Frontiers in Built Environment

TYPE Original Research
PUBLISHED 13 October 2025
DOI 10.3389/fbuil.2025.1667859

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RECEIVED 26 July 2025
ACCEPTED 05 September 2025
PUBLISHED 13 October 2025

CITATION
Shi L, Zhang Z, Zhang F, Liu S and Cao Y (2025) A study on the survey and evaluation of indoor lighting environment and improvement of traditional raw earth dwellings in western Hunan Province. *Front. Built Environ.* 11:1667859.
doi: 10.3389/fbuil.2025.1667859



# A study on the survey and evaluation of indoor lighting environment and improvement of traditional raw earth dwellings in western Hunan Province

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Due to the crystallization of regional culture and ecological wisdom, the quality of the lighting environment of traditional native dwellings in western Hunan directly affects the physical and mental health of older adult residents. Taking Laodong Village in Fenghuang County, western Hunan as an example, this study combines parametric modelling and simulation analysis to explore the key role of light environment on the improvement of ageing suitability with respect to natural lighting and passive lighting. The three-dimensional model is constructed using the Rhino-Grasshopper platform, and Ladybug tool is used to simulate the effects of different window sizes, positions and eave configurations on the indoor lighting, and optimization strategies are proposed based on the field research data. The study shows that the design of window openings with a sill height of 1.2 m, a horizontal center and a width of ≥1.5 m can significantly improve the illuminance and uniformity and in the passive technology, the reasonable layout of open tiles and skylights can supplement the natural light by more than 30%. The results of the study provide a scientific basis for traditional village renovation and a practical path for low-carbon sustainable rural construction.

KEYWORDS

**traditional raw earth dwellings, age-friendliness, light environment optimization, parametric simulation, indoor environment**

## 1 Introduction

### 1.1 Overview

So far, more than 60 million residents in China continue to inhabit various types of Raw Earth architecture, which is extensively distributed across the country. These structures are particularly widespread in economically disadvantaged rural regions, where traditional construction techniques remain a core part of daily life. In the countryside of Hunan Province, Raw Earth dwellings are especially common. The traditional Raw Earth villages in Western Hunan form a significant part of China's indigenous housing heritage. Over time, these dwellings have absorbed cultural influences from the Wu-Chu tradition, maintained historical continuity, and reflected local geographical characteristics. Their lasting environmental adaptability, combined with distinctive construction principles and spatial aesthetics, represents a synthesis of regional history, vernacular craftsmanship, and ethnic cultural values.

With the intensifying aging population, the construction of senior-friendly living environments has become one of the crucial measures to address the social issues arising from population aging, especially in the Xiangxi region, where the aging population is particularly severe. According to the data from the Seventh National Census, the population aged 60 and above in the region is 472,419, accounting for 18.9% of the total population, while those aged 65 and above are 374,182, making up 15.1%. Compared to the Sixth National Census, the proportion of people aged 60 and above increased by 4.5%, and the proportion of people aged 65 and above rose by 5.4%.

With aging, significant changes occur in the visual system of older adult individuals, including pupil constriction (senile miosis), yellowing and hardening of the lens, which result in reduced light entering the retina, decreased contrast sensitivity, and increased susceptibility to glare. This is especially true for seniors with declining vision, whose needs for proper lighting become more pronounced with age. Currently, China's lighting standards for the older adult stipulate that the lighting in residential spaces should meet at least 150 lx, particularly in frequently used areas such as bedrooms and kitchens. However, in the traditional adobe houses of the Xiangxi region, economic factors have led to the deterioration of these residences over time. The original architectural style and design did not adequately consider the growing lighting needs of the older adult. Consequently, the lighting conditions in these traditional homes fall far below the national lighting standards for the older adult. For the aging population, particularly those with vision impairments, the insufficient lighting environment has become a potential safety hazard, adversely affecting their physical health.Therefore, this study aims to assess and optimize the indoor lighting environment in these areas to enhance the quality of life and safety of older adult residents.

The optimization of indoor lighting environments in traditional architecture is attracting increasing scholarly attention, driven by the need to harmonize energy efficiency, visual wellbeing, and cultural preservation. Several case studies have highlighted widespread deficiencies in natural lighting. For instance, courtyard dwellings in Fujian experience restricted daylight autonomy (DA < 10%) due to limited courtyard dimensions (Gao et al., 2023). In the Taihang region, stone dwellings consistently fail to meet daylighting standards, and although cave dwellings perform somewhat better, they still fall short (Yang et al., 2024). He et al. documented significant issues with lighting uniformity in Xiamen's vernacular homes (He, 2016). In response, region-specific optimization strategies have emerged. Vatankhah et al. employed the Octopus algorithm in Grasshopper to adjust the orientation and window-wall ratios of contemporary buildings, based on traditional data from Iran's Gilan region, achieving 20%–35% energy savings (Vatankhah et al., 2024). Yang et al. enhanced thermal-lighting synergy by adding sunspaces to cave homes in cold climates, resulting in a 4.3°C temperature increase and a 39.1% extension in comfort hours (Yang et al., 2024). Gao et al. quantified Huizhou courtyard parameters and found that enlarging courtyard and window dimensions improved lighting uniformity (Gao et al., 2023). While several regional studies have advanced daylight optimization for vernacular architecture (e.g., Gao et al., 2023; Vatankhah et al., 2024), they often consider window size and passive daylighting strategies separately, without examining their combined effects. In contrast, this study integrates both factors to evaluate their interactive influence on indoor lighting. Moreover, prior methodologies typically focus on either quantitative simulations or qualitative assessments, rarely combining the two. Our approach bridges this gap by employing multi-factor parametric simulations alongside field-based measurements, providing a more comprehensive and realistic evaluation of daylight performance in rural vernacular dwellings.

While significant progress has been made in optimizing daylighting for traditional buildings, few studies have integrated the specific needs of particular regions (e.g., Western Hunan), building types (raw earth dwellings), and user groups (the older adult) with quantitative assessments of window parameter sensitivity and passive daylighting strategies. The innovation of this study lies in the development of a comprehensive research framework. Through field measurements, model validation, and parametric simulations, we systematically examine the current status and potential of indoor lighting environments in raw earth dwellings in Western Hunan. Specifically, this study not only identifies key architectural parameters that influence daylight performance but also quantitatively evaluates the practical benefits of passive daylighting technologies such as skylights and translucent tiles. Furthermore, we establish age-friendly lighting standards as a central optimization objective, providing both a scientific foundation and actionable pathways for age-friendly retrofits in these dwellings. This approach contrasts sharply with previous studies, which often focused on single-parameter optimization or failed to consider specific user populations, thus laying the groundwork for future multi-objective optimization, such as balancing daylighting, thermal performance, structural integrity, and heritage preservation.

However, in traditional settlements with a high concentration of raw earth structures, it is necessary to develop daylighting retrofit strategies suitable for contemporary use. This study focuses on Laodong Village in Fenghuang County, Western Hunan, aiming to optimize the indoor lighting environment while balancing cultural preservation and health performance. An age-friendly framework is adopted to account for age-related changes in the visual system, including reduced retinal illumination, senile miosis, and increased intraocular light scatter. To address these challenges, illuminance uniformity is employed as a primary performance indicator, alongside qualitative assessment of glare risks, ensuring that the proposed daylighting interventions provide not only adequate brightness but also enhanced safety and visual comfort for older adult occupants. Furthermore, parametric modeling and building performance simulation are used to analyze the sensitivity of core daylighting parameters to indoor illuminance distribution and uniformity, while passive lighting strategies are applied to optimize the utilization of natural light.

1. Based on extensive field research, on-site environmental monitoring, and software simulation—supplemented by a review of relevant literature—the study evaluates the indoor

lighting environment to better accommodate the living needs of residents in Raw Earth dwellings.

