (Köppen Cfa; mean July temperature 28.0 °C; mean annual relative

humidity 81%; tropical-cyclone season June–September; [40]) makes internal overheating a critical and under-addressed problem, and Lucheng District's Wuma Street is selected as the case-study cluster because it combines canonical urban-village morphology with strong transport accessibility and the potential transferability of its design principles.

1.2. RESEARCH OBJECTIVES

Building on the problem statement, this study pursues the following three parallel objectives:

O1. To identify and analyze the key aspects of building envelope and interior layout in Wenzhou's urban villages that require SBID optimization for summer indoor overheating mitigation.

O2. To analyze and document the passive design strategies in Wenzhou's vernacular architecture that provide climate adaptability in building envelope and interior layout from the SBID perspective.

O3. To assess the effectiveness of SBID interventions in mitigating summer indoor overheating in Wenzhou's urban villages through building envelope and interior layout optimizations.

1.3. RESEARCH QUESTIONS

The above objectives translate into the following three research questions, each mapped one-to-one to the corresponding objective:

Q1. What are the key aspects of building envelope and interior layout in Wenzhou's urban villages that can be optimized through SBID to mitigate summer indoor overheating?

Q2. How does vernacular architecture in Wenzhou achieve climate adaptability in its building envelope and interior layout from the perspective of SBID?

Q3. How effective are SBID interventions in improving indoor thermal conditions in Wenzhou's urban villages during summer, specifically through building envelope and interior layout optimizations?

2. METHODOLOGY

This study adopts a sequential mixed-methods research design in which field surveys, observations, and environmental measurements inform the parameterisation and validation of building-performance simulations [41].

The case study is the Wuma Street urban-village cluster in Lucheng District, central Wenzhou (27.99° N, 120.79° E). The cluster was selected because (i) it exhibits the canonical urban-village morphology of dense 3–6-storey self-built dwellings, (ii) it combines mixed residential and commercial use, (iii) it is transport-accessible for the research team, and (iv) it offers the potential transferability of its design principles to similar coastal-Chinese urban-village contexts.

Wenzhou has a humid-subtropical climate (Köppen Cfa). The annual mean air temperature is 18.0 °C, the mean July (hot-summer) temperature is 28.0 °C with daily peaks of 33–36 °C, and the mean annual relative humidity is 81%. The tropical-cyclone season (June–September) superimposes high wind-driven-rain events on the summer heat, making summer overheating the dominant indoor-environmental problem [40].

On-site measurement is carried out in 30 representative dwellings during summer 2024 (July–August). Each dwelling was monitored continuously for at least 14 days, according to the described monitoring protocol with a Testo 174H Temperature & Humidity Logger pair recording air temperature and relative humidity in the main living area. Instruments were described as factory-calibrated and cross-checked in the field each week, with logged observations averaged to hourly values. For reproducibility, the corresponding instrument logs and calibration records should accompany the final research dataset.

2.1. BUILDING PERFORMANCE SIMULATION

Five SBID retrofit scenarios (V1–V5) and one baseline (V0) are modelled in EnergyPlus 24.1 / DesignBuilder 7.0. V0 represents an as-found dwelling (no retrofit). The retrofit scenarios progressively combine the six SBID dimensions (D1–D6):

Weather data use the Typical Meteorological Year (TMY) for Wenzhou. Each model is calibrated against the measured hourly indoor air temperature of the corresponding dwelling using the ASHRAE Guideline 14-2014 criteria (CV-RMSE $\leq 30\%$ and NMBE $\leq \pm 10\%$).

Indoor thermal conditions are evaluated through predicted mean vote (PMV) and predicted percentage dissatisfied (PPD), interpreted using ASHRAE Standard 55-2020 and the relevant thermal-environment measurement principles in ISO 7726, supplemented by the adaptive thermal-comfort reference of de Dear and Brager [42]. Indoor overheating is quantified as the cumulative number of hours in which indoor air temperature exceeds 28 °C during the monitored period. Statistical analysis is performed in R 4.3; significance is set at $p < 0.05$.

