

Article

Research on Appropriate Technologies for Optimizing the Indoor Light and Thermal Environment of Traditional Stone-Slab Dwellings in Southwest Henan

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Abstract

Traditional stone-slab dwellings in Southwest Henan possess distinctive regional characteristics and inherent climate adaptability. However, previous studies have mainly focused on individual aspects of indoor environmental performance, while integrated optimization of daylighting, thermal environment, and renewable energy utilization under the constraints of heritage conservation has received limited attention. This study systematically evaluates the indoor light and thermal environment of traditional stone-slab dwellings through field measurements and validated numerical simulations, and proposes appropriate optimization technologies. The numerical model was first validated against field measurement data and subsequently employed to evaluate the proposed optimization strategies. The results indicate that the daylight factor in the main occupied rooms does not satisfy current standard requirements. In terms of thermal performance, indoor temperatures are excessively high in summer and excessively low in winter, while the relative humidity remains close to saturation. Based on psychrometric chart analysis and the conservation requirements of traditional dwellings, a series of optimization strategies are proposed and validated. The results demonstrate that the addition of skylights, the application of 60 mm polyurethane (PUR) insulation boards to the roof and exterior walls, and the installation of transparent Low-E insulating glass units for exterior windows are effective technologies for improving the indoor light and thermal environment of stone-slab dwellings in Southwest Henan. The potential for solar energy utilization is also evaluated. This study provides an integrated framework for the environmental optimization of traditional stone dwellings and offers practical guidance for their sustainable conservation, performance enhancement, and renewable energy utilization.

Keywords: Southwest Henan; stone-slab dwelling; traditional residence; light and thermal environment; appropriate technology



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1. Introduction

Traditional dwellings represent valuable cultural heritage and embody profound regional knowledge through their spatial organization, material selection, and construction techniques. Their forms and construction logic have evolved over generations in response to local climatic conditions, demonstrating remarkable environmental adaptability and ecological wisdom [1]. However, rapid urbanization and changing living requirements

have posed significant challenges to the preservation and adaptive utilization of traditional dwellings. Many existing traditional buildings are unable to satisfy contemporary standards for indoor environmental quality, particularly regarding thermal comfort. Meanwhile, excessive dependence on mechanical systems, such as fans and air conditioners, for environmental regulation inevitably increases energy consumption and electrical loads [2,3]. Therefore, under the dual pressures of energy scarcity and environmental sustainability, exploring passive design strategies embedded in traditional dwellings and adapting them to contemporary requirements has become an effective approach for improving building energy performance [4,5].

Traditional dwellings worldwide exhibit diverse architectural forms and strong regional characteristics. Existing studies on the indoor physical environment of traditional dwellings can generally be classified into two categories. The first category focuses on revealing the inherent environmental adaptation mechanisms and construction wisdom of traditional dwellings. For example, Yue Jin and Ning Zhang conducted field measurements and environmental evaluations of stilted houses of the Dong ethnic group in China, demonstrating their superior climatic adaptability compared with modern buildings and suggesting that further optimization of building envelopes could improve indoor acoustic performance [6]. A.S. Dili, M.A. Naseer, and other researchers investigated vernacular residences in Kerala, India, and revealed the passive environmental control strategies embedded in these buildings, which enabled acceptable indoor thermal conditions throughout different seasons [7].

The second category emphasizes the development of passive optimization strategies by identifying deficiencies in the indoor environmental performance of traditional dwellings. Wei Liu, Baofeng Liang, and colleagues investigated traditional dwellings in Liangshan, China, combining field measurements and numerical simulations to explore suitable technologies for improving indoor thermal environments [8]. Yongchun Hao, Zhe Li, and others analyzed the influence of different courtyard configurations on the daylighting performance of central rooms in L-shaped, U-shaped, and courtyard-type Tujia dwellings, providing insights into daylight optimization strategies for traditional buildings [9]. Atefeh Tamaskani Esfehankalateh, Mohammad Farrokhza, and colleagues selected fourteen representative dwellings in a cold region of Iran and conducted systematic bioclimatic analyses, proposing transferable passive design strategies [10]. These studies demonstrate that traditional dwellings have developed unique climate-responsive strategies through the integration of local materials, construction techniques, and regional environmental conditions. However, as modern requirements for indoor comfort continue to increase, the original environmental performance of many traditional dwellings may no longer satisfy contemporary standards. Consequently, climate-responsive renovation strategies that respect local construction logic are urgently needed. Furthermore, most existing studies have concentrated on individual environmental aspects, such as thermal performance or daylighting conditions [11–13], while limited attention has been given to the interaction and coupling mechanisms between indoor thermal and daylight environments. Therefore, achieving coordinated optimization of both thermal and light environments through integrated passive strategies remains an important research challenge.

Henan Province, located in central China, covers both the cold climate zone and the hot-summer and cold-winter climate zone according to the Standard of Climatic Regionalization for Architecture (GB 50178-93) [14]. The diversity of climatic conditions and regional cultures has resulted in various traditional residential forms. Lu, T. and Herman, S.S., together with other researchers, investigated four architectural styles in Northwest Henan using a random forest classification model to identify the influence of materials, construction techniques, decoration, and functions on their formation mechanisms [15]. F. Wang,

F.Y. Yu, and colleagues selected five cases from Shan County, Henan Province, to analyze the transformation of traditional sunken courtyards from the perspectives of rural land-use policies and the inherent limitations of courtyard forms [16]. Zhu, S., Choi, B., and colleagues selected six pit courtyard villages in Western Henan and applied the Delphi method and analytic hierarchy process (AHP) to evaluate their architectural value from four dimensions, including scientific, artistic, social, and functional values [17].

Located in Southwest Henan, Wuya Village has been included in the Chinese Traditional Village Protection List due to its distinctive stone-slab dwellings. These traditional houses mainly utilize locally sourced stone as the primary construction material and adopt a hybrid structural system consisting of dry-laid stone walls and timber frames. The thick stone walls provide structural stability and contribute to environmental regulation, while the spatial layout adapts to the natural terrain, forming compact and functionally organized living spaces [18]. From foundations and walls to courtyard boundaries, paths, and daily-use objects, stone materials are extensively integrated into the village's architectural system, creating a complete and distinctive stone-based building culture [19,20]. Compared with the brick-and-timber residential traditions in mountainous areas of Southern Henan [21] and the raw-earth construction techniques represented by loess cave dwellings in Western Henan [22], stone-slab dwellings in Wuya Village represent a unique form of mountain architecture in Southwest Henan with significant regional characteristics.

Current research on traditional dwellings in Henan Province has mainly focused on architectural styles, cultural evolution, and heritage value assessment, whereas quantitative investigations and performance-based evaluations of indoor physical environments remain relatively limited. This deficiency restricts a comprehensive understanding of the environmental characteristics and sustainable development potential of traditional stone-slab dwellings in Southwest Henan. Therefore, this study selects a representative stone-slab dwelling in Wuya Village, Nanyang City, Southwest Henan, as the research object. Field measurements and numerical simulations are integrated to systematically evaluate its indoor thermal and daylight performance. Based on the evaluation results, targeted optimization strategies are proposed, including passive environmental improvement measures and renewable energy applications, to enhance indoor environmental quality while maintaining the original architectural characteristics. The findings aim to provide scientific support for the conservation, adaptive reuse, and sustainable renovation of traditional stone-slab dwellings in Southwest Henan and similar climatic regions.

The aim of this paper is to quantitatively evaluate the indoor light and thermal environment of traditional stone-slab dwellings in Southwest Henan and to develop effective passive strategies for their sustainable conservation and adaptive improvement. Unlike previous studies that mainly focus on the architectural characteristics, cultural values, or qualitative assessments of traditional dwellings, the innovative contributions of this work are embodied and quantitatively verified in the following three aspects.

At the perspective level, this study breaks through the conventional limitation of previous studies that mostly concentrated on either thermal or daylighting performance in isolation [22–24]. It is the first to treat the indoor daylight and thermal environments of traditional stone-slab dwellings in Southwest Henan as a coupled system with inherent trade-offs and synergistic mechanisms, conducting a coordinated optimization. Through simultaneous field measurements and correlation analysis, the study reveals the advantages of the “heavy envelope + extremely small window-to-wall ratio” construction mode in terms of winter heat retention and summer thermal insulation, while quantitatively diagnosing the consequent problems of severe daylight deficiency, limited natural ventilation, and high summer humidity. This systematic diagnosis provides a solid foundation for the precise targeting of subsequent passive strategies.

At the methodological level, this study establishes an integrated analytical framework of “field measurement, numerical calibration and strategy simulation”. Using EnergyPlus and Ladybug Tools as the core simulation engines, the model is rigorously calibrated against hourly measured data in both winter and summer (temperature errors within 5%, illuminance errors within 10%), ensuring the reliability of the simulation results. The psychrometric chart analysis module in Climate Consultant 6.0 is then employed to quantify the annual applicable hours of each passive strategy. Finally, quantitative comparison and screening of multiple combined schemes are achieved. This methodological pathway not only guarantees the scientific validity of the findings but also provides a replicable and transferable template for quantitative performance studies on other types of traditional dwellings.

At the strategy verification and quantitative discovery level, this study is the first to propose and validate a combined passive optimization strategy that respects the preservation of traditional architectural character, namely “rear-roof skylights + polyurethane (PUR) insulation boards applied to the roof and exterior walls + transparent Low-E insulating glazing for exterior windows”. In addition, this study is the first to quantitatively examine, for the courtyard stone dwellings in Southwest Henan, the applicability of an attached passive sunspace. Furthermore, it is the first to systematically assess the photovoltaic potential of the south-facing pitched roof, presenting a quantitative solution that installing approximately 3.1 m² of PERC photovoltaic modules can meet the average annual household electricity demand of about 700 kWh. Together, these quantitative findings and the proposed strategy combination constitute a complete technical pathway for the stone-slab dwellings in Southwest Henan, integrating daylight-thermal synergistic optimization and renewable energy utilization, and providing clear, actionable engineering guidance and policy references for the sustainable conservation, performance improvement, and adaptive reuse of traditional dwellings in this region and in similar climatic contexts.

2. Methods

2.1. Research Area

The Southwest Henan region primarily refers to present-day Nanyang City, Henan Province, located at the junction of Henan, Hubei, and Shaanxi provinces. It is surrounded by mountains on the north, east, and west, with the central area forming the “Nanyang Basin,” which opens southward toward the Jiangnan Plain. This unique geographical setting has endowed traditional architecture in Southwest Henan with distinctive regional characteristics. Climatically, the region lies in a transitional zone between the temperate continental climate and the subtropical monsoon climate, exhibiting pronounced transitional features with four distinct seasons. According to the Standard of Climatic Regionalization for Architecture, Nanyang City belongs to the hot-summer and cold-winter climate zone. Winters are cold and dry, summers are hot and humid, and the spring and autumn seasons are comfortable. Meteorological data from 2011 to 2021 show that the monthly average temperature peaks in July at approximately 33.1 °C, while the lowest value occurs in January at around −1.9 °C, resulting in a significant annual temperature range [23]. Wuya Village is located in Zhaqu Town, Neixiang County, Nanyang City, Henan Province. Its geographic coordinates are approximately 111°75′ E and 33°03′ N, about 9 km west of Neixiang County seat (Figure 1). The village sits at an elevation between 246 m and 253 m, fully following the natural mountain terrain in a stepped layout. The entire settlement is distributed across platforms at different heights, with an internal elevation difference of up to 30 m. Most buildings are arranged parallel or perpendicular to the contour lines, forming a well-proportioned, layered mountain settlement pattern (Figure 2). The village contains 93 relatively intact stone building complexes, comprising approximately 200 rooms, with

over 80% of the traditional dwellings well preserved. The architectural layout generally follows the northern Chinese courtyard style, featuring single-courtyard or multi-courtyard arrangements, with the main houses typically constructed as single-story buildings.

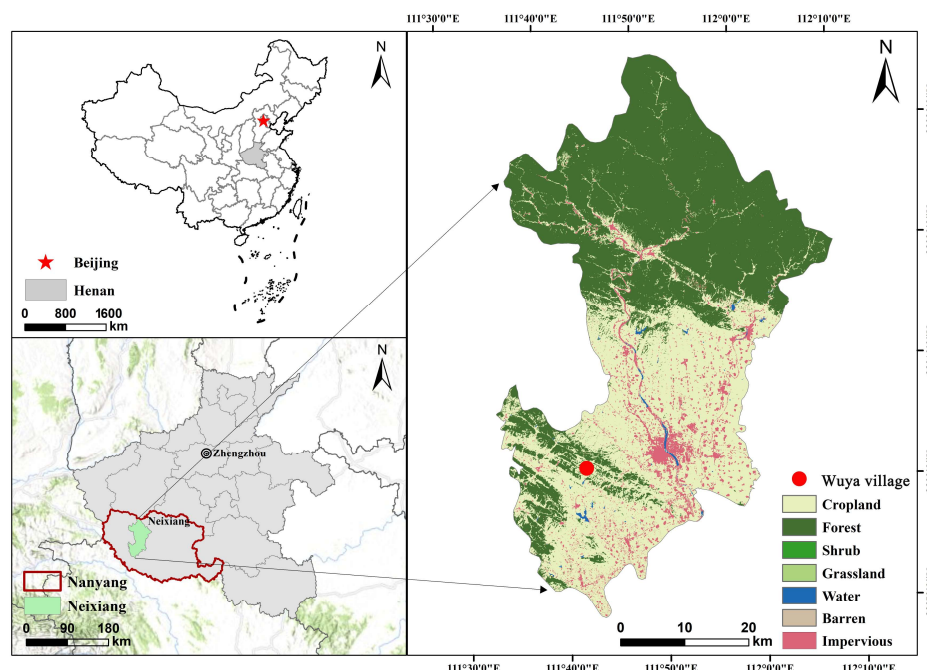


Figure 1. Location map of Wuya Village.