2. Using Rhino, Grasshopper, and Ladybug tools, along with meteorological data and precise field measurements, daylight simulation experiments were conducted to explore the influence of window forms and placements on the optimization of the lighting environment in Raw Earth structures.
3. A comprehensive analysis of passive lighting technologies—including prismatic light-guiding windows, reflectors, light tubes, skylights, and translucent tiles—was performed to evaluate their suitability and effectiveness in improving the daylight conditions of traditional architecture.

## 1.2 Objectives of the study

The primary objectives of this study are as follows:

1. To investigate and evaluate the current indoor lighting conditions of traditional Raw Earth dwellings in Western Hunan through comprehensive field measurements and resident surveys.
2. To identify the key architectural parameters (e.g., window position, window size, eave dimensions) that significantly influence the indoor daylighting performance of these dwellings using advanced parametric simulation techniques.
3. To propose and assess the effectiveness of low-cost, passive daylighting strategies (e.g., skylights, translucent tiles) that are suitable for the conservation and sustainable improvement of these heritage buildings.
4. To provide a set of scientific-based, practical guidelines for the retrofitting of these dwellings to enhance the indoor lighting environment and improve the living quality of residents, particularly the older adult.

# 2 Materials

## 2.1 Research area

Field investigations conducted by the research team indicate that Raw Earth dwellings are widespread across Xiangxi Tujia and Miao Autonomous Prefecture. By the end of 2022, Fenghuang County alone had 22 villages listed in the "Catalogue of Chinese Traditional Villages." Among these, Shujiadang Village, Laodong Village, Laojiazhai Village, Liangdeng Village, Zhushan Village, Sumahe Village, and Luoshan Village stand out for their large-scale preservation of Raw Earth buildings, collectively accounting for 31.8% of the county's total listed traditional villages. Additionally, there are over 14,900 Raw Earth dwellings made from rammed earth or adobe still in existence within the county, covering a total preserved area of more than 1.3 million square meters. Throughout history, various ethnic groups in the region have continuously adapted to the local environment, resulting in the development of a highly distinctive form of traditional Raw Earth vernacular architecture.

However, the traditional Raw Earth dwellings in Hunan Province do not meet current demands for functionality, architectural form, and long-term durability. Many existing Raw Earth buildings have been repurposed for storage or abandoned entirely. In many cases, these buildings are in poor structural condition, highlighting significant concerns for the preservation of Raw Earth architecture (Zhang et al., 2022). Due to the lack of innovation in architectural form and expression, Raw Earth dwellings are often viewed as symbols of backwardness and poverty. Furthermore, the indoor environmental quality of these dwellings fail to meet the needs of modern occupants.

This research focuses on the traditional Raw Earth dwellings in Western Hunan, renowned for their meticulous preservation of architectural and cultural traditions. To date, most studies on Xiangxi's traditional dwellings have emphasized spatial morphology and indoor thermal-humidity performance (Ding et al., 2024). However, investigations into daylighting conditions remain limited. Field surveys indicate that most traditional homes in the region suffer from inadequate indoor lighting, highlighting the need for appropriate retrofitting.

## 2.2 Subject of objective

The Xiangxi region is characterized by a subtropical monsoon humid climate, with distinct seasonal variations. Due to the frequent overcast and high cloud cover, the region experiences relatively low natural sunlight. The average annual sunshine hours for the region are only about 1,200–1,400 h, which accounts for roughly 27%–32% of the possible sunlight hours throughout the year. Xiangxi is one of the areas with the lowest sunlight in China, located at the edge of the cloudy and low-sunlight zone, and is known as the "low-light center" of the country, where sunshine is scarce. According to China's lighting climate classification, Xiangxi falls into the Lighting Climate Category V (sky brightness coefficient $K \approx 1.2$), which indicates relatively poor natural lighting conditions.

The seasonal variation in sunlight is significant in Xiangxi. Winter is the period with the least sunlight. For example, in January, the average monthly sunlight is only about 42.7 h (less than 2 h of sunlight per day on average). The sunlight hours in December and February are also quite low, with the entire winter period often being cloudy and dim. In contrast, summer provides the most sunlight, with longer daylight hours. For instance, in July, the average monthly sunlight is about 177 h, and in August, it can reach 190.6 h, with more than 6 h of sunlight per day on average. Thus, sunlight hours in midsummer are more than four times that of midwinter. The sunlight in summer is particularly abundant after the rainy season, when the sky clears and the days grow longer. However, in winter, the days are short and often foggy, leading to the lowest sunlight levels. Spring and autumn serve as transition periods, with spring sunlight gradually increasing (e.g., April has about 90 h, and May has about 112 h), while autumn sunlight decreases (e.g., October has about 97 h).

Overall, the summer months of June to August contribute the largest proportion of annual sunlight, while December to February (winter) have the least. This seasonal difference creates a "bright summer, dark winter" sunlight pattern in Xiangxi. Due to limitations in building materials and design concepts, the current lighting conditions in residential homes, particularly for older adult residents, have caused significant discomfort, further increasing safety risks. Therefore, researching and optimizing the indoor lighting environment in this region is of utmost importance.

For this research, Laodong Village in Fenghuang County was selected as a representative example of traditional Raw Earth dwellings in Xiangxi. The village serves as a typical model of traditional dwellings in western Hunan Province, with its remote location, well-preserved landscape, and older adult-dominated population offering valuable insights into current living conditions.

Laodong Village is located in the central area of Machong Township, Fenghuang County, Xiangxi Province, Hunan. Geographically, it lies at 27°58′N latitude and 109°24′E longitude, with an altitude of approximately 664 m. Established during the Ming Dynasty, the village spans an area of 8.2 square kilometers (1,184 acres), with a resident population of approximately 680 people out of a total household population of 1280. The village is home to numerous historically protected buildings, and its streets and lanes are closely interconnected. Among these, the expansive Majia Courtyard architectural complex is regarded as the "Magnificent Palace of the Miao Village" (Fu et al., 2021). Historically shaped by external turmoil, Xiangxi villages, including Laodong, incorporate defensive planning strategies in both their site selection and spatial organization, making the village an exemplary case for studying these features (Figure 1A).

The overall village layout of Laodong Village is influenced by historical conditions and the topography of the mountain. The village features a leaf-vein type road network, with the main road going up the slope and the branch roads running parallel to the mountain's contour. The system results in significant variations in building orientations and spacing. The streets and lanes interconnect the buildings, either enclosing or bifurcating them, to create a spatial pattern that follows both the longitudinal and transverse directions of the mountain. The intricate and interlacing arrangement of streets and lanes forms a unique and cohesive spatial organization (Figure 1B).

More than 50.4% of the traditional houses in Laodong Village date back to the Ming and Qing periods. Their dense distribution has fundamentally shaped the village's overall architectural identity. Of these, 23 historic buildings from the Ming and Qing eras remain well-preserved. The proportions of well-preserved, moderately preserved, and poorly maintained houses in Laodong Village are 83.5% (15,418 $m^2$), 33.9% (6,259 $m^2$), and 1.7% (309 $m^2$), respectively. Overall, the housing stock is in relatively good condition.

Buildings with three floors account for 9.7% (1,797 $m^2$) of the total residential area in Laodong Village. Single-story and two-story dwellings are primarily concentrated in the village interior, comprising 44.4% (8,199 $m^2$) and 45.9% (8,474 $m^2$), respectively. Most of the two-story houses were constructed around the year 2000, a period marked by significant demolition and reconstruction due to improving economic conditions (Figure 1C).

# 3 Research methods

This study is based on actual research, on-site monitoring to collect relevant data, and software simulation, supplemented by literature analysis. Drawing on previous research on light environments, the primary focus is on the real-world conditions of Laodong Village, including the existing environment, the health status of the villagers, and the field monitoring data.