3. RESULTS AND DISCUSSION

This section reports the empirical results of the field survey, on-site measurement, and calibrated simulation campaign, and discusses the implications for urban-village thermal-environment retrofit. Results are organised around the three operationalised research objectives (RO1–RO3) introduced in Section 1.2. Section 3.1 identifies the envelope and interior-layout features that drive summer indoor overheating in Wuma Street dwellings. Section 3.2 documents the passive climatic-design strategies extracted from Wenzhou vernacular buildings (Furong Ancient Village case study). Section 3.3 reports the DesignBuilder simulation outcomes for the V0 baseline against the V1–V5 SBID retrofit scenarios. Section 3.4 discusses the findings in relation to cultural continuity, residents' agency, and social equity. Section 3.5 distils the analysis into transferable design guidelines.

3.1. SIX SBID-RELEVANT ASPECTS OF WENZHOU'S URBAN-VILLAGE DWELLINGS (O1)

On-site surveys and semi-structured interviews were conducted with ten households in the Wuma Street urban-village cluster during summer 2024. Each visit recorded dwelling geometry, envelope materials, shading configuration, window-to-wall ratio (WWR), interior layout, and the household's self-reported thermal experience. Photographs, sketches, and resident quotations were cross-checked between two researchers to ensure reliability.

Through thematic coding of the survey data, six envelope and interior-layout aspects were repeatedly identified as the primary drivers of summer indoor overheating: (i) building orientation, which governs exposure to south-westerly solar gain and prevailing southerly breezes; (ii) envelope materials, where single-leaf clay-brick walls and un-insulated metal roofs dominate and offer limited thermal resistance; (iii) window-to-wall ratio (WWR), typically 20–30%, which constrains both daylight and cross-ventilation; (iv) shading design, where horizontal shading devices are either absent or ineffective against high-angle summer sun; (v) façade colour, with dark, low-albedo finishes prevalent on retrofitted envelopes; and (vi) interior spatial layout, where kitchens, bathrooms, and storage encroach on living rooms, fragmenting ventilation paths. These six aspects jointly produce inadequate ventilation and heat accumulation, and they map directly onto the six SBID design dimensions operationalised in Section 1.1.

The identification of these six aspects reframes indoor overheating from an abstract experiential complaint into a set of tangible architectural challenges amenable to targeted intervention. The shift from mechanical-cooling reliance to envelope and layout optimisation is particularly relevant for resource-constrained urban-village communities.

3.2. PASSIVE CLIMATIC-ADAPTIVE STRATEGIES OF WENZHOU VERNACULAR ARCHITECTURE (O2)

Furong Ancient Village in Yongjia County was selected as a representative Wenzhou vernacular case. Field surveys and architectural documentation were carried out on ten representative traditional dwellings (stone-and-timber construction, 100–300 years old), recording plan, orientation, openings, shading devices, envelope materials, and observed indoor microclimate.

The surveyed vernacular dwellings consistently employ five climate-responsive strategies: (a) a north–south orientation with enclosed or semi-enclosed courtyards that channel southerly breezes through the central living spaces; (b) south-east-facing windows of modest size to admit low morning sun while limiting afternoon heat gain; (c) deep eaves combined with timber-lattice shading screens that intercept high-angle summer sun; (d) high-thermal-mass envelope materials (stone plinths, rammed-earth infill, timber partitions) that buffer the diurnal temperature swing; and (e) layered indoor–outdoor transitions (covered verandas, ventilated double-skin walls) that delay and attenuate heat transfer.

Together, these five strategies form a coherent passive regulation system that enables robust thermal adaptability without mechanical cooling. Their function-oriented logic—deep eaves intercepting high-angle summer sun, modest WWR enabling stack-effect ventilation, high-mass envelopes buffering diurnal heat flux—is transferable into the contemporary urban-village context through SBID interventions. This comparison establishes a plausible design rationale linking historic climate-responsive practices to the V1–V5 retrofit scenarios, while the effectiveness of each adaptation depends on the measured conditions and simulation assumptions.

3.3. EFFECTIVENESS OF SBID STRATEGIES IN CALIBRATED THERMAL SIMULATION (O3)

Five dwellings in the Wuma Street cluster were selected as representative urban-village samples. Geometry, envelope U-values, infiltration rates, internal gains, and HVAC schedules were derived from the on-site measurement campaign and input into DesignBuilder / EnergyPlus 24.1. Each model was calibrated against the measured indoor air temperature and relative humidity of summer 2024 to within ± 0.5 °C RMSE before the SBID scenarios were applied.

The baseline scenario (V0) represents the as-found envelope and interior layout. Five progressive SBID retrofit scenarios (V1–V5) were then layered onto V0, each adding a subset of the six SBID dimensions: V1 — shading device

upgrade; V2 — V1 + envelope insulation; V3 — V2 + WWR optimisation; V4 — V3 + façade recolouring to high-albedo finishes; V5 — V4 + interior layout reconfiguration.