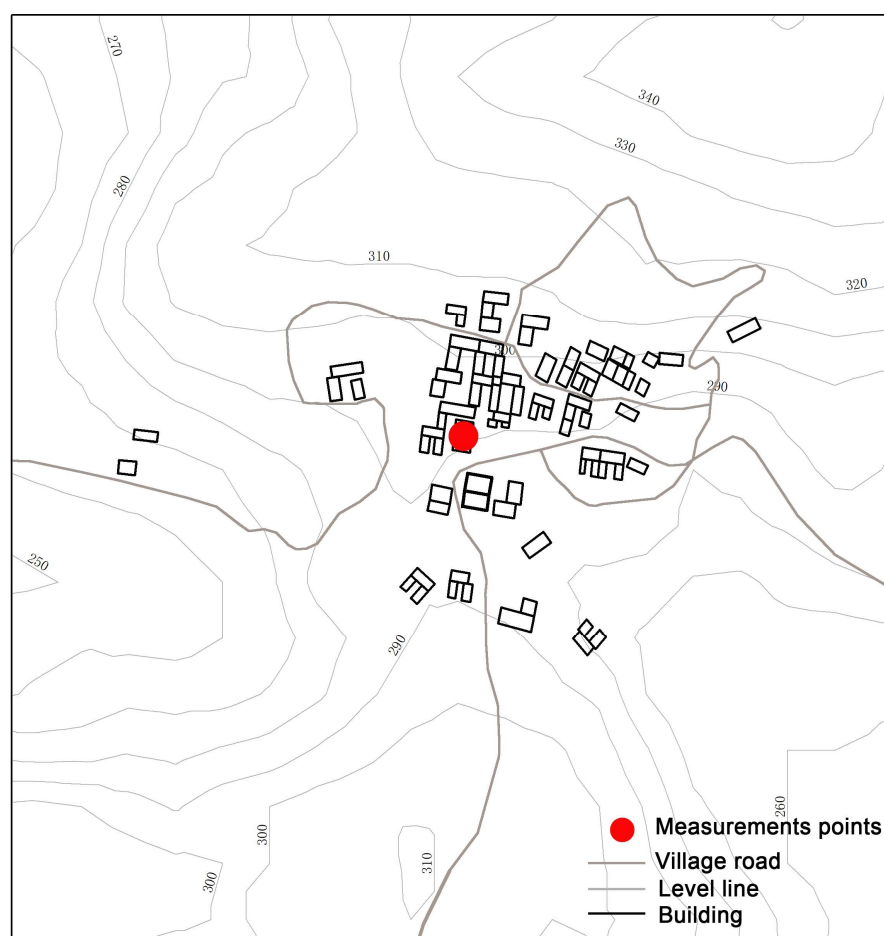


Figure 2. Plan drawing of Wuya Village.

The selected building for this study is a typical representative that is still inhabited. The building is an L-shaped courtyard house, with both the main house and the wing houses being single-story. The main house has a clear width of 8.46 m (east–west) and a depth of 5.64 m (north–south), with a ridge height of approximately 4.2 m and an eaves height of 3.0 m. The main house faces south and consists of three bays: the central room (3.20 m × 6.09 m, approximately 19.49 m²) serves as the living room, while the east and west side rooms (each 2.87 m × 6.09 m, 17.48 m²) are bedrooms. The living room and side rooms are separated by adobe walls that extend only to the bottom of the beams. The doors and windows of the main house are all traditional wooden structures; the doors are traditional wooden doors with a height of 2.2 m, and the lattice wooden windows (each approximately 0.9 m × 0.9 m) are fixed panels without glass glazing, resulting in a total window area of only 1.62 m² and a window-to-wall ratio of approximately 0.06. The walls are constructed of roughly squared stone blocks laid dry in staggered courses, with a total thickness of approximately 450 mm. The interior surfaces of the walls are finished with a yellow mud plaster base (10 mm thick). The roof is typically covered with traditional grey tiles laid in overlapping rows over a timber frame, with a total roof area of approximately 61.03 m².

2.2. Field Measurement Methods

The field measurements for the thermal environment were conducted from 14 July to 21 July 2025 (summer) and from 11 January to 18 January 2026 (winter). All measurement days were sunny or partly cloudy, covering the hottest month (July) and the coldest month (January). Air temperature (T_a) and relative humidity (RH) were recorded using USB-type COS-04-0 automatic temperature and humidity data loggers (Shandong Renke Control Technology Co., Ltd., Jinan, China). Wind speed (V_a) was measured using an RS-HSQXZ-USB-2 mechanical handheld weather station (Shandong Renke Control Technology Co., Ltd., Jinan, China). According to the relevant provisions of the Standard for Thermal Environment Testing Methods in Buildings (JCJ/T 347-2014) [25], the measurement locations were set as the outdoor courtyard, the living room, and the two bedrooms (Figure 3).

The field measurement of the luminous environment covered four working conditions: (1) winter clear sky (16 January 2026, cloudless, corresponding to the CIE standard clear sky model); (2) winter overcast sky (20 January 2026, fully cloud-covered, corresponding to the CIE standard overcast sky model); (3) summer clear sky (18 July 2025, cloudless, corresponding to the CIE standard clear sky model); and (4) summer overcast sky (22 July 2025, fully cloud-covered, corresponding to the CIE standard overcast sky model). For each working condition, measurements were taken four times on the same day at 10:00, 12:00, 14:00, and 16:00, and the average values were used for comparative analysis. The measurements were taken in the main occupied rooms, namely the living room and the two bedrooms of the main house. According to the Method of Daylighting Measurements (GB/T 5699-2017) [26], measurement points were set at a height of 750 mm above the floor. Artificial lighting was turned off; the operator wore dark-colored clothing and kept a distance from the light receiver. The measuring instrument was a Biaozhi GM1020 illuminance meter (Shandong Renke Control Technology Co., Ltd., Jinan, China) (measurement range: 0–200,000 lx; accuracy: ± 1 lx). The specific layout of measurement points for the light and thermal environment is shown in Figure 4.

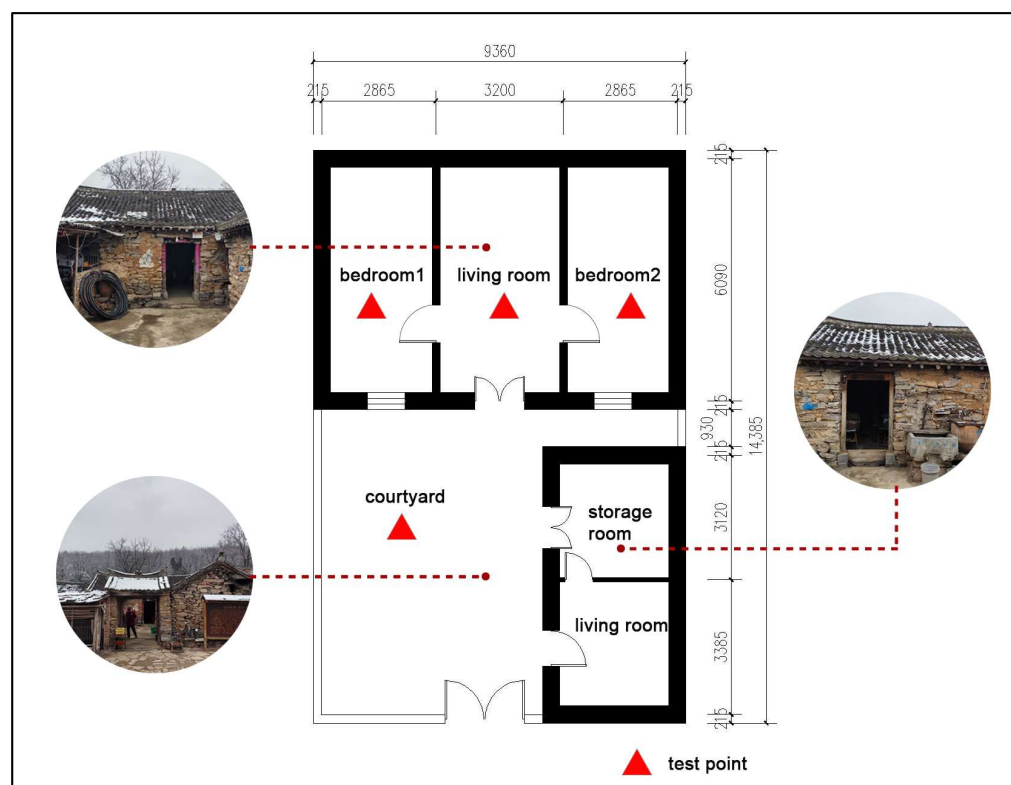


Figure 3. Layout of thermal environment measurement points.

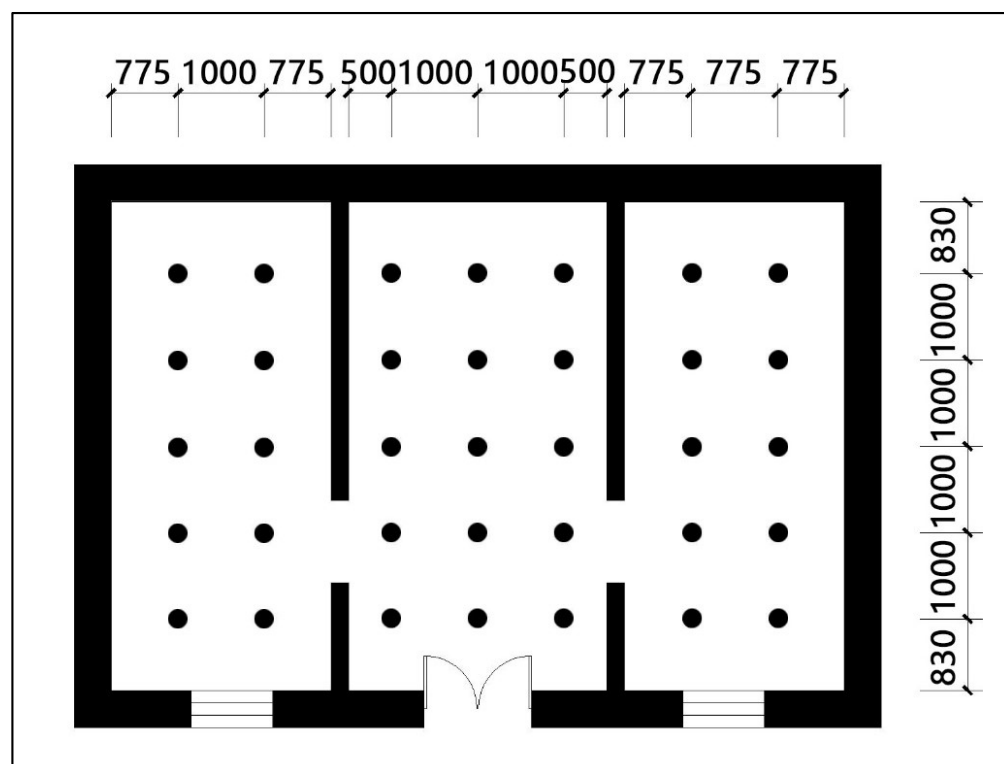


Figure 4. Layout of light environment measurement points.

2.3. Software Calculation Methods

2.3.1. Thermal Environment Simulation Software

EnergyPlus (9.6.0) is a professional building energy simulation software program developed under the leadership of the U.S. Department of Energy (DOE). It is widely recog-

nized as one of the most powerful and accurate simulation engines in this field. Employing an integrated, simultaneous solution approach and a core algorithm based on the heat balance method, EnergyPlus can accurately simulate complex physical processes such as heat transfer through building envelopes, daylighting and artificial lighting, HVAC systems, and renewable energy systems with user-defined time steps [27,28]. The traditional dwellings in Wuya Village are typical stone masonry buildings in the mountainous area of Southwest Henan. Their unique construction and material characteristics are fundamentally different from those of modern buildings. Selecting EnergyPlus as the thermal environment simulation software for this study allows for a precise analysis of the dynamic thermal effects of physical environmental factors—such as temperature, humidity, and solar radiation—on this heterogeneous, composite envelope structure under extreme summer and winter weather conditions. This capability helps researchers objectively evaluate the current thermal environment of traditional dwellings in Southwest Henan and the actual effectiveness of retrofitting measures for summer thermal insulation and winter thermal preservation.