To systematically assess and optimize the indoor lighting environment of traditional adobe dwellings, this study employs daylight simulation methods. The necessity of this approach is reflected in several aspects: First, simulations enable the quantification and analysis of dynamic daylight conditions throughout the year, overcoming the time and spatial limitations of on-site measurements. Second, through parametric modeling, the sensitivity of indoor illuminance to various building parameters (such as window size and position) can be efficiently tested, a task that is difficult to achieve with traditional experimental methods. Finally, simulations provide a scientific predictive tool for evaluating and verifying the effectiveness of passive daylighting retrofit strategies, thereby guiding practical renovation efforts.

## 3.1 Survey status

The study centers on optimizing the light environment in Raw Earth buildings in Laodong Village, with a particular emphasis on passive improvement methods. The primary research objective is to investigate the most prominent lighting issues in the indoor environment, specifically related to window opening forms and their locations. In the Raw Earth dwellings of Xiangxi, wooden windows dominate, comprising more than 90% of the window types. These windows can be broadly categorized into two types based on their opening styles: side-hinged (casement) windows and vertical sliding windows. Casement windows are favored for their cost-effectiveness and practicality, while vertically sliding windows are typically installed above door and window lintels on tall facades to mitigate the excessive height of the wall (Trihamdani and Nurjannah, 2022) (Figure 2A).

Field surveys and measurements indicate that the horizontal window dimensions in Laodong village's Raw Earth dwellings range from 0.2 to 2.3 m, with an average width of 0.98 m vertical window sizes range from 0.3 to 1.85 m, with an average height of 1.04 m. The window areas vary from 0.75 to 3.6 $m^2$, with an average area of 1.1 $m^2$, while the total window area in the houses ranges from 1.1 to 14.2 $m^2$, with an average area of 3.55 $m^2$ (Figure 2B). According to GB_T5824-2021 (Standardization Administration Of China, 2021), which specifies the preferred window dimensions for civil buildings, the recommended width for window openings is 0.6–2.1 m, and the height should be either 0.6 m or 2.1 m. The window dimensions in Laodong Village's Raw Earth dwellings are significantly smaller than the recommended sizes.

The current status of the indoor lighting environment (Figure 2C) indicates that even on sunny days, daylight penetration is limited primarily to areas near windows. This issue is exacerbated by randomly placed indoor objects and interior walls that are either finished with cement plaster or directly exposed Raw Earth, both of which have low reflectivity. Furthermore, prolonged exposure to indoor cooking fires has caused significant smoke deposition on wall surfaces, resulting in darker interiors. Consequently, even

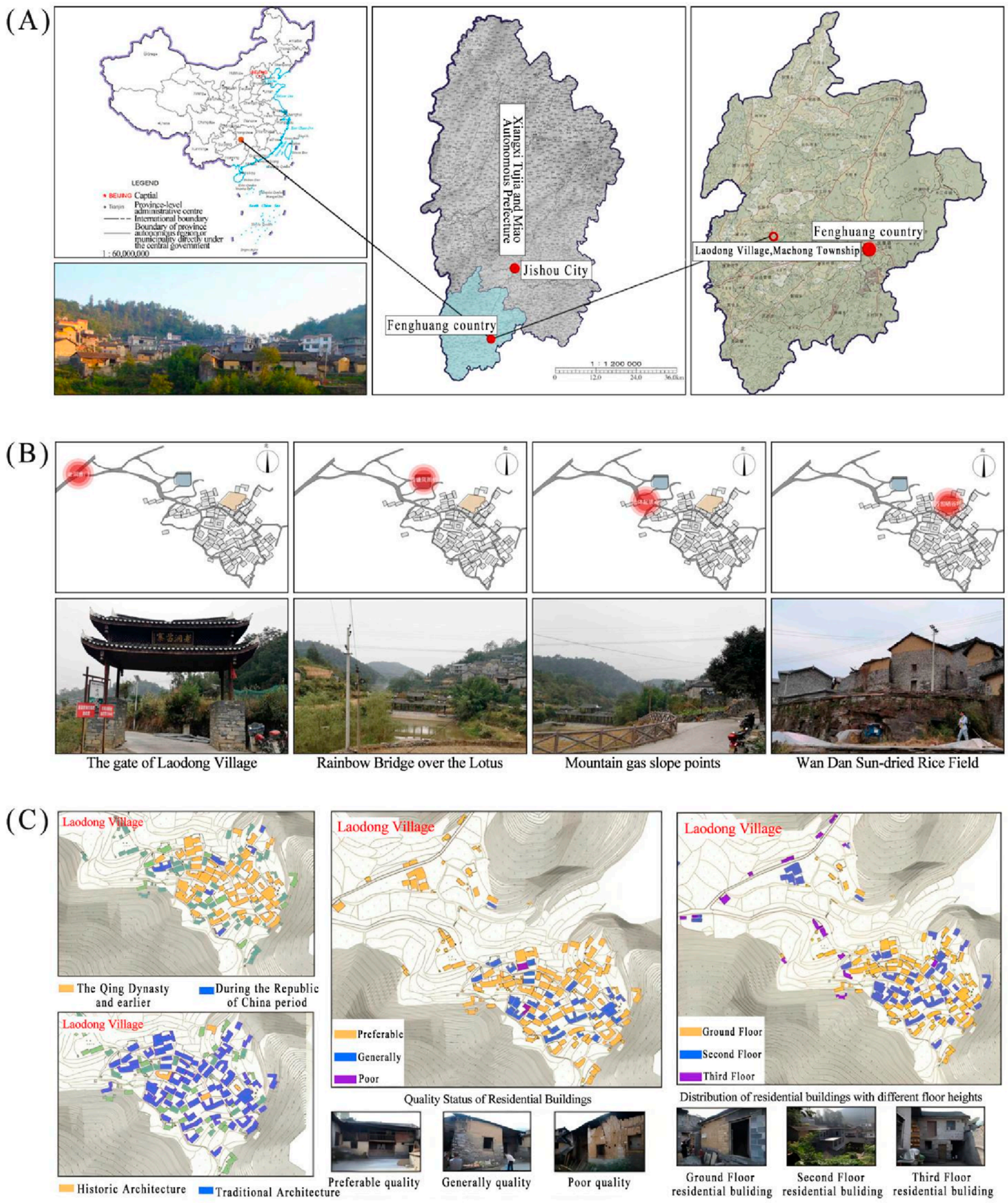


FIGURE 1
Location information for Laodong Village **(A)** Specific location map of Laodong Village **(B)** Main spatial nodes in Laodong Village **(C)** Distribution of residential buildings in Laodong Village.

during daytime, artificial lighting remains necessary in areas distant from windows. Interviewees revealed that the residents perceive bedrooms and kitchens as having the poorest indoor lighting conditions, followed by functional spaces closer to windows, such as halls and fire-pit areas. Currently, the interior illumination primarily relies on individual energy-saving lamps, typically with only one installed per functional space. Over time, lampshades have accumulated soot deposits, significantly reducing their illumination efficiency. Moreover, as permanent residents age, their declining vision compounds the problem. Thus, inadequate indoor lighting poses potential safety risks and accessibility concerns, particularly affecting the older adult population.

## 3.2 Monitoring methodology

Lao Dong Village, located in the Xiangxi region of Hunan Province, is a representative traditional settlement characterized by vernacular earthen architecture. Over 85% of the residential dwellings in the village are oriented southward (i.e., sitting north facing south), reflecting a predominant south-facing orientation. The majority of these earthen houses were constructed over 50 years ago and have been continuously inhabited, highlighting both their historical longevity and ongoing use. The vernacular dwellings can be categorized into three primary layout types: “L”-shaped, “U”-shaped (courtyard style), and “I”-shaped (linear) configurations.