Across the five calibrated models, SBID strategies were reported to reduce indoor overheating hours relative to V0. The largest incremental improvement among the sequential packages was attributed to the addition of envelope insulation in V2, after the shading upgrade introduced in V1; the complete results are needed to establish the magnitude and statistical significance of that improvement. WWR optimisation (V3) and façade recolouring (V4) further reduced afternoon peak indoor air temperature by 1.2–1.8 °C on average. Among the simulated retrofit configurations, the complete SBID package (V5) was reported to produce the greatest reduction in indoor overheating hours and the highest adaptive-comfort acceptance rate; however, the underlying numerical outputs should be provided to substantiate the comparison. Combining multiple design strategies may produce interacting effects, but a quantitative comparison of their separate and joint contributions is needed before synergy can be claimed for the V5 configuration. Predicted mean vote (PMV) was reported to shift from approximately +2.5 (warm) under V0 to approximately +0.8 (slightly warm) under V5. The accompanying predicted percentage dissatisfied (PPD) values and adaptive-comfort acceptability calculations were not included in the supplied manuscript; an 80% adaptive-comfort acceptability criterion is not equivalent to a PPD threshold of 80%.

Subject to verification of the complete simulation outputs, these results offer initial quantitative support for the SBID framework and close the loop of problem identification (O1), strategy development (O2), and effect verification (O3). The model structure also offers a potentially replicable technical procedure for testing SBID in other hot-humid, high-density, resource-constrained residential contexts.

3.4. DISCUSSION: CULTURAL CONTINUITY, RESIDENTS' AGENCY, AND SOCIAL EQUITY

The SBID strategy does not treat vernacular architecture as static heritage. Instead, it reinterprets vernacular design as a dynamic system of climate-responsive logic. During strategy development, emphasis shifts to functional principles—how deep eaves intercept high-angle summer sun, how elevated WWR facilitates stack-effect ventilation, how light-coloured surfaces minimise solar heat gain. This function-focused approach enables the reapplication of traditional climatic intelligence using contemporary materials and construction techniques, preserving the wisdom of vernacular design while avoiding rigid replication of historical forms. Cultural continuity is thereby re-embedded into everyday spatial practice rather than reduced to decorative motifs.

Many contemporary urban-village renewal initiatives prioritise total demolition or uniform façade repainting. In some contexts, such top-down approaches may disrupt neighbourhood networks, alter established spatial practices, and displace low-income tenants through rent increases. In contrast, the internal micro-renovations proposed under SBID are implemented without modifying building exteriors, compromising property rights, or interrupting daily routines. All design proposals are grounded in observational and interview data from the ten Wuma Street households: residents close west-facing windows in the afternoon, combine kitchens with living rooms due to spatial constraints, and dry clothing on balconies to enhance evaporative cooling. SBID responds to these non-standard yet authentic needs with flexible, adaptable solutions, respecting residents' agency and improving comfort within existing spatial and socioeconomic conditions.

The intended affordability and relative technological simplicity of SBID may make it suitable for resource-limited cities and vulnerable communities. Many high-performance green retrofit solutions rely on imported materials, smart technologies, or specialised labour, which are often prohibitively expensive for informal settlements. In contrast, most SBID strategies require minimal financial investment and can be implemented autonomously by residents themselves. This “affordable green” approach lowers barriers to renovation and supports participatory engagement. For migrant workers dependent on urban-village dwellings, micro-renovations that require no changes to property rights and trigger no rent increases help safeguard fundamental housing rights. SBID can therefore function not merely as an environmental intervention but also as a practice of social inclusion and environmental justice under conditions of material and institutional constraint.

The discussion above suggests that technical effectiveness and attention to residents' needs need not be mutually exclusive; they can, and should, coexist. SBID offers an incremental renewal pathway that enhances environmental quality while respecting social realities—not by imposing uniform standards, but by acknowledging diverse forms of spatial ingenuity already present in Wenzhou's urban villages.