2.3.2. Light Environment Simulation Software

Ladybug Tools (1.72.5) is an open-source, parametric building environmental performance simulation toolset developed by Mostapha's team based on the Rhino-Grasshopper platform. Its core modules include Ladybug, Honeybee, Butterfly, and Dragonfly. The toolset integrates authoritative simulation engines such as EnergyPlus and Radiance, enabling meteorological data analysis, building energy calculation, daylighting and sunlight analysis, outdoor wind environment CFD simulation, and urban microclimate simulation. Its greatest advantage lies in achieving seamless integration between architectural form design and performance simulation, supporting parametric multi-scenario iterative optimization, and offering ease of operation. Currently, this toolset is widely used in passive design of green buildings, low-carbon energy optimization, residential area microclimate creation, and academic simulation research in building environmental engineering, making it a mainstream research tool in the field of numerical simulation of building physical performance.

2.3.3. Building Climate Analysis Software

The comfort level and energy efficiency of the indoor thermal environment are influenced by outdoor climatic conditions and human thermal comfort requirements. Therefore, the relationship among climate, indoor thermal comfort, and building design must be considered simultaneously in the design process. Building climate analysis software can organically integrate these three aspects, accurately analyzing multi-year meteorological data for a specified region and proposing passive strategies suitable for the local climate at the early stage of schematic design [8]. Climate Consultant 6.0 can load the annual 8760-hourly weather data for a target location and efficiently convert them into dozens of intuitive visual charts, such as solar radiation analysis diagrams, wind speed analysis diagrams, and psychrometric charts. Particularly critical is its psychrometric chart analysis module, which not only reveals subtle climatic characteristics and their impact on building form but also accurately calculates the percentage of annual hours falling within the favorable zones for 16 passive design strategies, ultimately generating an automatically adapted passive design strategy guide for the project location.

This study takes Nanyang City in Southwest Henan as the research subject. First, Climate Consultant software is used to quantitatively analyze its meteorological data. Subsequently, an enthalpy–humidity diagram is drawn based on local climatic characteristics, and the applicable duration of each passive design strategy throughout the year is

thoroughly interpreted. Finally, based on the analysis results, the most suitable passive optimization strategies for traditional dwellings in Southwest Henan are extracted.

3. Results

3.1. Analysis of Measurement Results

3.1.1. Thermal Environment

The Southwest Henan region experiences cold winters, hot summers, and large diurnal temperature variations. According to the measured data from 11 to 18 January (winter), the outdoor minimum temperature dropped to 2.3 °C, and the maximum reached 18.1 °C. The most dramatic fluctuation occurred on 12 January, with an outdoor diurnal temperature difference of 15.7 °C. During the same period, the diurnal temperature difference in the living room was 3.3 °C, in Bedroom 1 was 2.5 °C, and in Bedroom 2 was 3.4 °C. The measured data from 14 to 21 July (summer) show that the outdoor minimum temperature was 24.7 °C and the maximum reached 38.2 °C. The greatest fluctuation occurred on 20 July, with an outdoor diurnal difference of 11.6 °C, whereas the living room had a difference of only 1.1 °C, Bedroom 1 1.2 °C, and Bedroom 2 0.9 °C (Figure 5). Even under extreme winter and summer weather conditions, despite large outdoor temperature fluctuations, the indoor environment maintains relatively stable thermal conditions. This fully demonstrates that the stone-slab dwellings in Southwest Henan possess good thermal insulation in winter and thermal insulation in summer. The reason is that the walls of these mountain stone-slab dwellings in Southwest Henan are built entirely from local stone. This heavy material has a high thermal mass and very low thermal conductivity. Therefore, in winter, the walls absorb and store the limited solar radiation heat during the day and release it slowly indoors at night, effectively resisting sudden drops in outdoor temperature. In summer, the thick stone walls act as a massive insulating barrier, blocking outdoor high-temperature radiation and keeping the interior cool. This clearly demonstrates the construction wisdom of stone-slab dwellings in Southwest Henan.

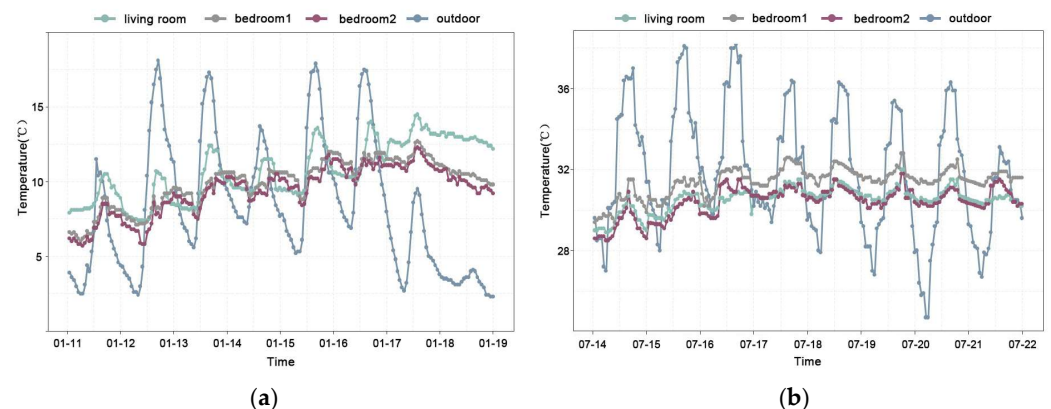


Figure 5. Measurement results of indoor and outdoor thermal environment: (a) winter; (b) summer.

According to the Design Standard for Energy Efficiency of Rural Residential Buildings (GB/T 50824-2013) [29], for the hot-summer and cold-winter climate zone, the indoor calculated temperature is 30 °C in summer and 8 °C in winter. The surveyed building only failed to reach 8 °C on 11 January (winter) in terms of average room temperature; at all other times it met the requirement. However, during most of the summer, the average indoor temperature exceeded 30 °C. It can be seen that the mountain stone-slab dwellings in Southwest Henan still require summer thermal insulation measures to lower indoor temperatures to meet the standard requirements.

In terms of humidity, in winter, the highest measured outdoor humidity occurred at night, reaching 74.4%, while the lowest occurred in the afternoon at 16.6%. The most dramatic fluctuation still occurred on 12 January, with an outdoor diurnal humidity difference of 28.7%. During the same period, the humidity difference in the living room was 11.1%, in Bedroom 1 was 11.3%, and in Bedroom 2 was 11.7%. In summer, the lowest outdoor humidity was 64% and the highest reached 98%. The greatest fluctuation occurred on 18 July, with an outdoor humidity difference of 34%. In comparison, the humidity difference in the living room was 24%, in Bedroom 1 was 4%, and in Bedroom 2 was 1% (Figure 6). It is worth noting that indoor humidity in summer was generally high, approaching saturation levels during some periods. The main reason is that in summer, when hot and humid outdoor air infiltrates indoors through door and window gaps, or when moisture generated by occupant activities encounters the relatively low-temperature stone walls, condensation occurs on the stone walls, causing indoor humidity to approach saturation.

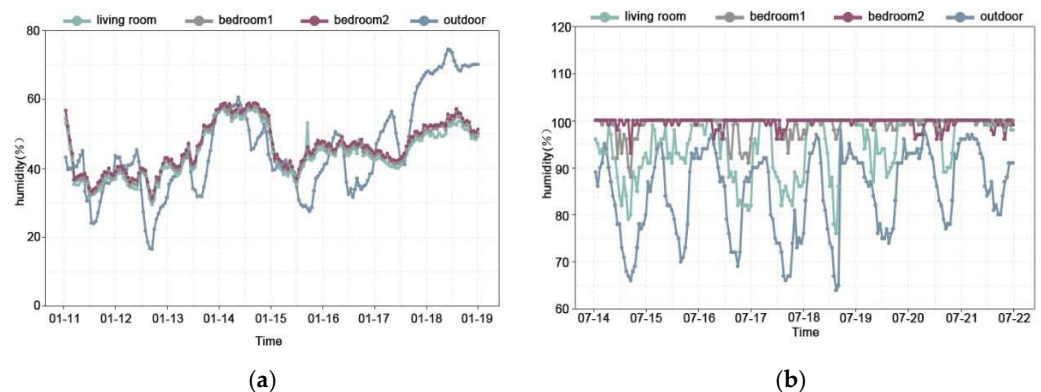


Figure 6. Measurement results of indoor and outdoor humidity (a) winter; (b) summer.

To quantitatively evaluate the specific impact of high humidity on occupant comfort, the Fanger thermal comfort model was employed to calculate the PMV (Predicted Mean Vote) and PPD (Predicted Percentage Dissatisfied) indices for the main occupied rooms during the summer measurement period. Since the field measurements did not include direct measurement of the Mean Radiant Temperature (MRT), this study approximates MRT using the measured air temperature, under the assumption that the indoor envelope thermal performance is relatively uniform, with no intense radiant sources or asymmetric radiation fields. This simplified approach is permitted by both ASHRAE 55 [30] and ISO 7730 [31] for preliminary thermal comfort assessments. The air velocity was taken as the default value for sedentary indoor conditions recommended by ASHRAE 55 (0.15 m/s). Based on the local residents' clothing habits, the clothing insulation was set to 0.5 clo, and the metabolic rate was taken as 1.2 met (sedentary activity). Taking 16 July as an example, the average summer thermal comfort indices for each room are presented in Table 1.

Table 1. PMV/PPD indicators for major rooms in summer.

	Average Temperature (°C)	Average Relative Humidity (%)	PMV	PPD (%)	Thermal Sensation
Living room	30.5	92	2.09	81	warm
Bedroom 1	31.4	98	2.46	93	warm
Bedroom 2	30.6	99	2.20	85	warm

According to Table 1, the PMV values of all three rooms far exceed the recommended comfort range of ISO 7730 (−0.5 to +0.5), and the PPD exceeds 80%, indicating that over 80% of occupants will feel dissatisfied. Bedroom 1 has the most severe thermal discomfort due to its high relative humidity of 98%, PMV of 2.46, and PPD of 93%. The above

results clarify the significant negative impact of high humidity on living comfort—even at temperatures around 30–31 °C, near saturation relative humidity hinders sweat evaporation and significantly increases perceived temperature. The vast majority of residents cannot accept this hot and humid environment.

Furthermore, the unique window design also influences indoor temperature and humidity: windows are placed only on the south facade and are relatively small (window-to-floor area ratio of approximately 0.05). This further reinforces the climate adaptability. South-facing windows ensure that low-angle winter sunlight can enter the rooms, supplementing heat. The extremely small window area significantly reduces cold air infiltration and heat loss in winter, while in summer it effectively blocks west solar exposure and excessive heat radiation. Thus, on the basis of the thermal storage and insulation provided by the walls, the indoor thermal environment is regulated. However, this also results in insufficient indoor ventilation, which is also the reason for the small variation in indoor temperature and humidity.

3.1.2. Light Environment

Taking the actual measurement results of the main rooms used on 16 January 2026 (living room, bedroom 1, bedroom 2) as an example, the minimum illuminance in all three rooms was 0 lx. In the living room, the maximum illuminance was 764 lx, the average illuminance was 184 lx, and the average daylight factor was 1.36%. In Bedroom 1, the maximum illuminance was 351 lx, the average illuminance was 96 lx, and the average daylight factor was 0.73%. In Bedroom 2, the maximum illuminance was 101 lx, the average illuminance was 24 lx, and the average daylight factor was 0.02%. The measured indoor illuminance conditions are shown in Figure 7.

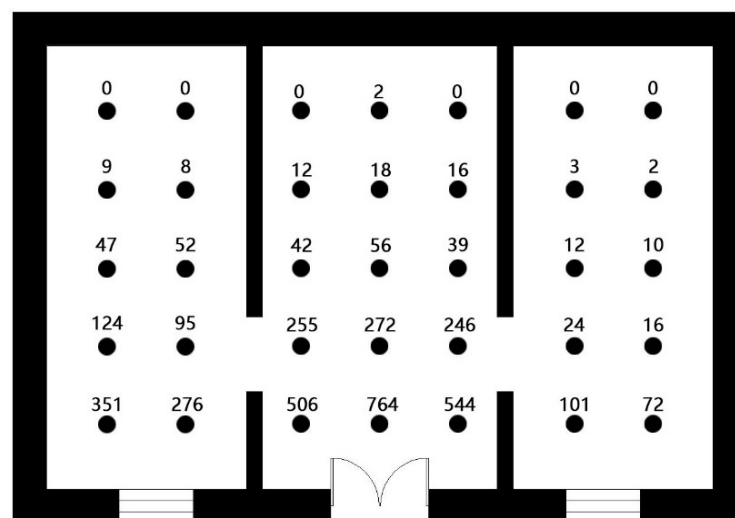


Figure 7. Measurement results of indoor light environment.