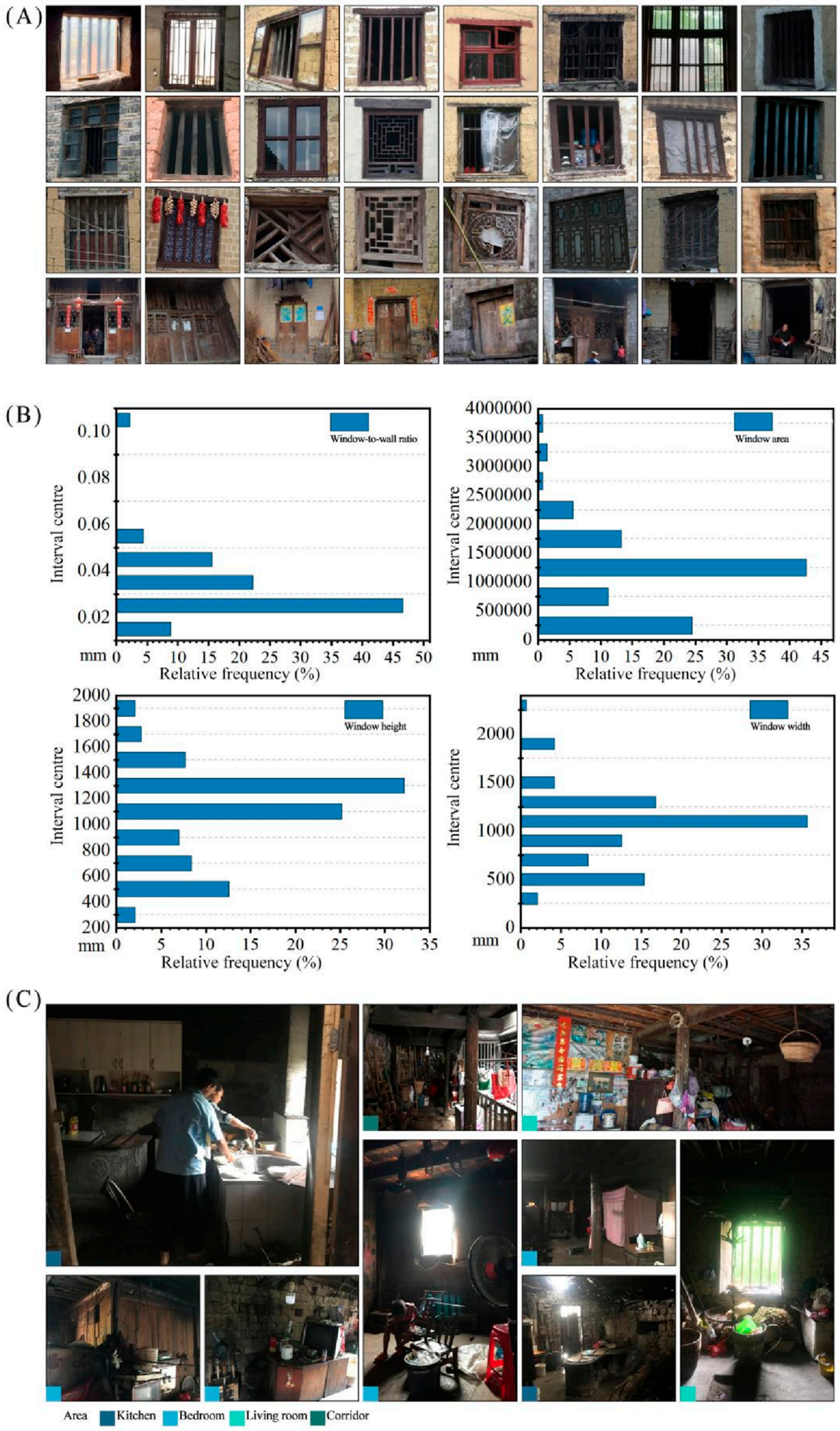


FIGURE 2
Field research in Laodong Village **(A)** Survey of the Current Condition of Doors and Windows in Raw Earth Dwellings in Laodong Village **(B)** Distribution of window sizes in Raw Earth dwellings in Laodong Village **(C)** Distribution of window sizes in Raw Earth dwellings in Laodong Village.

Prior to the field survey, the research team communicated with the village Party secretary, the village director, and a representative of the Women's Federation to explain the study's objectives and obtained permission and support for the investigation. The selection criteria included: (1) typical building orientation (predominantly south-facing); (2) occupancy by older adult residents; and (3) well-preserved physical condition of the house. To ensure diversity and representativeness, the chosen sample covers all four cardinal

TABLE 1 Light intensity monitoring instrument and its parameters.

| Instrument | Measurement content | Monitoring method | |
|---|---|---|---|
| TESTO540 illuminance meter | Illuminance (lx) | Handheld |  |
| Accuracy | Measurement Range | Resolution | |
| ±3(Comparison reference value) | 0–99,999 lx | 10 lx | |

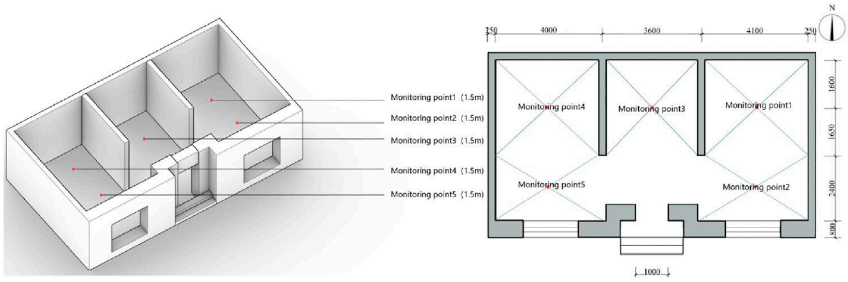


FIGURE 3
Monitoring point location diagram.

orientations (east, south, west, north). In the field, each dwelling's orientation was verified using a compass to ensure the accuracy of the recorded orientation data.

In accordance with the Chinese national standard GB/T 38439–2019 (Standardization Administration Of China, 2019), indoor lighting conditions of traditional Raw Earth dwellings in Laodong Village were systematically monitored. A TESTO 540 handheld illuminance meter was used to measure the illuminance across various functional areas (Table 1). Vertical illuminance was recorded at eye level, at a height of 1.5 m above the floor, with the sensor oriented in the direction of typical human visual perception (Huang and Dong, 2021) (Figure 3). Except for the solar radiometer, all measurement instruments were carefully positioned to avoid direct exposure to sunlight. During the monitoring period, artificial lighting and open flames were excluded to ensure that the measured illuminance values represented natural daylighting conditions exclusively. Weather conditions on the measurement day were clear, and no standing water was observed either indoors or outdoors.

The monitoring results indicate that the hall generally has the best indoor lighting conditions among the areas studied. The average illuminance levels recorded in the halls of indigenous dwellings in Laodong village range from 5 to 1,001 lx, 160–1,230 lx,68–1,136 lx and 7–1,390 lx. Natural lighting in the bedrooms is generally low, with average illuminance values ranging from 38.42 lx to 42 lx. The kitchens have the second-lowest illuminance levels, averaging between 79 lx and 635 lx. Moreover, the minimum illuminance recorded in some houses for functional areas such as fireplaces, bedrooms, halls, and kitchens is notably low, ranging from 0 to 10 lx, while the maximum illuminance ranges from 150 to 300 lx. These results suggest that, without artificial lighting, the natural illumination in these dwellings is insufficient for residents' daily activities and does not meet existing residential lighting standards. Thus, improving the indoor lighting environment of Raw Earth dwellings in Laodong Village is essential to enhancing livability and address contemporary residents' needs.

Based on the light intensity required for each behavioral activity of the older adult in the Standard Specification for the Design Code for Residential Buildings for the older adult (GB50340-2016) (Ministry Of Housing And Urban-Rural Development Of The People'S Republic Of China, 2016) and the Standard for Lighting Design of Buildings (Standardization Administration Of China, 2019) (Table 2), combined with the survey findings on the indoor lighting environment of existing Raw Earth dwellings in Laodong Village, the older adult are rarely involved in fine activities on a daily basis, and are mainly engaged in general daily activities, and the location of the meal is the parish hall area without an exclusive dining room, taking into account the Design Standards for Residential Buildings for the older adult, which stipulate that the illuminance value of kitchen, bathroom, living room, bedroom and corridor is 100–150 lx, only the location of the restaurant standard value of 200 lx, take 150 lx as the basis of illumination evaluation of the indoor light environment evaluation and analysis (Ministry Of Housing And Urban-Rural Development Of The People'S Republic Of China, 2016).