3.5. DESIGN GUIDELINES FOR SUBTROPICAL URBAN-VILLAGE RETROFIT

Synthesising the results above, the following prioritised guidelines emerge for Wenzhou and comparable subtropical urban-village retrofit: (i) evaluate roof-envelope insulation first where the baseline roof exhibits substantial heat gain, while confirming its relative effectiveness for the building under study; (ii) combine external horizontal shading with internal cross-ventilation paths; (iii) optimise WWR by façade orientation and local shading conditions to balance daylight, solar gains, and ventilation rather than imposing an unverified universal numerical target; (iv) adopt high-albedo, low-VOC

interior finishes; (v) reconfigure interior layouts to release ventilation corridors before introducing mechanical equipment; (vi) embed passive climatic logic drawn from vernacular precedents (deep eaves, courtyards, double-skin walls) using contemporary materials; and (vii) design every intervention to be implementable by residents themselves without changes to property rights.

These guidelines are expected to be transferable to older neighbourhoods and self-built dwellings in other hot-humid regions of southern China (Pearl River Delta, Yangtze River Delta, Fujian, and Hainan), subject to local climate and regulatory recalibration.

4. CONCLUSIONS, LIMITATIONS, AND FUTURE WORK

This study investigated summer indoor overheating in Wenzhou's urban-village dwellings through the lens of Sustainable Building Internal Design (SBID). A sequential mixed-methods design—combining field survey of ten households, on-site measurement of 30 dwellings, vernacular case-study documentation in Furong Ancient Village, and calibrated EnergyPlus / DesignBuilder simulation of five retrofit scenarios and a baseline (V0–V5)—yielded four principal conclusions: (1) six envelope and interior-layout aspects systematically drive summer indoor overheating in Wuma Street urban villages; (2) Wenzhou vernacular architecture embodies a coherent set of passive climatic-adaptive strategies that are functionally transferable into contemporary retrofit; (3) calibrated simulation confirms that the layered SBID package (V5) reduces indoor overheating hours, lowers PMV from approximately +2.5 to +0.8, and is reported to improve adaptive-comfort acceptance, subject to verification of the comfort-model selection and accompanying numerical outputs; and (4) SBID may function simultaneously as an environmental intervention, a vehicle of cultural continuity, and a practice of social inclusion under resource-constrained conditions.

Three limitations should be acknowledged. First, the field survey and interview sample is restricted to ten households in the Wuma Street cluster; while informative, the sample does not capture vertical thermal variation across building levels nor the full demographic range of urban-village residents. Second, the SBID framework is bounded by an internal-design-first, envelope-supporting demarcation; envelope-dominated interventions such as full façade replacement, deep structural retrofit, or replacement of the existing roof structure fall outside the present scope. Third, the simulation relies on the Wenzhou TMY weather file and on EnergyPlus / DesignBuilder modelling assumptions; the V0–V5 results are therefore most directly applicable to typical meteorological years and to the specific urban-village typology studied, and should be extrapolated with caution to extreme heatwave years and to other hot-humid cities.

Future research will extend the SBID framework along five trajectories. (i) Expand the sample to first-floor and second-floor dwellings in Wenzhou's Lucheng District and replicate the study in Ouhai and Longwan Districts to establish vertically stratified, geographically distributed comparative data. (ii) Diversify participant demographics by actively recruiting younger tenants (currently under-represented) through community partnerships and online channels, to enrich analysis of generational differences in thermal perception and renovation acceptance. (iii) Integrate large-scale surveys, multi-point automated monitoring, and statistical modelling with grounded-theory qualitative coding, to quantify the relative influence of structural, climatic, and behavioural factors on indoor overheating. (iv) Diversify thermal-regulation technologies by exploring moderately active, modular, low-energy fresh-air and radiant-cooling systems that can be added incrementally to the passive SBID baseline under extreme heat events. (v) Upgrade monitoring precision by deploying high-accuracy, multi-parameter sensors and wearable devices to capture long-term, high-frequency objective and subjective thermal data. Collectively, these extensions will support the development of integrated, climate-responsive, equity-oriented retrofit frameworks for hot-humid urban-village housing.

Author contributions

The authors contributed equally to the study, as stated in the submitted manuscript. A detailed description of individual contributions should be confirmed before final submission.

Conflict of interests

The authors declare that they have no conflicts of interest related to the research presented in this manuscript.

Data availability

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Declaration of generative AI and AI-assisted technologies in the writing process

In the course of preparing this manuscript, the authors employed ChatGPT to improve the linguistic quality and readability of the content. After utilizing this AI tool, the authors conducted comprehensive review and necessary revisions to ensure the accuracy, integrity, and scientific rigor of the manuscript. All authors bear full responsibility for the final content of the published work, including any errors or inconsistencies that may arise.

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