The above results indicate that the daylighting conditions in the main occupied rooms of the surveyed building are extremely poor, all failing to meet the requirements of the Standard for Daylighting Design of Buildings (GB 50033-2013) [32] and the General Code for Building Environment (GB 55016-2021) [33], which stipulate that the side daylight factor for residential buildings should not be less than 2.2% (for climate zone IV). The situation is most severe in Bedroom 2, where the south facade is blocked by a wing house, resulting in a daylight factor of less than 0.5% in most areas. This is also due to the aforementioned feature of stone-slab dwellings in Southwest Henan—windows are only placed on the south facade. While this is beneficial for indoor thermal insulation and heat retention, it is extremely unfavorable for daylighting.

3.2. Analysis of Simulation Results

3.2.1. Simulation Parameter Settings

(1) Thermal environment simulation parameter settings

Since Wuya Village lacks meteorological data in CSWD format, the outdoor climate data of Nanyang City, which has a high climatic similarity to and is geographically close to Wuya, were used as an approximation. The ground boundary condition is defined as natural ground (outdoor), with heat exchange with the soil taken into consideration. The thermal conductivity, specific heat capacity, and dry density of the main materials were determined according to the calculation parameters for physical properties of building materials specified in the Code for Thermal Design of Civil Buildings (GB 50176-2016) [34]. The wall construction layers (from outside to inside) are: 10 mm smoothed yellow mud plaster + 450 mm stone wall + 10 mm smoothed yellow mud plaster. The thermal conductivity of the yellow mud plaster is $0.349 \text{ W/(m}\cdot\text{K)}$, and that of the stone wall is $1.37 \text{ W/(m}\cdot\text{K)}$. The thermal performance of each building material is shown in Table 2. According to the “Code for Thermal Design of Civil Buildings” (GB 50176-2016), a one-dimensional thermal resistance series model with steady-state heat transfer is adopted. The external surface heat transfer resistance R_{se} is $0.04 \text{ (m}^2\cdot\text{K)/W}$, and the internal surface heat transfer resistance R_{si} is $0.11 \text{ (m}^2\cdot\text{K)/W}$. The specific calculation process is as follows (where d is the thickness; λ is the thermal conductivity):

External plastering layer thermal resistance R_1 :

$$R_1 = \frac{d}{\lambda} = \frac{0.01}{0.349} = 0.02865 \text{ (m}^2 \cdot \text{K)/W} \quad (1)$$

Stone wall thermal resistance R_2 :

$$R_2 = \frac{d}{\lambda} = \frac{0.45}{1.37} = 0.32847 \text{ (m}^2 \cdot \text{K)/W} \quad (2)$$

Internal plastering layer thermal resistance R_3 :

$$R_3 = \frac{d}{\lambda} = \frac{0.01}{0.349} = 0.02865 \text{ (m}^2 \cdot \text{K)/W} \quad (3)$$

Total thermal resistance R_{tot} :

$$R_{tot} = R_{se} + R_1 + R_2 + R_3 + R_{si} = 0.53577 \text{ (m}^2 \cdot \text{K)/W} \quad (4)$$

Wall heat transfer coefficient U_{wall} :

$$U_{wall} = \frac{1}{R_{tot}} = 1.87 \text{ W/(m}^2\cdot\text{K)} \quad (5)$$

The external wall's heat transfer coefficient U_{wall} is calculated as $1.87 \text{ W/(m}^2\cdot\text{K)}$. The roof construction (from top to bottom) consists of grey tile roofing, a 20 mm bonding layer, a 5 mm bamboo mat, and timber roof trusses with purlins. Because the material layers of the roof follow traditional construction methods and their corresponding material parameters are not available in the standard, materials with similar thermal conductivity were input into the software. Calculations show that the heat transfer coefficient of the roof is $1.88 \text{ W/(m}^2\cdot\text{K)}$. The ground consists of rammed earth, a cushion layer, and a surface soil layer, with a heat transfer coefficient of $1.84 \text{ W/(m}^2\cdot\text{K)}$.

Internal Heat Gains and Occupancy Assumptions: Based on on-site surveys and local residents' living habits, this study sets the occupant density at 0.05 person/m^2 (equivalent to one person active during the daytime in a 16.98 m^2 living room, and two persons

during the nighttime sleeping period). The sensible heat gain is 75 W/person, and the latent heat gain is 55 W/person. Lighting power density is set at 5 W/m², used only after sunset (18:00–22:00). The average power density of household appliances (including TV, refrigerator, etc.) is set at 3.5 W/m², operating continuously throughout the day.

Ventilation Strategy and Air Infiltration: During the winter measurement period, the building was kept in a closed state, with air infiltration through door and window gaps at 2 air changes per hour, reflecting the typical airtightness level of traditional wooden doors and windows in the closed position. During the summer measurement period, the air change rate was also set to 2 ach to match the occupants' usage pattern during the actual measurement period.

Table 2. Thermal parameters of main building materials.

Material	Thickness (m)	Thermal Conductivity (W/(m·K))	Density (kg/m ³)	Specific Heat (kJ/(kg·K))
yellow mud plaster	0.010	0.349	1600	1.050
Stone wall	0.450	1.370	2400	0.920
grey tile	0.015	0.580	2000	0.920
Wheat straw mud bonding layer	0.040	0.700	1600	1.010
bamboo mat	0.005	0.140	800	1.200

(2) Light environment simulation parameter settings

The location was set as Nanyang City, with a daylight climate zone of IV. The analysis plane height was 750 mm. The number of light reflection calculations was three. The simulated sky condition was overcast, with an outdoor design illuminance of 13,500 lx. The ceiling is a dark-colored timber structure with a transmittance of 0.1. The floor is gray brick with a transmittance of 0.32. The walls are smoothed yellow mud plaster with a transmittance of 0.15. For the single-layer wooden windows, the structural shading coefficient is 0.7, so the glass transmittance was set to 1. For the single-layer wooden doors, based on residents' habit of keeping them open during the day, the light-transmitting area ratio was set to 1.

To ensure simulation accuracy, this study calibrates the model using the statistical metrics recommended by the ASHRAE Guidelines, namely the Normalized Mean Bias Error (NMBE) and the Coefficient of Variation of the Root Mean Square Error (CVRMSE), with convergence criteria set at $\text{NMBE} \leq 5\%$ and $\text{CVRMSE} \leq 25\%$ [35]. The calibration employs the "hourly measured data versus simulated data comparison" method. The specific steps are: (1) replacing the temperature and humidity data in the EnergyPlus typical meteorological year file with actual measured meteorological data to eliminate errors caused by differences in weather data; (2) adjusting the internal heat gain schedules based on the occupants' daily routines obtained from on-site surveys; and (3) comparing the simulated hourly indoor temperatures with the corresponding measured values at the same time points, and then calculating the NMBE and CVRMSE.

3.2.2. Simulation and Measurement Fitting Analysis

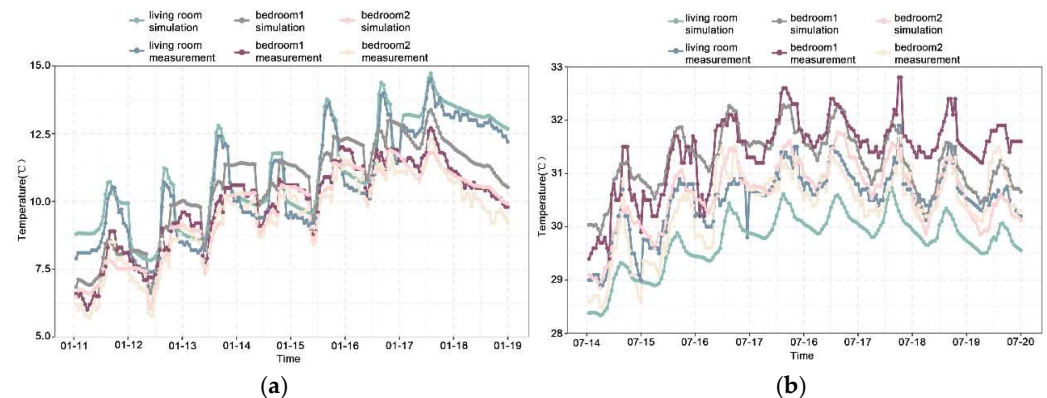
(1) Thermal environment fitting analysis

To ensure the accuracy of the thermal environment simulation, this study replaced the measured outdoor temperature and humidity with the corresponding meteorological data in EnergyPlus. The fitting between simulated and measured temperatures during the measurement period is shown in Table 3.

Table 3. Temperature Error Statistics during Measurement Cycle.

Test Room	Season	NMBE (%)	CVRMSE (%)
Living room	Winter	3.5	3.7
	Summer	2.5	2.5
Bedroom 1	Winter	4.4	5.3
	Summer	0.6	1.4
Bedroom 2	Winter	2.6	3.2
	Summer	0.7	1.2

During the winter measurements (11–18 January 2026) and summer measurements (14–21 July 2026), the temperature errors for the main occupied rooms in this model were all below 5%. Taking January 13 (winter) as an example (Figure 8): the measured average temperature in the living room was 10.1 °C, the simulated value was 9.8 °C (error 3.1%); in Bedroom 1, measured 10.2 °C vs. simulated 9.5 °C (error 4.1%); in Bedroom 2, measured 9.1 °C vs. simulated 9.1 °C (error 0%). Taking 16 July (summer) as an example: the living room measured 29.8 °C vs. simulated 30.5 °C (error 2.3%); Bedroom 1 measured 31.6 °C vs. simulated 31.4 °C (error 0.6%); Bedroom 2 measured 30.8 °C vs. simulated 30.6 °C (error 0.7%). These results show that the overall trend and temperature fluctuation magnitude of the model are highly consistent with the measured data, and the errors are all within acceptable limits, validating the accuracy of the model parameter settings and its applicability for subsequent research and analysis.

**Figure 8.** Fitting of simulated and measured indoor temperatures (a) winter; (b) summer.

The errors in the living room and Bedroom 1 are greater than those in Bedroom 2. It is hypothesized that this is due to the presence of implicit heat sources in actual operation, such as short-term occupancy of people, lighting, and standby electrical appliances in both the living room and Bedroom 1, which were not considered in the model. The model assumes the dwelling is in a closed state with a fixed air change rate of two times per hour. However, in the actual dwelling, factors such as door and window gaps, occupant entry and exit, and wind pressure variations cause the air change rate to vary dynamically in both time and space.

(2) Light environment fitting analysis

To comprehensively verify the applicability of the light environment model under different sky conditions and seasons, this paper compares the measured average illuminance of four measurement conditions with the simulated values of Ladybug Tools. The error statistics are shown in Table 4.

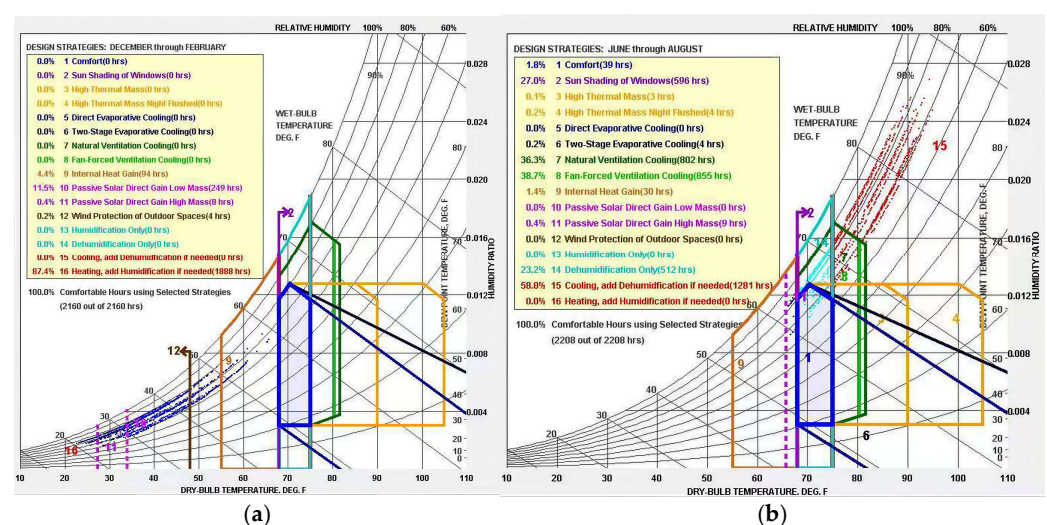
Table 4. Error Statistics between Simulated and Actual Average Illumination Values of Each Room under Different Operating Conditions.