Based on results from on-site monitoring and field surveys, both subjective satisfaction and objective measurements of indoor lighting across functional spaces in the Raw Earth dwellings of Laodong Village indicate that the current lighting conditions do not meet the residential needs of the older adult. These traditional

TABLE 2 Lighting standards for ordinary buildings and buildings for the older adult.

| Name measurement plane | Building lighting design standards | | Design standards for residential buildings for the older adult | |
|---|---|---|---|---|
| | General activities | Fine motor skills | General activities | Fine motor skills |
| Living room 0.75 m horizontal plane | 100 1x | 300 1x | 150 1x | 300 1x |
| Bedroom 0.75 m horizontal plane | 75 1x | 150 1x | 100 Ix | 200 1x |
| Corridor, entrance hall 0.75 m horizontal plane | 50 1x | 60 1x | 75lx | |
| Restaurant 0.75 m horizontal plane | 150 1x | | 200lx | |
| Kitchen 0.75 m horizontal plane | 100 1x | 150 1x | 150 1x | 200 1x |
| Bathroom 0.75 m horizontal plane | 100 1x | | 150 1x | 200 1x |

dwellings were originally self-built by villagers, and constraints in construction materials and techniques limited the design and size of doors and windows. Additionally, the remote geographic location resulted in a lack of scientific guidance from relevant standards. Therefore, the indoor lighting environment requires urgent improvement.

## 3.3 Experimental simulation

In terms of research methodology, this study draws upon the lighting environment research of Campanile et al. (2015), Khidmat et al. (2021), Yoon et al. (2019). Rhino software and its parametric plugin Grasshopper were used for model construction, while the Ladybug plugin was employed for performance simulation. Together, these tools form one of the most widely used approaches for building performance simulation at present.

The actual mapping size of residential houses was determined using climate parameters from Jishou City's meteorological monitoring data in the early stage of modelling. According to the specifications in General technical requirements for wood windows and doors (GB/T 29498-2025) (Standardization Administration Of China, 2024), standard window openings range from 0.6 m to 2.1 m in width, with a typical height of 1.5 m and a modular increment of 0.3 m. Considering that larger window openings generally result in higher indoor illuminance levels, and that the raw-earth dwellings in western Hunan show significantly lower light levels than the 300 lx recommended for older adult residents, the window dimensions in the base model were set at 1.5 m in height and 2.2 m in width (Cao et al., 2015).

According to the control variable method by changing the single factor variables (e.g., vertical position of the window, Horizontal position of the window, Horizontal dimensions of windows, Vertical dimensions of windows, and Eave size) (Figure 4). In order to carry out the study of its sensitivity to the indoor light environment. Finally, based on the single-factor test, an orthogonal test was used to explore the effects of its sill, window, and eave multifactor on the indoor light environment. In the selection of evaluation indexes, based on the previous research on the indoor environment of the older adult in Laodong Village, combined with the lighting standards for ordinary buildings and residential buildings for the older adult, the evaluation is based on the illuminance value of 150 lx as the evaluation illuminance value (Noell-Waggoner, 2017). Based on this, the indoor lighting environment was evaluated using indoor light satisfaction (S) and indoor light uniformity (U) as evaluation indexes (Equations 1, 2), and the minimum illuminance value was calculated based on the point-by-point calculation method.

$$S = \frac{N_{E \geq 150 lx}}{N} \tag{1}$$

$$U = \frac{E_{min}}{E_{av}} \tag{2}$$

Here, $N_{E \geq 150lx}$ represents the number (or area) of simulation grids with illuminance values sufficient for older adult indoor activities, N denotes the total number (or area) of indoor simulation grids, $E_{min}$ refers to the minimum illuminance value, and $E_{av}$ refers to the average illuminance value.

This experiment utilized the Ladybug plugin in Grasshopper to simulate the indoor lighting environment for residential spaces. The simulation was conducted at 2:00 p.m. on the winter solstice, under overcast conditions, with an outdoor natural illuminance of 23.5 klx. The region is classified as a Type V light climate zone, with a K value of 1.20. According to surveys, the interior surface materials in the Raw Earth dwellings of Laodong Village, Fenghuang County, have relatively low reflectance, typically ranging between 0.16 and 0.23, which is below the standard-specified suitable range, thereby affecting indoor lighting quality. These materials collectively contribute to the unique indoor lighting environment of the local earthen dwellings (Villalba et al., 2021).

Based on the typical houses in Laodong village, the sensitivity of the indoor lighting environment was investigated by setting different windowsill heights. Considering the moisture-proof and durability measures of the Raw Earth wall and the wall base, the height of the windowsill is set at 0.6, 0.9, 1.2, 1.5, 1.8, 2.1, and 2.4 m for seven working conditions (Figure 4). The height and width of the windows are set to 1.5 × 2.2 m. The horizontal dimension of the eaves is set to 1 m, the height of the ceiling is set to 4 m. During the simulation period, the windows and doors are all open, and the windows are all set at the horizontal center.

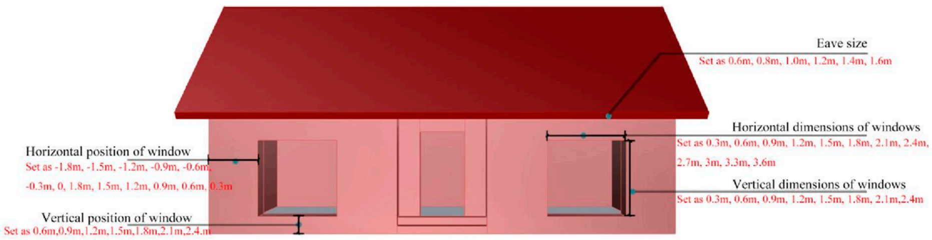


FIGURE 4
Schematic diagram of control room lighting environment dependent variables.

The same research method was used as described above to investigate the sensitivity effects of different sill level positions on the indoor light environment of Raw Earth dwellings in Western Hunan. The relative centers of the horizontal positions of the sills for the simulation tests were set at −1.8 m, −1.5 m, −1.2 m, −0.9 m, and −0.6 m, respectively, −0.3 m, 0, 1.8 m, 1.5 m, 1.2 m, 0.9 m, 0.6 m, 0.3 m (horizontally left is negative, horizontally right is positive) (Figure 4), a total of 13 groups of conditions. The height and width of the windows are set to 1.5 × 2.2 m. The horizontal dimension of the eaves is set to 1 m, the ceiling height is set to 4 m, the horizontal dimension of the eaves protruding from the roof is set to 1 m, and the height of the windowsill is set to 1.2 m in consideration of the moisture-proofing of the wall, and the doors and windows are open during the simulation.

The same research methodology as mentioned above was used to investigate the sensitivity effect of different window level sizes on the indoor light environment of the Raw Earth dwellings in Laodong Village. Based on the results of the above research, when the horizontal position is 0–0.6, the satisfaction is the highest, and the uniformity is also in a good range, so the window sill position is set in the center as in the current situation of traditional houses, and the height of the window sill is set at 1.2 m, the height of the window is set at 1.5 m in consideration of the moisture-proofing of the wall surface, the eave protrudes out of the horizontal dimension at 1 m, and the width of the window is set at 0.3 m, 0.6 m, 0.9 m, 1.2 m, 1.5 m, 1.8 m, 2.1 m, 2.4 m, 2.7 m. The horizontal window dimensions are set as 0.3 m, 0.6 m, 0.9 m, 1.2 m, 1.5 m, 1.8 m, 2.1 m, 2.4 m, 2.7 m, 3 m, 3.3 m, 3.6 m, and a total of 12 groups (Figure 4). During the simulation period, the doors and windows were opened. The value of 150 lx was chosen as the evaluation illuminance value.