Condition	Date	Sky Model	Room	MAPE (%)	Maximum Deviation (%)
Winter clear sky	16 January 2026	CIE Clear Sky	Living room	6.4	8.2
			Bedroom 1	9.3	11.5
			Bedroom 2	8.3	10.1
Winter overcast sky	20 January 2026	CIE Overcast Sky	Living room	7.2	9.1
			Bedroom 1	8.6	10.2
			Bedroom 2	9.4	12.1
Summer clear sky	18 July 2025	CIE Clear Sky	Living room	6.3	7.5
			Bedroom 1	8.5	9.2
			Bedroom 2	8.9	11.0
Summer overcast sky	22 July 2025	CIE Overcast Sky	Living room	7.0	8.5
			Bedroom 1	8.2	10.3
			Bedroom 2	9.2	11.8

According to Table 4, the Mean Absolute Percentage Error (MAPE) of each room under all operating conditions is below 10%, and the maximum deviation is controlled within 12.5%. This indicates that the light environment model established in this study has good prediction accuracy under different sky conditions (sunny/cloudy) and seasons (winter/summer), and can support subsequent analysis of lighting optimization strategies.

3.2.3. Strategy Applicability Analysis

According to the enthalpy–humidity diagram analysis generated by Climate Consultant 6.0 (Figure 9), the percentage of time that Wuya Village remains within the comfort zone is 0% in winter and 1.8% in summer, indicating that both winter and summer are uncomfortable. In winter, 87.4% of the time requires an increase in indoor temperature and humidity, while in summer, 58.0% of the time requires a decrease in indoor temperature and humidity. Among the passive strategy effectiveness rankings provided by the winter enthalpy–humidity diagram, passive solar direct gain (low mass) accounts for the highest proportion at 11.5%. In the summer ranking, fan-forced ventilation cooling accounts for 38.7%, natural ventilation accounts for 36.3%, and dehumidification only accounts for 23.2%.

**Figure 9.** Enthalpy–humidity diagram of the Southwest Henan region (a) winter; (b) summer.

Considering that fan-forced ventilation cooling is not a passive strategy, and taking into account the actual field conditions, the stone-slab dwellings in Wuya Village should increase direct solar radiation gain in winter, and enhance natural ventilation and reduce

humidity in summer. This conclusion is consistent with the measurement results: the local stone-slab dwellings have small window openings and only on the south facade (Bedroom 2 is also blocked by the south-facing wing house), resulting in insufficient passive solar gain in winter, poor natural ventilation and high humidity in summer, as well as poor indoor daylighting. Therefore, how to simultaneously address the issues of daylighting, ventilation, humidity reduction, and passive solar utilization without affecting the traditional architectural appearance and structure of Southwest Henan has become a key challenge that must be prioritized in the renovation of this type of dwelling.

Given that improvements in daylighting, ventilation, humidity reduction, and solar radiation are all closely related to the position and area of window openings, enlarging existing window openings or creating new ones would significantly impact the traditional architectural character, and cutting openings in load-bearing stone walls would also compromise building safety. Therefore, this study preliminarily proposes adding skylights on the rear side of the building (to minimize interference with the traditional appearance) as the primary retrofitting measure. Additionally, taking into account the requirement for winter thermal insulation, insulation technologies for the building envelope are proposed as the secondary retrofitting measure, in order to comprehensively resolve the issues of thermal insulation in both winter and summer as well as indoor daylighting. The applicability of the proposed retrofitting measures is validated below, and further improvements are also made.

3.3. Optimization Technologies for Indoor Light and Thermal Environment

3.3.1. Roof Skylight

Installing roof skylights not only helps improve indoor ventilation, achieving summer cooling and increased solar radiation gain in winter, but also enhances daylighting conditions, thereby improving the overall comfort of the dwelling. According to the provisions for daylighting grade IV in the Standard for Daylighting Design of Buildings (GB 50033-2013) [32] (daylighting for bedrooms and living rooms in residential buildings should not be lower than this grade standard value), the window-to-floor area ratio for top lighting should reach 1:13. Considering that the study area belongs to daylight climate zone IV, a correction factor $K = 1.1$ must be applied, so the actual window-to-floor area ratio is taken as 11:130. Measurements show that the usable floor area of the living room in the surveyed building is 16.98 m^2 , and each of the two bedrooms is 14.716 m^2 . Based on these figures, the required skylight area for the living room is at least 1.44 m^2 , and for each bedroom at least 1.25 m^2 . Based on the above area requirements, it is preliminarily determined that skylights will be placed centrally on the rear side of each room. The skylight area is uniformly set to 1.44 m^2 ($1.2 \text{ m} \times 1.2 \text{ m}$) (Figure 10), which not only meets the daylighting requirement of the living room but also exceeds the minimum standard for the bedrooms. At the same time, this facilitates uniform construction and materials, and reduces the impact on the traditional architectural character.

The comparison of the indoor daylight factor before and after the addition of skylights is shown in Figure 11. Under the current condition, natural daylight illuminance exists only near the doors and windows. The structural transmittance of the window frames is relatively low (approximately 0.7), and Bedroom 2 is additionally blocked by the south-facing wing house. Consequently, both the daylight factor and illuminance in the depth direction of the rooms are very low, even reaching zero in some areas. Residents rely entirely on artificial lighting for their daily activities, which is detrimental to health and also increases building energy consumption. However, after installing skylights on the roofs of the living room and the two bedrooms, the daylighting in the main occupied rooms has been significantly improved. The illuminance in the depth direction has been greatly

increased, and the effective daylighting area has been expanded. The average daylight factor of the living room and the two bedrooms has increased from the original 1.36%, 0.73%, and 0.02% to 5.32%, 3.73%, and 3.42%, respectively. In particular, for Bedroom 2, which previously had extremely poor daylighting, the maximum illuminance has increased from 101 lx to 274.7 lx, and the minimum illuminance from 0 lx to 80.10 lx. This significantly enhances the visual comfort of the dwelling and reduces energy consumption. In the living room, the maximum indoor illuminance has increased from 764 lx to 927.8 lx, and the minimum illuminance from 0 lx to 160.37 lx. In Bedroom 1, the maximum indoor illuminance has increased from 351 lx to 446 lx, and the minimum illuminance from 0 lx to 166.27 lx. These results fully demonstrate that with the addition of skylights, natural daylight is distributed more evenly throughout the living room and bedrooms, greatly improving visual comfort.

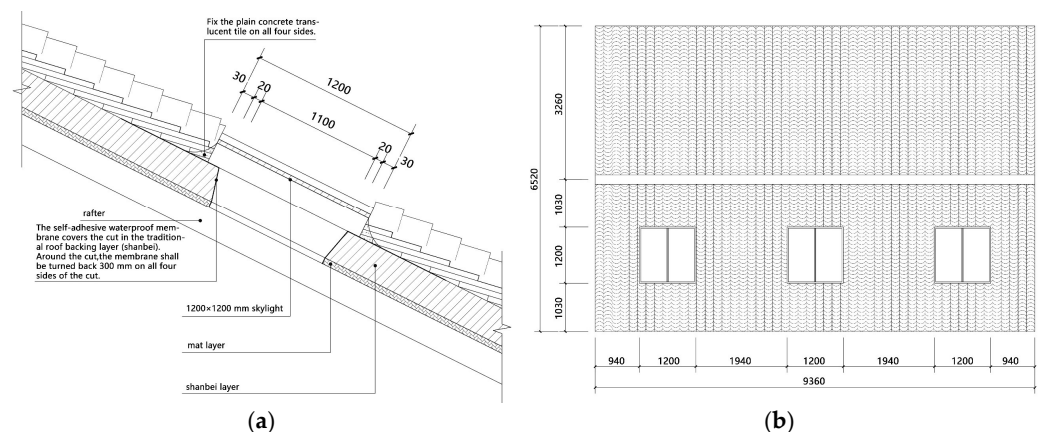


Figure 10. Location and construction details of the roof skylight. (a) Roof Skylight Construction Detail; (b) Roof Skylight Location Detail.

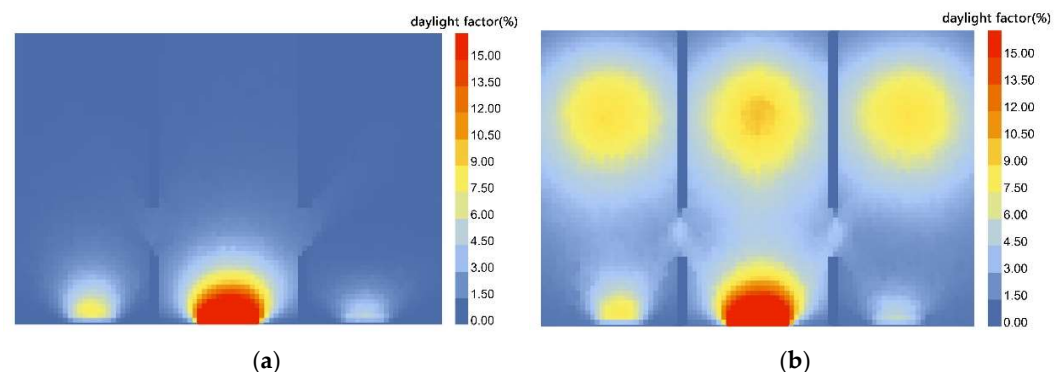


Figure 11. Comparison of indoor daylight factor before and after adding skylights. (a) Before adding skylights; (b) After adding skylights.

The wind speed at a height of 1.6 m in the main occupied rooms after the addition of skylights was simulated, and the results are shown in Figure 12. After adding skylights, indoor ventilation was improved to a certain extent: the average wind speed in the living room increased from 0.32 m/s to 0.68 m/s, and in Bedroom 1 from 0.45 m/s to 0.52 m/s. However, it is worth noting that the average wind speed in Bedroom 2 decreased from 0.73 m/s to 0.56 m/s. Thus, the addition of skylights has a more significant effect on improving ventilation in the living room; in summer, the opened skylights can be used to create indoor stack ventilation (the stack ventilation section of the living room is shown in Figure 13). Although the effect of adding skylights on ventilation in the two bedrooms is less satisfactory, overall, it still has many positive effects on indoor ventilation.

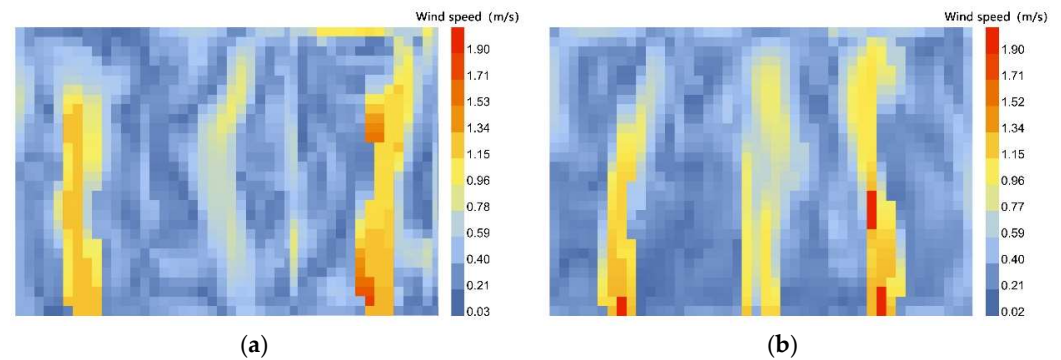


Figure 12. Comparison of indoor ventilation at a height of 1.6 m before and after adding skylights (a) Before adding the skylight; (b) After adding a skylight.

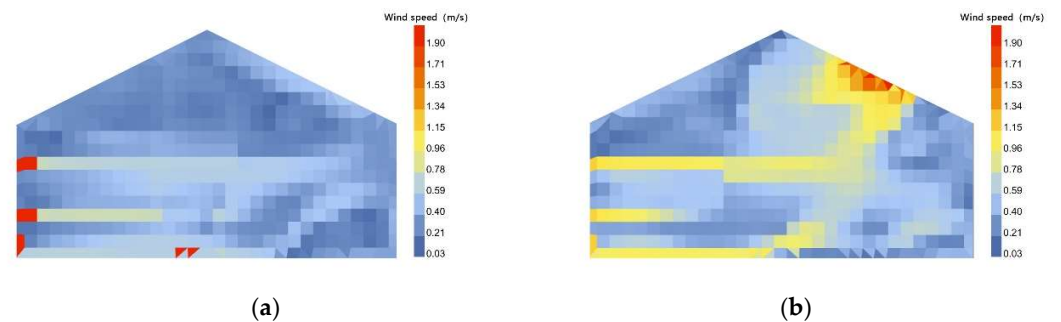


Figure 13. Comparison of living room section ventilation before and after adding skylights (a) Before adding the skylight; (b) After adding a skylight.

Using EnergyPlus software, the indoor thermal environment after the installation of skylights was simulated and validated. The results show that after adding skylights, the average summer temperature in each main occupied room increased, while the average winter temperature decreased. Taking the living room as an example, the temperature change before and after adding the skylight is shown in Figure 14. In winter (13 January), the average temperature dropped from 9.8 °C to 8.7 °C; in summer (16 July), the average temperature rose from 30.5 °C to 31.5 °C. It can be seen that although skylights have significant advantages in improving indoor daylighting and living room ventilation, they have an adverse effect on the thermal insulation performance of the rooms. Therefore, corresponding thermal environment improvement measures need to be taken to balance the comprehensive requirements of daylighting, ventilation, and thermal comfort.