The same research methodology was used as described in the previous section to investigate the sensitivity effects of different window vertical dimensions on the sensitivity of indoor daylighting conditions in Raw Earth dwellings in Laodong Village. In the model parameters, the window sill is in the central position, the height of the window sill is set at 1.2 m, the width of the window is set at 2.2 m, the horizontal dimension of the eave projection is set at 1 m, and the height of the window is set at 0.3 m, 0.6 m, 0.9 m, 1.2 m, 1.5 m, 1.8 m, 2.1 m, and 2.4 m, with 8 groups in total (Figure 4). During the simulation period, the windows and doors are all open. The illuminance value of 150 lx is selected for evaluation.

The same research method was used as described above to investigate the sensitivity effects of different window vertical dimensions on the indoor light environment of Xiangxi Raw Earth dwellings. In the simulation test, the horizontal dimensions of the eaves were set to 0.6 m, 0.8 m, 1.0 m, 1.2 m, 1.4 m, 1.6 m, and there were 6 working conditions (Figure 4), the height of the window sill was set to 1.2 m, the height and width of the window were set to 1.5 × 2.2 m, and during the simulation period, the windows and doors were open, and the illuminance value of 150 lx was selected for the evaluation.

# 4 Results and discussion

## 4.1 Window position optimization results

The simulation results of indoor lighting in residential houses with different vertical positions of window sills show (Figure 5A) that the area near the window has the best indoor lighting environment. The lighting conditions on the south side are noticeably better than those on the north side. The light intensity in the direct sunlight area is more than 4,000 lx, and the area with light intensity of more than 2000 lx is the largest in working conditions 1, 2, and 3, and the areas covered by light blue, yellow, and red zones are smaller as the height of the window sill increases, i.e., the more areas in the interior are less than 50 lx of light intensity. Due to traditional construction concepts, windows are seldom installed in the traditional indigenous dwellings in Laodong Village. Due to the influence of traditional construction concepts, the traditional indigenous houses in Laodong Village seldom have windows on the north, east and west sides, which leads to the fact that except for the area near the windows on the south side, other areas of the interior do not have a good lighting environment, especially the area on the north side which is far away from the windows.

The distribution of indoor light intensity at different vertical positions of windowsills in residential buildings (Figure 5B) shows that as the height of the windowsill increases, both the maximum and average indoor light intensities decrease. When the windowsill height increases from 0.6 m to 0.9 m, the lighting intensity decreases slightly, with the average indoor light intensity at 0.9 m (1,421 lx) being 10 lx higher than at 0.6 m (1,411 lx). Between 0.9 m and 2.1 m, the indoor lighting environment significantly deteriorates, with both the average and median illuminance values gradually decreasing. For every 0.3 m increase in height, the maximum value decreases by 50–100 lx, while the minimum value decreases by less than 5 lx. Overall, when the windowsill height is within the ranges of 0.3–0.6 m and 2.1–2.4 m, the indoor light intensity is

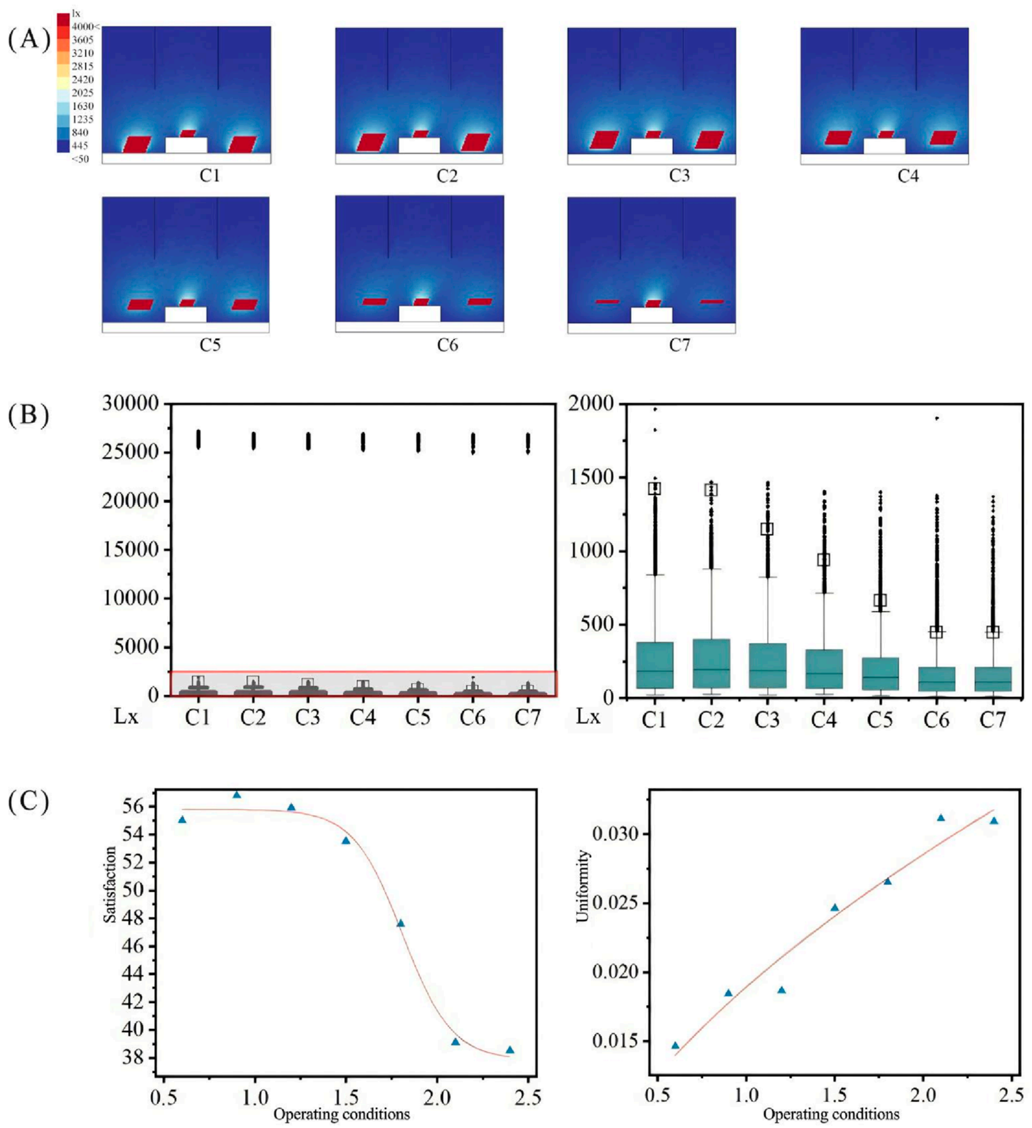


FIGURE 5
Different vertical positions of window sills **(A)** Simulation results of indoor lighting in residential buildings with different vertical positions of window sills **(B)** Distribution of indoor light intensity in residential buildings at different vertical positions of window sills **(C)** Curve fitting of light intensity satisfaction and uniformity as a function of vertical position.

not significantly affected by changes in height. However, between 0.6 m and 2.4 m, the indoor light intensity decreases linearly with increasing height.

The indoor light uniformity, satisfaction and sill height were fitted by appealing to the light simulation results for different sill vertical positions (Figure 5C). The relationship between the windowsill height of the dwellings and indoor illuminance uniformity follows an Allometric model (Equation 3), with a coefficient of determination $R^2 = 0.96$, and fits a polynomial model. The sigmoidal curve was fitted with the following equation:

$$U = 37.86 + \frac{17.95}{1 + 10^{(1.81-x)*p}} \tag{3}$$

where U represents indoor illuminance uniformity, and x represents the windowsill height of the dwelling.

The fit was consistent with the results of the distributions, with the best satisfaction at sill heights of 0.6–1.5 m, which exceeded 50%, and then declined significantly to less than 40% in the range of 1.5–2.1 m as height increased. Uniformity increased with height, the relationship between the windowsill height of the dwellings and indoor lighting satisfaction follows a Dose–Response model (Equation 4), with a coefficient of determination $R^2 = 0.96$, and fits a polynomial model. The fitted equation of the curve is given by:

$$\mathrm{Sat} = 0.02 * x^{0.59} \tag{4}$$

where: Sat represents indoor lighting satisfaction, and x represents the windowsill height of the dwelling.

But the overall range of uniformity was less than 0.04,This metric is critical for visual comfort, particularly for older adult residents. According to the Illuminating Engineering Society (IES), a uniformity index below 0.4 is generally considered acceptable for older adult individuals. However, for optimal visual comfort, higher values are recommended, especially in areas where older adult individuals are likely to spend the majority of their time. so the magnitude of the effect was not significant. There was a significant correlation between satisfaction and sill height, and sills in the range of 0.6–1.5 m were the more desirable heights.

The results of the distribution of indoor light intensity at different vertical positions of the windowsill in residential buildings (Figure 6A) indicate that the indoor lighting environment on the south side is significantly better than that on the north side. As the horizontal position of the windowsill changes, the average, minimum, and maximum values of indoor light intensity do not show significant changes. The average illuminance is highest when the windowsill is centrally positioned, with an average illuminance of 1,411 lx, and which also corresponds to the highest median value. In contrast, the lowest average indoor illuminance occurs when the windowsill is positioned farthest to the right, i.e., 1.8 m to the right of the central position, with an average value of 1,333 lx. The maximum difference in average indoor illuminance across all conditions is 78 lx, the minimum difference is 31 lx, and the maximum difference is 1,263 lx. Overall, as the windowsill shifts from the central position of the wall to the left or right sides, the indoor lighting environment decreases slightly, but the decrease is not significant. The maximum, minimum, average, and median values do not indicate a significant reduction. Within the range of −0.9–1.5 m, the light blue and red areas of the indoor lighting zone do not differ significantly (Figure 6B).

Indoor light intensity uniformity and satisfaction levels vary with the horizontal position of the windowsill (Figure 6C). When the horizontal position of the windowsill is centered to the right, the uniformity of light intensity is significantly better than on the left side. When the horizontal position is between −1.5 and −0.6 m, the closer the horizontal position is to the central position, the better the uniformity of indoor light intensity. However, when the horizontal position is between 0.5 and 1.8 m, the uniformity is less affected by the horizontal position. The uniformity is best within the range of −0.6 and 0.6 m. Additionally, the relationship between the horizontal position of the dwelling windowsill and indoor lighting satisfaction follows a Dose–Response model (Equation 5), with a coefficient of determination $R^2 = 0.96$, and fits a polynomial model. The fitted equation of the curve is:Sat

$$\mathrm{Sat} = 0.29 * x + 1.14 * x^2 \tag{5}$$

where: Sat represents indoor lighting satisfaction, and x represents the horizontal position of the dwelling windowsill.

The overall indoor satisfaction level is good, with satisfaction exceeding 50% under all conditions. Satisfaction follows a symmetrical distribution trend, meaning that indoor lighting satisfaction is optimal at the horizontal center position. Within the range of −0.6 to 0.6 m, satisfaction is also optimal. As the position shifts further to either side, indoor satisfaction decreases. Therefore, positions within a 0.6 m range to the left or right of the horizontal windowsill position are considered relatively ideal locations.

## 4.2 Research on window size optimization

The distribution of indoor light intensity in residential buildings with different horizontal window dimensions (Figure 7A) shows that as the horizontal dimension of the window increases, the area with a light blue color on the plane (≥1,235 lx) red areas (≥3,210 lx) also significantly increase, and the lighting conditions in the northern part of the room are notably improved. When the horizontal window size is 0.3 m, the area with indoor light intensity exceeding 1,630 lx accounts for less than one-fifth of the total area, while when the window size is 3.6 m, it approaches half. The lowest indoor light intensity occurs at condition 0.3 m, with an average value and median of 516 lx and 73 lx, respectively. The average values are 0.38 and 0.24 of those at 1.8 m and 3.6 m, respectively, while the medians are 0.39 and 0.25 of those at 1.8 m and 3.6 m, respectively. For every 0.3 m increase in the horizontal dimension of the window, the average indoor light intensity also increases by 150–200 lx, and the minimum indoor value increases by 2–5 lx. Research has found that when the horizontal dimension exceeds 3.3 m, further increases in dimension continue to improve the indoor light environment, but the improvement is far less significant than when the dimension is increased by 0.3 m (Figure 7B).

When the horizontal dimension of the window is between 0.3 and 2.1 m, the uniformity of indoor lighting increases significantly as the dimension increases. When the dimension continues to increase to 3.6 m, the uniformity first decreases and then increases. The uniformity is best when the horizontal dimension is 2.1 m (Figure 7C). Additionally, the relationship between the horizontal size of dwelling windows and indoor lighting satisfaction follows an ExpDecl model (Equation 6), with a coefficient of determination $R^2 = 0.99$, and fits a polynomial model. The fitted equation of the curve is:

$$\mathrm{Sat} = -53.73 * \exp\left(-\frac{x}{1.39}\right) + 70.63 \tag{6}$$

where: Sat represents indoor lighting satisfaction, and x represents the horizontal size of the dwelling windows.

Satisfaction increases with window dimensions; however, the rate of improvement diminishes as dimensions become larger.

The simulation results of indoor lighting in residential houses with different vertical window sizes show that (Figure 8A), with the increase of vertical window size, the indoor areas represented by light blue (≥1,235 lx), yellow, and red regions increase significantly. When the vertical size of the window is 0.3 m, less than one-fifth of the indoor area of these areas, and when the size is 2.1 m, the area of these areas is close to half of the area of the indoor lighting environment has been significantly improved, but in the area near the north side, there is still nearly one-fifth of the area with dark blue color, i.e., light intensity <445 lx. Significantly improved, but near the north side of the area, there are still nearly one-fifth of the area of the color of dark blue, that is, the light intensity <445 lx. At the same time, in the period of 0.3–1.2 m, when the vertical size of the window increases, the increase in the area of indoor red area is more significant than 1.5–2.4 m, indicating that with the increase of the vertical size of the window to 1.5 m, although the length of the window continues to increase, it is not easy to increase the length of the window, but it is easy to increase the length of the window to 1.5 m. This indicates that as the vertical size of the window increases