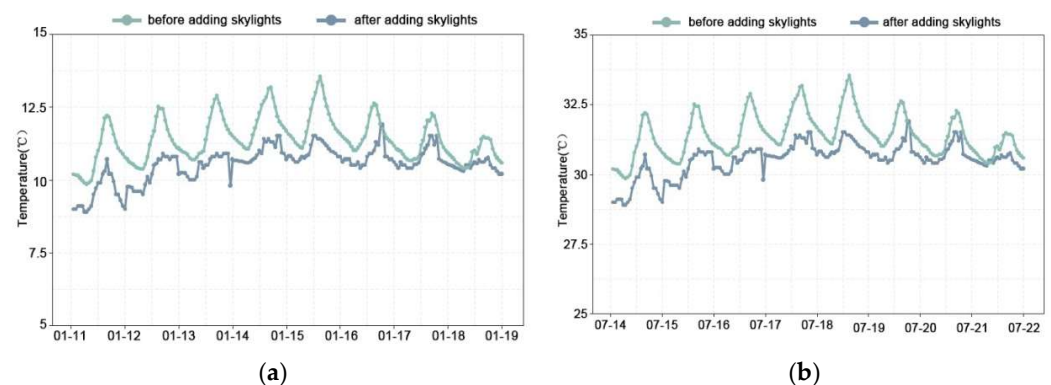


Figure 14. Comparison of living room temperature before and after adding skylights. (a) winter; (b) summer.

3.3.2. Building Envelope

The building envelope of traditional dwellings includes exterior walls, roofs, and exterior windows. Since it is in direct contact with the outdoor environment, it has a significant impact on the indoor thermal environment and building energy consumption. During the retrofitting process, both the preservation of traditional architectural character and the income level of rural residents must be taken into account. Therefore, retrofitting technologies for exterior walls and roofs should minimize damage to the building's appearance while also emphasizing the cost-effectiveness of building materials.

The current conditions of the roof and walls of the surveyed building are as follows: the roof construction from bottom to top consists of rafters, bamboo mats, a 40 mm thick straw-mud bonding layer, and alternately stacked roof tiles. The exterior walls are built of roughly squared stone blocks laid in staggered courses, with a wall thickness of approximately 450 mm. The interior surface of the walls is finished with a yellow mud plaster. This construction reflects the local wisdom of adapting to local conditions and using local materials. Although this construction provides a certain capacity for thermal insulation, its thermal storage performance is poor. According to calculations, the heat transfer coefficient (U-value) of the exterior wall is approximately $1.87 \text{ W}/(\text{m}^2 \cdot \text{K})$, which fails to meet the requirement of the Design Standard for Energy Efficiency of Rural Residential Buildings (GB/T 50824-2013) that the exterior wall heat transfer coefficient should be less than $1.8 \text{ W}/(\text{m}^2 \cdot \text{K})$ for hot-summer and cold-winter climate zone A. Based on references, local retrofitting practices, and the affordability of residents, In this study, 60 mm thick Extruded Polystyrene (XPS), Expanded Polystyrene (EPS), Polyurethane (PUR), and Rock Wool boards were uniformly selected to compare their effects on the indoor thermal environment [8]. The specific material properties are shown in Table 5. According to calculations, the heat transfer coefficients of the walls all meet the requirement of being less than $1.8 \text{ W}/(\text{m}^2 \cdot \text{K})$. Software simulations of indoor temperature using the above insulation materials were carried out, and the results are shown in Figure 15. Figure 15 shows that PUR performs best in terms of thermal insulation: on 13 January (winter), the average temperature rises from 8.7°C to 10.7°C , an increase of approximately 2°C ; on 16 July (summer), the average temperature drops from 31.5°C to 30.4°C , a decrease of about 1.1°C . However, the summer room temperature still fails to meet the 30°C requirement stipulated by the Design Standard for Energy Efficiency of Rural Residential Buildings (GB/T 50824-2013).

To objectively evaluate the economic suitability of insulation materials, this study compared four candidate materials under the same thermal performance requirement (exterior wall heat transfer coefficient $K \leq 1.8 \text{ W}/(\text{m}^2 \cdot \text{K})$). The thermal conductivities of EPS, XPS, rock wool, and PUR are 0.039, 0.030, 0.041, and $0.024 \text{ W}/(\text{m} \cdot \text{K})$, respectively, with corresponding required thicknesses of 70, 54, 74 and 43 mm, and unit area material costs of approximately 35, 50, 40, and 50 RMB/ m^2 , respectively. Based on a retrofit area of 80 m^2 , the total material costs for PUR and XPS are equal (4000 RMB each), which is 1200 RMB higher than that of EPS (2800 RMB). According to EnergyPlus simulations, PUR provides an additional annual energy saving of approximately 189 kWh compared to EPS. Based on the current residential electricity tariff of 0.56 RMB/kWh, the additional annual benefit is approximately 106 RMB, yielding an incremental payback period of approximately 11.3 years. Although the financial payback period of PUR is relatively longer, its service life (over 30 years) is significantly longer than that of EPS (15–20 years). Over a 30-year life cycle, EPS would require one replacement, resulting in a total material cost of 5600 RMB, which is higher than PUR's 4000 RMB. Moreover, PUR requires the smallest thickness (43 mm), resulting in the minimal additional structural load on the

traditional stone masonry walls. Considering thermal performance, structural safety, and life-cycle cost, PUR is the recommended choice.

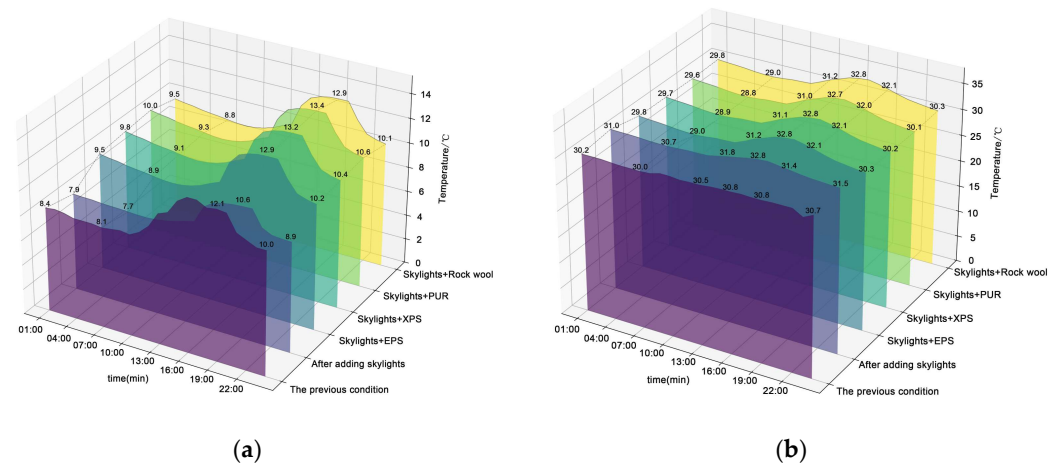


Figure 15. Comparison of the effects of different insulation materials. (a) winter; (b) summer.

Table 5. Properties of insulation materials.

	Conductivity (W/m·K)	Density (Kg/m ³)	Specific Heat (kJ/kg·K)
EPS board	0.039	20	1.38
XPS board	0.030	35	1.38
PUR board	0.024	35	1.38
Rock wool board	0.041	60	1.22

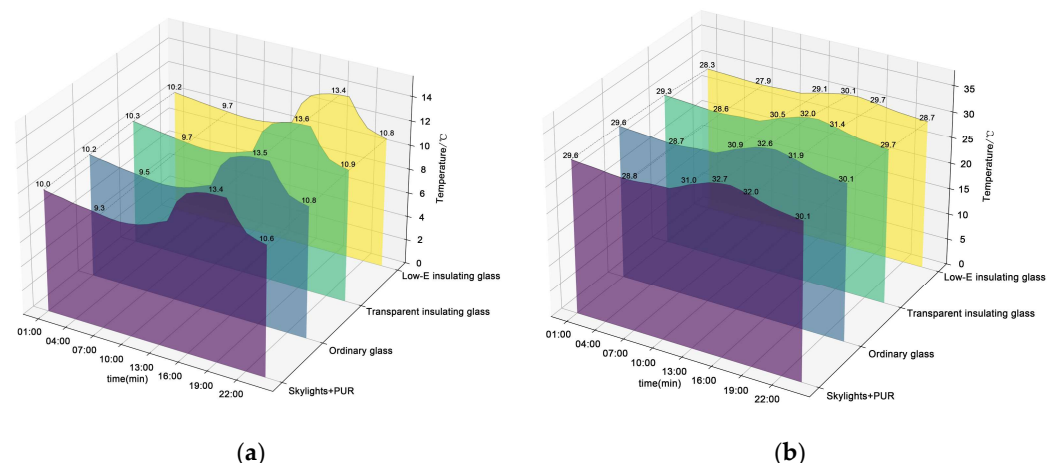
Wall Insulation Layer Configuration: The retrofit employs an interior insulation strategy. The layered construction of the exterior wall, from exterior to interior, comprises the original stone wall (450 mm), a yellow mud plaster leveling coat (10 mm), an adhesive layer, a 60 mm PUR insulation board, and a fire-resistant finishing layer. This interior insulation approach is adopted for three primary reasons: (1) to preserve the external stone masonry facade without compromising the traditional village character; (2) to avoid any drilling or anchoring into the load-bearing stone walls, thus maintaining structural integrity; and (3) to ensure reversibility, allowing for future maintenance or removal in accordance with heritage conservation principles.

The exterior doors of the surveyed building are traditional wooden door leaves; changing their material would significantly affect the traditional architectural character. The exterior windows, however, are wooden window frames with openwork and no glazing covering, which is extremely detrimental to indoor thermal insulation. Adding removable glass panes to these windows would not compromise their traditional appearance. This study selects three different types of glazing materials for the exterior windows: ordinary glass, transparent insulating glass, and Low-E insulating glass. The properties of each glazing material are shown in Table 6. Simulations of indoor temperature after installing the above three types of glazing were carried out, and the results are shown in Figure 16. The addition of glazing has no significant effect on winter thermal insulation, increasing the daily average temperature by only 0.1–0.2 °C. However, its effect on summer thermal insulation is significant. In particular, transparent Low-E insulating glass reduces the indoor temperature from 30.4 °C to 28.8 °C, thereby meeting the required summer standard of below 30 °C.

Table 6. Performance of various glass materials.

	U-Factor ($\text{W}/\text{m}^2 \cdot \text{K}$)	Solar Heat Gain Coefficient	Visible Transmittance
ordinary glass (6 mm clear glass)	5.70	0.85	0.90
transparent insulating glass (6 mm clear glass + 12 mm air + 6 mm clear glass)	2.59	0.75	0.81
Low-E insulating glass (6 mm medium-transmittance Low-E + 12 mm air + 6 mm clear glass)	1.79	0.43	0.57

Taking the living room as an example, Table 7 presents the average temperatures under different retrofit stages on typical winter (13 January) and summer (16 July) days. It can be seen that adding skylights alone reduces the winter temperature by 1.1 °C and raises the summer temperature by 1.0 °C, indicating a negative impact on the thermal environment. When PUR insulation is added on top of the skylights, the winter temperature rebounds to 10.7 °C (+0.9 °C above the baseline), while the summer temperature returns to 30.4 °C (almost the same as the baseline), demonstrating that the insulation effectively offsets the heat loss in winter and heat gain in summer caused by the skylights. With the further addition of Low-E insulating glass, the winter temperature rises slightly to 10.9 °C, and the summer temperature drops significantly to 28.8 °C (−1.7 °C below the baseline). The combined scheme meets the thermal performance requirements of the Design Standard for Efficiency of Rural Residential Buildings (GB/T 50824-2013) in both winter and summer.

**Figure 16.** Comparison of the effects of different glazing materials for exterior windows. (a) winter; (b) summer.**Table 7.** Comparison of indoor temperatures after multiple measures are combined.

	The Previous Condition (°C)	After Adding Skylights (°C)	Skylights + PUR (°C)	Skylights + PUR + Low-E Insulating Glass (°C)
Winter	9.8	8.7	10.7	10.9
Summer	30.5	31.5	30.4	28.8

Unfortunately, after simulation, the above measures show no effect on dehumidification in summer. The indoor relative humidity remains near saturation, so mechanical dehumidification is still required in summer.

In summary, no single measure can bring the indoor light and thermal environment of the surveyed building to an ideal state; a combination of measures is required for holistic improvement. Based on the simulation results of the stone-slab dwellings in Southwest

Henan presented above, the following combination is finally determined as the appropriate strategy for enhancing the indoor light and thermal environment: add skylights on the roof, apply 60 mm thick polyurethane (PUR) insulation boards on the roof and exterior walls, and install transparent Low-E insulating glass units on the exterior windows.

Among the combined measures, adding skylights contributes the most to the improvement of indoor daylighting, whereas the subsequent addition of PUR insulation and Low-E insulating glass has only a marginal effect on daylight availability. Table 8 compares the average daylight factors of the main occupied rooms under different schemes. As shown in the table, the combined scheme does not exhibit any significant daylighting offset; all rooms meet the requirement of a minimum daylight factor of 2.2% for residential buildings in climate zone IV, as stipulated by GB 50033-2013. Skylights remain the dominant factor in daylight improvement, while insulation and glazing measures have negligible influence on the overall daylight performance.

Furthermore, since the addition of PUR insulation and Low-E insulating glass does not introduce any new ventilation openings, these measures have no impact on indoor ventilation.

To evaluate the economic feasibility of the proposed integrated renovation scheme, this study estimated its primary material costs. Based on 80 m² of insulation area (PUR board at 50 RMB/m²), 3 roof skylights (1.44 m² each at 200 RMB/m²), and 2 exterior windows with Low-E insulating glass (0.8 m² each at 16.9 RMB/m²), the total material cost is approximately 4891 RMB. After the renovation, the annual energy saving is estimated at 1200–1500 kWh. Based on the current residential electricity tariff of 0.56 RMB/kWh, the annual electricity cost saving is approximately 672–840 RMB, yielding a static payback period of approximately 5.8–7.3 years. Over the design service life of 15–25 years, the life-cycle energy saving benefit is approximately 10,000–21,000 RMB. Based on the 2025 per capita disposable income of rural residents in Nanyang City (23,177 RMB) and an average household size of 3–4 persons, the material cost accounts for approximately 5.3–7.1% of annual household income, indicating good economic feasibility.

Table 8. Comparison of indoor average sunshine coefficient after multiple measures combined.

	The Previous Condition (%)	After Adding Skylights (%)	Skylights + PUR + Low-E Insulating Glass (%)
Living room	1.36	5.32	5.48
Bedroom 1	0.73	3.73	3.85
Bedroom 2	0.02	3.42	3.59

3.3.3. Solar Energy Utilization Potential

Solar energy is a renewable resource. According to the National Solar Radiation Total Amount Grade and Regional Distribution Table issued by the National Energy Administration of China, Henan Province is classified as a “relatively rich area in solar energy resources.” Efficient use of solar energy in rural dwellings not only helps reduce building energy consumption and save conventional energy, but also significantly improves indoor thermal comfort. Therefore, promoting the application of technologies such as passive sunspaces and active photovoltaic power generation according to local conditions [36] has important practical significance for improving rural living environments and promoting energy structure optimization. Field investigations found that most local residents lack adequate heating and cooling measures in both summer and winter. In winter, they often use stoves for heating, but stoves produce harmful gases such as carbon monoxide, which is extremely detrimental to residents’ health. In summer, they use mechanical devices such as electric fans, which causes unnecessary electricity consumption and is not conducive to building energy conservation, emission reduction, and sustainable development. It can be

seen that the current dwellings lack efficient, clean active heating and cooling equipment as well as passive regulation mechanisms for thermal environment control. Therefore, this study explores the potential for solar energy utilization, aiming to propose an economically feasible, healthy, and environmentally friendly solar energy solution.

(1) Passive sunspace

In the stone-slab dwellings of Southwest Henan, the L-shaped plan consisting of a main house and wing houses is the most common layout. To make full use of winter sunlight, this paper proposes constructing a glass sunspace inside the courtyard to investigate its effect on the indoor thermal environment (Figure 17). The glazing material is common transparent insulating glass (6 mm ordinary glass + 12 mm air layer + 6 mm ordinary glass). Based on the previously determined strategies for improving the indoor light and thermal environment (i.e., adding roof skylights, applying 60 mm thick PUR insulation boards on the roof and exterior walls, and installing transparent Low-E insulating glass on exterior windows), this study uses EnergyPlus software to simulate two scenarios—with and without a sunspace in the courtyard—in order to verify its impact on indoor thermal comfort. The simulation results are shown in Figure 18. Figure 18 shows that after adding the sunspace, the typical winter daily average temperature of the living room increases from 10.87 °C to 11.23 °C, while the typical summer daily average temperature rises from 28.79 °C to 29.38 °C. Thus, adding a sunspace in the courtyard of stone-slab dwellings in Southwest Henan does not significantly improve the indoor temperature in winter; instead, it leads to an increase in summer indoor temperature. Therefore, under the specific configuration conditions adopted in this study (clear insulating glass, without nighttime insulating curtains or external shading devices, without dedicated summer ventilation openings), the improvement effect of the courtyard-type passive sunspace on the indoor thermal environment of stone-slab dwellings in Southwest Henan is limited.

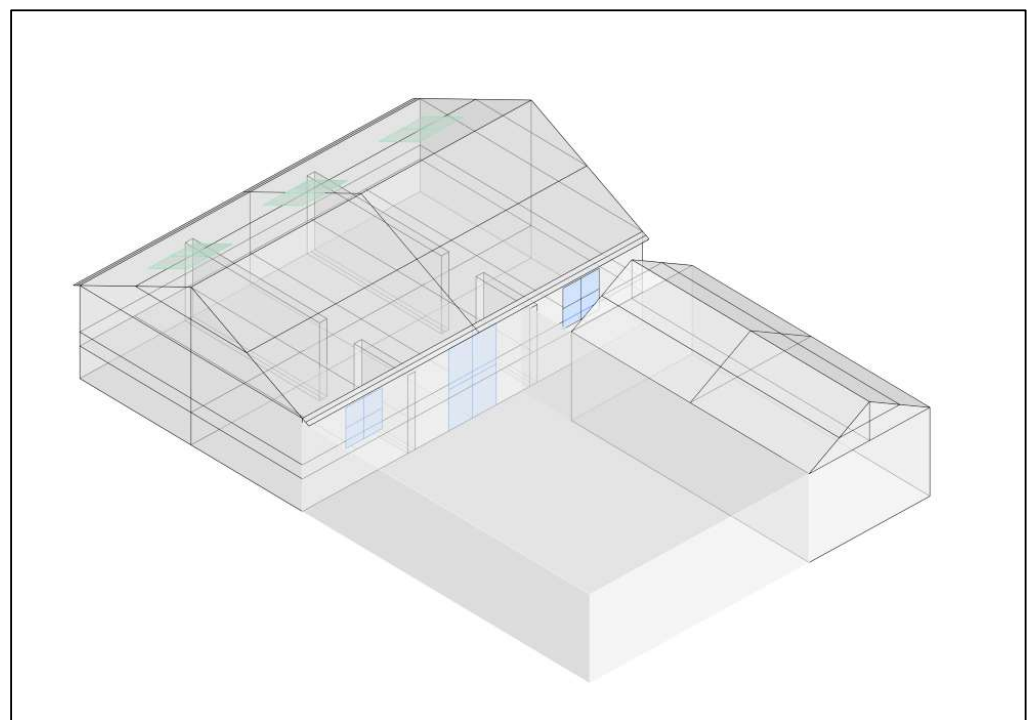


Figure 17. Schematic diagram of adding a sunspace in the courtyard.

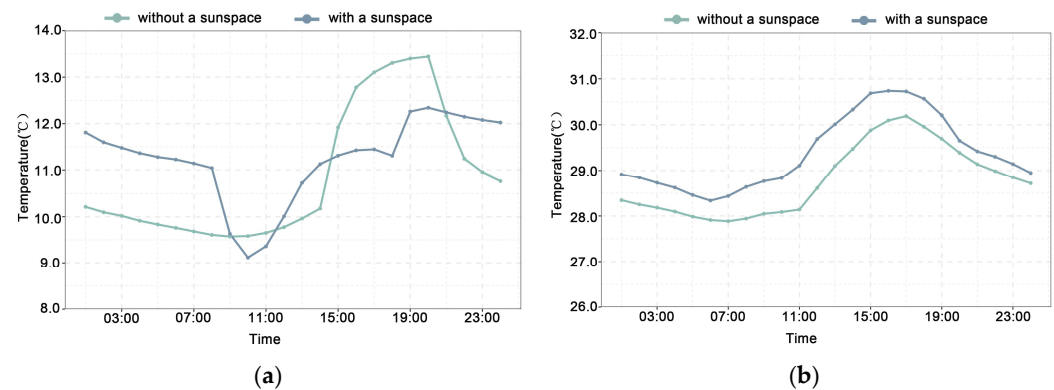


Figure 18. Comparison of indoor temperature before and after adding a sunspace. (a) Winter; (b) summer.

(2) Rooftop photovoltaic utilization

According to the Classification of Solar Energy Resources—Global Radiation (GB/T 31155-2014) [37], the annual total solar radiation level is classified as “abundant” when it ranges between $1050 \leq G < 1400 \text{ kWh/m}^2$. Simulated using Ladybug Tools (Figure 19), the annual horizontal plane radiation on the south-facing slope of the main house roof and the west-facing slope of the wing house roof is approximately 1331 kWh/m^2 , indicating that the stone-slab dwellings in Southwest Henan have a certain potential for photovoltaic utilization.

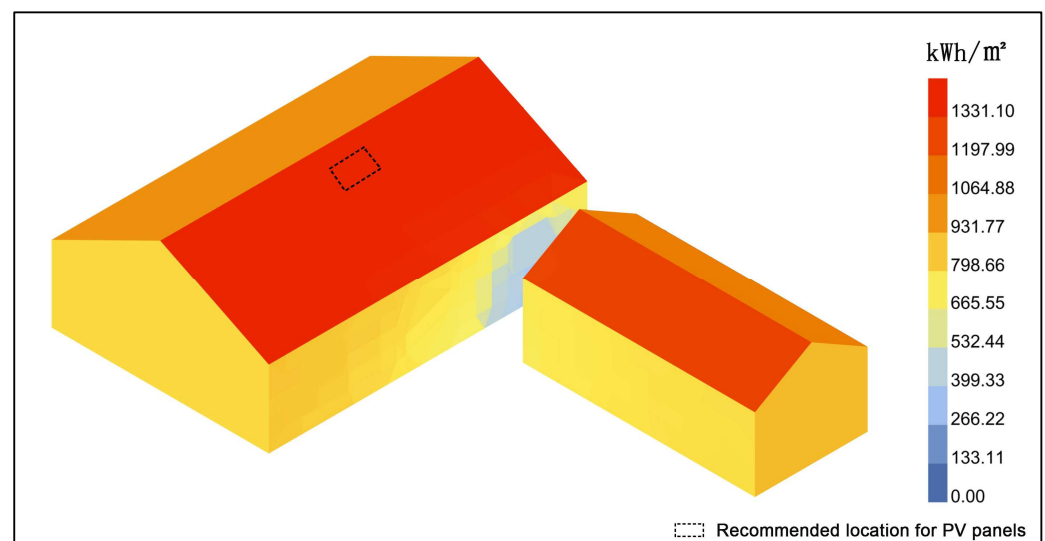


Figure 19. Solar radiation distribution of the surveyed building.

If photovoltaic (PV) modules are installed on the roof, taking the commonly used PERC PV module as an example, its conversion efficiency (η) under standard test conditions is 22%. However, in actual engineering practice, the power generation efficiency of a PV system is affected by multiple factors, and the following derating factors should be considered: temperature derating (3–10%), inverter losses (2–4%), module mismatch losses (1–3%), DC/AC cable losses (2–3%), soiling (1–5%), module degradation (approximately 2% in the first year, followed by gradual annual degradation), and system availability (1–2%). Taking all derating factors into account, the overall system efficiency (performance ratio, PR) is taken as 85%. According to Equation (6), the annual power generation per unit area (E) is calculated to be approximately 249 kWh/m^2 . Based on this calculation, installing 2.9 m^2 of PV panels can meet the average annual household electricity demand of 700 kWh.

The above calculation results are theoretical estimates. In actual engineering, there may be some deviation in power generation due to the influence of roof orientation, inclination angle, shading conditions, and local meteorological factors.

$$E = G \times \eta \times PR, \quad (6)$$

where E is the annual power generation per unit area; G is the annual total solar radiation; η is the conversion efficiency; PR is the performance ratio.

4. Discussion

4.1. Case Representativeness and Generalizability of the Proposed Strategies

Before discussing the detailed findings, it is necessary to clarify the representativeness of the selected case and the extent to which the proposed retrofit strategies can be generalized to similar vernacular buildings in the region. This study is based on a single case-study dwelling in Wuya Village, and we address the issue of external validity from the following three perspectives.

At the building typology level, the selected L-shaped courtyard house is broadly representative of the traditional stone dwellings in Wuya Village. The dwellings in this village share a high degree of consistency in material system (locally quarried dry-stacked stone walls), construction logic (stone-timber hybrid load-bearing), spatial configuration (predominantly L-shaped and linear courtyard layouts), and facade characteristics (south-facing single-side windows, with a window-to-floor area ratio of approximately 0.05). The selected building's key parameters—wall thickness (approximately 450 mm), roof construction, and window detailing—are consistent with other well-preserved dwellings in the village, and its layout, with the main house facing south and the wing house on the west side, is also one of the most common typologies in the settlement.

At the physical mechanism level, the environmental performance issues revealed by this case—namely, high thermal inertia, daylight deficiency, limited ventilation, and high summer humidity—originate from the shared construction logic and material properties that characterize stone-slab dwellings throughout the region, rather than being accidental phenomena. The proposed combined optimization strategy (skylights + insulation + Low-E glazing) is based on universal building physics principles, and its effectiveness in improving daylight availability, thermal insulation, and heat protection can be extended to other stone dwellings with comparable construction characteristics, with only appropriate adjustments to parameters such as skylight area and insulation thickness.

At the applicability boundary level, the conclusions of this study are most reliably applicable to the following range of buildings: dwellings featuring stone masonry envelopes, single-story pitched roofs, extremely low window-to-floor area ratios, and single-sided south-facing windows, as well as climatic conditions similar to Southwest Henan (hot-summer and cold-winter zones). For dwellings with different layout configurations, topographical settings, or occupancy states, specific implementation details such as the number, size, and position of skylights require site-specific adjustments. Nevertheless, the “field measurement-numerical calibration-strategy simulation” methodological framework and the strategic logic of “daylight-thermal synergy with heritage conservation and renewable energy supplementation” provide broad reference value.

4.2. The Light and Thermal Environment of Traditional Buildings Requires Coordinated Optimization

The results of this study indicate that the thick stone walls, with a thermal inertia index (D-value) of 4.67, endow the building with excellent thermal inertia, effectively moderating indoor temperature fluctuations under extreme winter and summer weather conditions,

reflecting the local passive design wisdom of “heavy envelope and small window openings.” However, this construction strategy also leads to serious light environment deficiencies: the window-to-floor area ratio is only about 0.05, and windows are provided only on the south facade, causing the average daylight factor of the main rooms to fall far below the national standard requirement of 2.2%, with Bedroom 2 even having large areas of zero illuminance. More critically, there is an inherent contradiction among the requirements for daylighting, ventilation, and passive solar heat gain with respect to window size and position: enlarging window openings can improve daylighting and ventilation but at the cost of weakening winter thermal insulation and summer thermal insulation. The roof skylight solution proposed in this study, although placed on the rear side to minimize interference with the traditional appearance and significantly improve the daylight factor and living room ventilation (average wind speed rising from 0.32 m/s to 0.68 m/s), also has negative effects: winter room temperature drops by approximately 1.1 °C and summer room temperature rises by about 1.0 °C. This result reveals an important principle: in the performance improvement of traditional dwellings, a single passive measure often struggles to simultaneously optimize multiple physical dimensions such as light, heat, and air; synergistic improvement through combined strategies is essential.

4.3. Passive Sunspaces Have Limited Applicability in This Region, While Rooftop Photovoltaics Show Certain Potential

This study found that adding a transparent passive sunspace in the L-shaped courtyard of the Southwest Henan region has no significant effect on raising the indoor temperature in winter (only an increase of 0.36 °C), and instead causes a rise of 0.59 °C in summer indoor temperature. The reasons are as follows: in Southwest Henan, the winter solar altitude angle is low. Although a sunspace can capture some radiant heat [38], the region has a relatively high proportion of cloudy or overcast days in winter. Moreover, the thick stone walls of the stone-slab dwellings have a high thermal mass and heat up slowly, limiting the effective transfer of heat from the sunspace to the interior. In summer, strong solar radiation can create a greenhouse effect inside the sunspace [39,40], exacerbating the risk of overheating. Therefore, in traditional mountain dwellings with similar climatic characteristics, blindly promoting passive sunspaces is not appropriate. Resources should instead be directed toward more effective insulation, heat protection, and shading measures. In contrast, rooftop photovoltaic utilization shows better prospects. Installing PERC photovoltaic modules on the usable roof area yields an estimated annual power generation of approximately 224 kWh/m², which can basically meet the annual electricity demand of the household for lighting, fans, and small appliances. However, the initial investment for a photovoltaic system is still relatively high for rural households, and promotion will need to be supported by government subsidies or rural energy transition policies.

4.4. Discussion on Passive Dehumidification Scheme for High Humidity in Summer

The PMV/PPD analysis above indicates that high indoor humidity in summer significantly exacerbates thermal discomfort (PPD > 80%), while the passive measures proposed in this study have little effect on dehumidification. Therefore, three low-cost passive dehumidification strategies are discussed below from the perspective of “appropriate technologies”.

Natural ventilation optimization: Given that the stone walls are essentially all load-bearing, new window openings should not be directly cut into the walls. It is recommended to prioritize the installation of operable skylights or ventilation towers on the roof to enhance stack-effect ventilation, combined with cross-ventilation using existing doors and windows during summer nights. This strategy has low initial cost and zero operating expenses, making it the preferred passive dehumidification measure, though its effectiveness is limited by outdoor weather conditions.

Earth-air heat exchange system (EAHE): This system utilizes the stable soil temperature to pre-cool and dehumidify incoming air through condensation. Wuya Village has open terrain suitable for burying pipes. Although the initial investment is relatively high, the operating cost is extremely low, and the pipes can be reserved during new construction or renovation.

Phase-change humidity-control materials: These materials passively regulate indoor humidity through the moisture adsorption and desorption properties of porous materials. The interior yellow-mud plaster of the stone dwellings inherently possesses some hygroscopicity, which can be enhanced using affordable materials such as diatomaceous earth. High-performance composite materials can be considered as a long-term technological reserve.

In summary, it is recommended that priority be given to roof-mounted operable skylights or ventilation towers for natural ventilation enhancement, with EAHE systems as a supplementary option and phase-change humidity-control materials as a long-term reserve. Under extreme hot-humid weather conditions, mechanical dehumidification should still be employed as a final safeguard.

4.5. Limitations of the Research Methodology

The representativeness of the research sample is limited. There are 93 relatively intact stone-slab dwellings in Wuya Village, and this study selected only one typical L-shaped courtyard house that is still inhabited as the research subject. Although this building is broadly representative in terms of materials, construction, and layout, the indoor light and thermal environment may vary considerably among different courtyard houses due to differences in terrain elevation, orientation deviations, surrounding obstructions, and occupant usage habits. Future research should expand the sample size to include more stone-slab dwelling cases with different orientations and layouts (e.g., single-courtyard and multi-courtyard compounds) in order to enhance the generalizability of the conclusions.

Furthermore, there are limitations in the research methodology. The study did not account for the dynamic effects of occupants' behavioral adaptations (e.g., actively opening windows in summer, hanging cotton curtains in winter, etc.) on the indoor environment. In the daylighting simulation, traditional wooden doors were assumed to be always open (light-transmitting area ratio = 1), which may differ from the actual usage habits of some residents. Future research could introduce longer-term on-site monitoring (covering the entire year) and occupant behavior surveys to further improve simulation accuracy and the practicality of the strategies.

The proposed optimization measures for the light and thermal environment are almost ineffective in addressing the high-humidity problem in summer; the indoor relative humidity remains near saturation. The fundamental reason for this phenomenon is that in Southwest Henan, hot and humid summer air condenses upon contact with the cool stone walls, and insufficient natural ventilation fails to expel the moisture in time. Although the skylight improves ventilation in the living room to some extent, the wind speed in Bedroom 2 actually decreases, indicating that the location and opening mode of the skylight require further optimization. Future research should further explore low-energy passive dehumidification technologies such as displacement ventilation and earth-to-air heat exchange systems for cooling and dehumidification.

Furthermore, the optimization technologies proposed in this study have not yet been validated through actual engineering applications. Although measures such as skylights, internal PUR insulation, and Low-E glass have shown good results in simulations, issues related to construction techniques in real environments (e.g., bonding reliability of insulation boards to stone walls, waterproofing details at skylight penetrations), resident

acceptance (e.g., skylight cleaning and maintenance, glass safety), and long-term durability (e.g., aging of PUR boards, risk of condensation) still need to be verified through pilot retrofits and long-term monitoring. Future research should select one or two dwellings for demonstration renovations and conduct year-long follow-up measurements to obtain implementable optimization technologies.

It should be noted that the sunspace simulation was based on a single fixed configuration (clear insulating glass, without nighttime curtains, external shading, or dedicated summer ventilation), and no systematic optimization of key design parameters was conducted. Sunspace thermal performance is influenced by multiple factors, including space height and depth, glazing area and orientation, ventilation opening size and position, insulating curtains, and external shading devices, and performance under different parameter combinations can vary considerably. For instance, adding operable high-side windows or adjustable external shading in summer could effectively reduce overheating risk, while nighttime insulating curtains in winter could enhance heating contributions. Therefore, the conclusion should not be interpreted as a complete rejection of passive sunspaces in Southwest Henan, but rather as an objective finding under the specific configuration studied. Future research should conduct systematic sensitivity analysis and multi-objective optimization of these parameters to define the applicable conditions and optimal design strategies for sunspaces in this region, potentially also assessing annual performance under different operational modes.

5. Conclusions

This study investigated a typical stone-slab dwelling in Wuyacun Village, Southwest Henan, through a combination of field measurements and numerical simulations. The indoor light and thermal environment was systematically evaluated, and appropriate optimization technologies were identified and verified while considering the conservation requirements of traditional dwellings. The main conclusions are as follows:

- (1) Stone-slab dwellings exhibit strong thermal inertia due to their massive envelope, resulting in significantly smaller indoor temperature fluctuations than outdoors in both summer and winter. However, the existing indoor environmental performance is unsatisfactory. The daylight factor in the principal occupied spaces fails to satisfy current standards, with illuminance approaching zero in some interior areas. Summer indoor temperatures generally exceed the upper comfort limit of 30 °C, while relative humidity remains close to saturation. In winter, 87.4% of the occupied hours require simultaneous heating and humidification. These deficiencies mainly arise from the traditional architectural configuration, particularly the extremely low window-to-floor area ratio (0.05) and the single-sided south-facing window layout, which restrict daylight availability, natural ventilation, and passive solar heat gains.
- (2) The integrated retrofit strategy consisting of rear-roof skylights, 60 mm polyurethane (PUR) insulation boards applied to the roof and exterior walls, and transparent Low-E insulating glazing for exterior windows provides the most effective improvement in indoor environmental performance while preserving the architectural characteristics of the dwelling. This combined solution significantly enhances daylight availability, improves winter thermal insulation, reduces summer overheating, and strengthens natural stack ventilation. However, high indoor humidity during summer remains difficult to mitigate through passive measures alone, indicating that supplementary mechanical dehumidification is still required under hot-humid conditions.
- (3) Under the sunspace configuration conditions adopted in this study (clear insulating glass, without nighttime insulating curtains or external shading devices), the passive sunspace provides limited winter heating improvement for stone-slab dwellings in

Southwest Henan (daily average temperature increase of only 0.36 °C in the living room), while exacerbating summer overheating risks (daily average temperature increase of 0.59 °C). The comprehensive performance of sunspaces is significantly influenced by design parameters such as space height, glazing area ratio, ventilation opening configuration, shading methods, and insulating curtains, and performance differences under different design conditions may be substantial. Therefore, the above conclusion should be understood as an objective presentation of sunspace performance under a specific configuration, rather than a complete rejection of the applicability of this technology type in Southwest Henan. In contrast, rooftop photovoltaic systems demonstrate considerable application potential. The annual solar radiation on the south-facing pitched roof reaches approximately 1331 kWh/m², corresponding to a “very abundant” solar resource. Taking PERC photovoltaic modules (conversion efficiency of 22%) as an example, and considering engineering factors such as temperature derating, inverter losses, cable losses, module mismatch losses, soiling, and degradation, the overall system efficiency (performance ratio, PR) is taken as 85%, yielding an estimated annual power generation of approximately 249 kWh/m². Installing 2.9 m² would be sufficient to meet the local average annual household electricity demand of about 700 kWh.

- (4) The economic analysis indicates that the material cost of the proposed integrated renovation scheme is approximately 4891 RMB, accounting for 5.3–7.1% of local annual household income, with a static payback period of approximately 5.8–7.3 years and a life-cycle energy saving benefit of approximately 10,000–21,000 RMB, demonstrating good economic feasibility. PUR board requires the smallest thickness (43 mm) to achieve the same thermal performance, has a lower life-cycle material cost than EPS (which would require replacement), and causes the least disturbance to the structural safety of traditional stone masonry walls, making it a reasonable choice under the priority of heritage conservation.
- (5) Although the proposed optimization strategy has been demonstrated to be effective for the typical stone-slab dwelling investigated in this study, its applicability to other traditional dwellings with different layouts, envelope characteristics, and climatic conditions requires further verification. Future research should further investigate the long-term hygrothermal performance of traditional dwellings, occupant comfort responses, and the coupled effects of passive retrofit measures and active environmental control systems to support the sustainable conservation and adaptive reuse of traditional vernacular buildings.

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