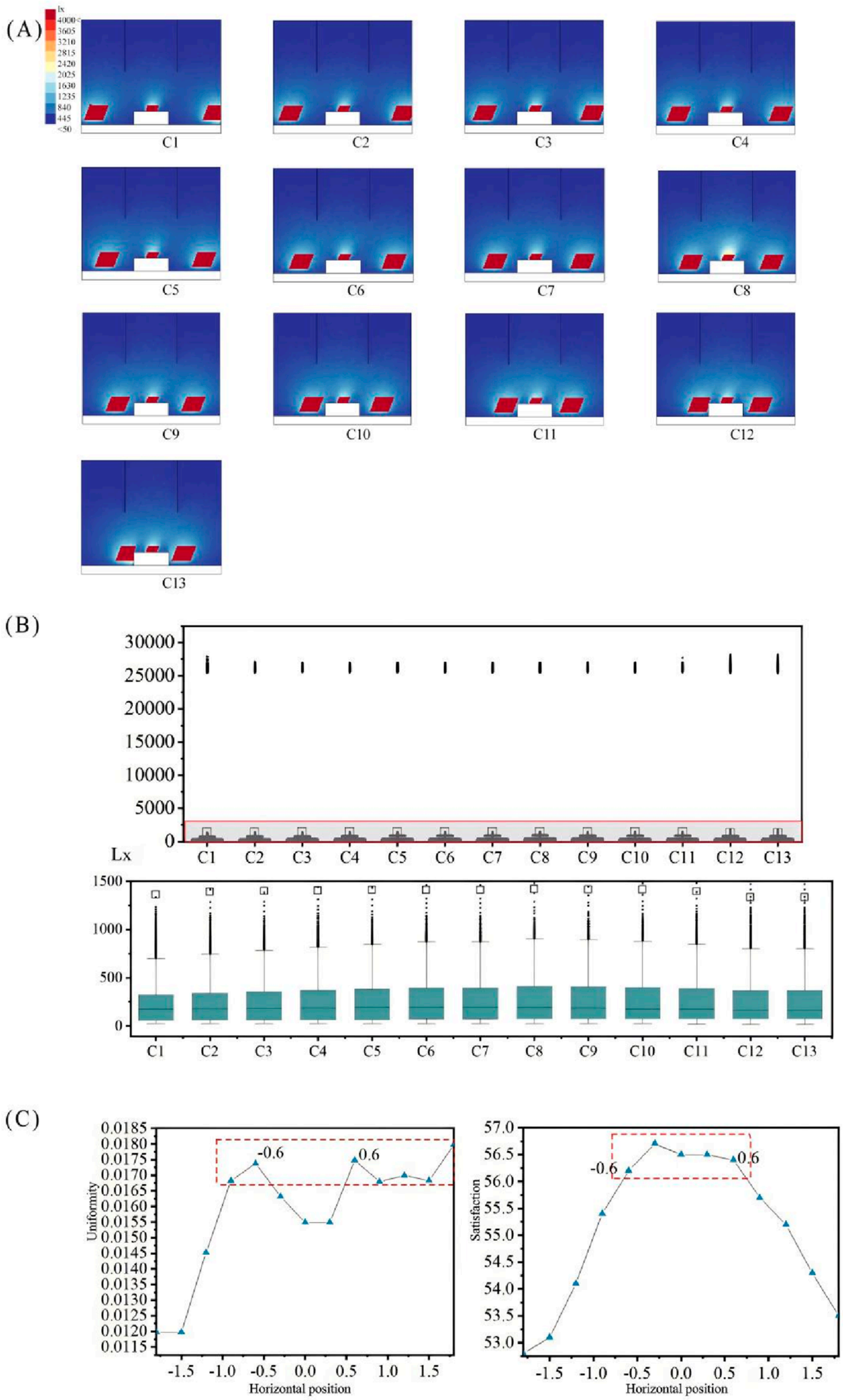


FIGURE 6
Different horizontal position of the window sills **(A)** Simulation results of indoor lighting in residential buildings with different window sill levels **(B)** Distribution of indoor light intensity in residential buildings at different vertical positions of window sills **(C)** Satisfaction with indoor light intensity and uniformity as a function of vertical position on the window sill.

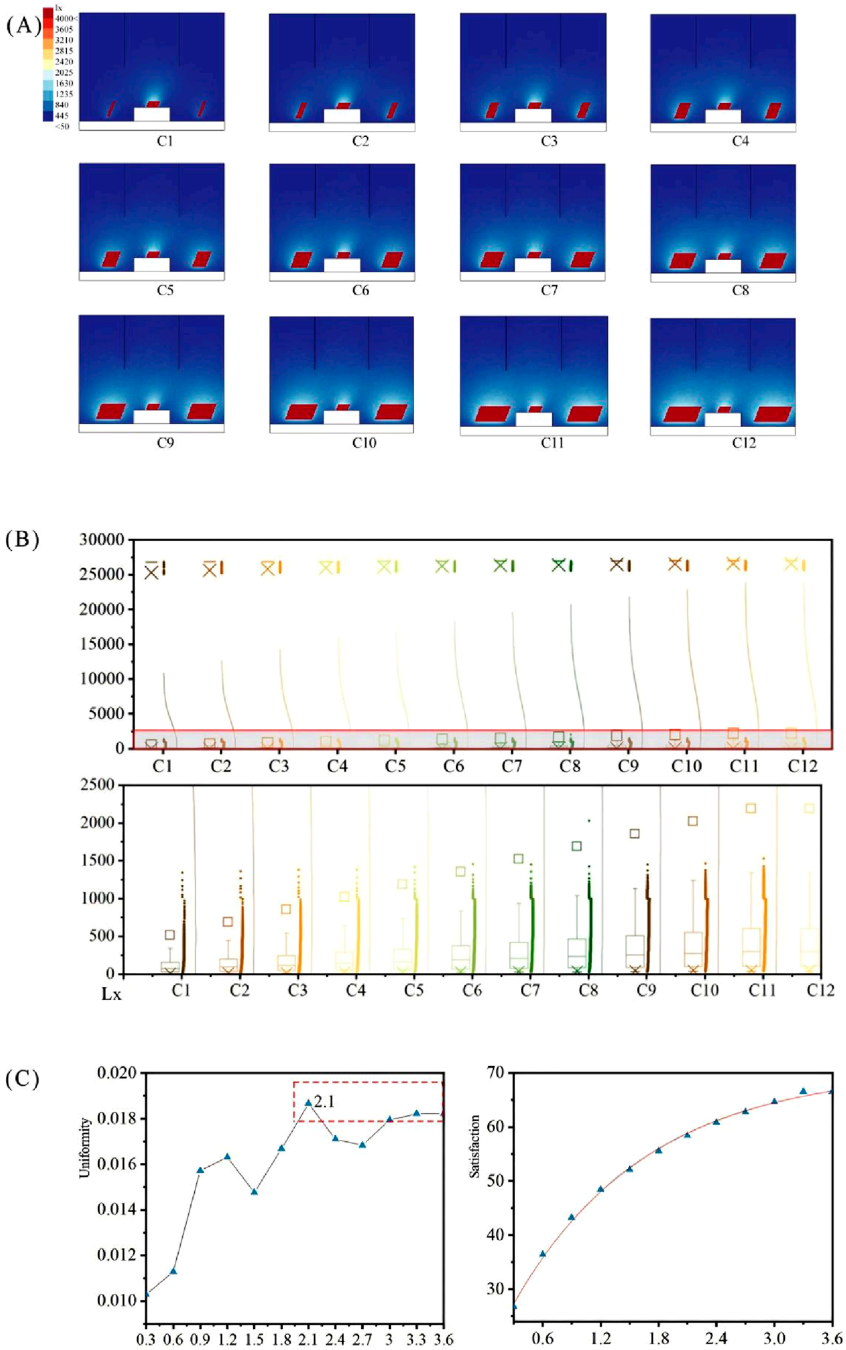


FIGURE 7
Different horizontal dimensions of window sills **(A)** Simulation results of indoor lighting in residential buildings with different horizontal window dimensions **(B)** Distribution of indoor light intensity in residential buildings with different horizontal window dimensions **(C)** Satisfaction with indoor light intensity and uniformity as a function of window horizontal dimensions.

at 1.5 m, the length of the window continues to increase, which further improves the indoor environment, but the effect is worse than that in the range of 0.3–1.2 m.

The results of the distribution of indoor light intensity in residential houses with different vertical sizes of windows show that (Figure 8B), the maximum value of indoor light intensity in each working condition does not have much difference, while the mean and median increase with the increase of vertical size of the window, and when the vertical size of the window is increased from 0.3 m to 0.6 m, 0.9 m and 1.2 m, the mean light intensity increases by 285 lx, 224 lx and 2174 lx, but when increasing from 1.2 m to 0.02 m, the increase is 25 lx, 13 lx, 9 lx, 4 lx, respectively. At the same time, with the increase of vertical size of the window, the minimum value of the indoor light intensity increases gradually and the increase is

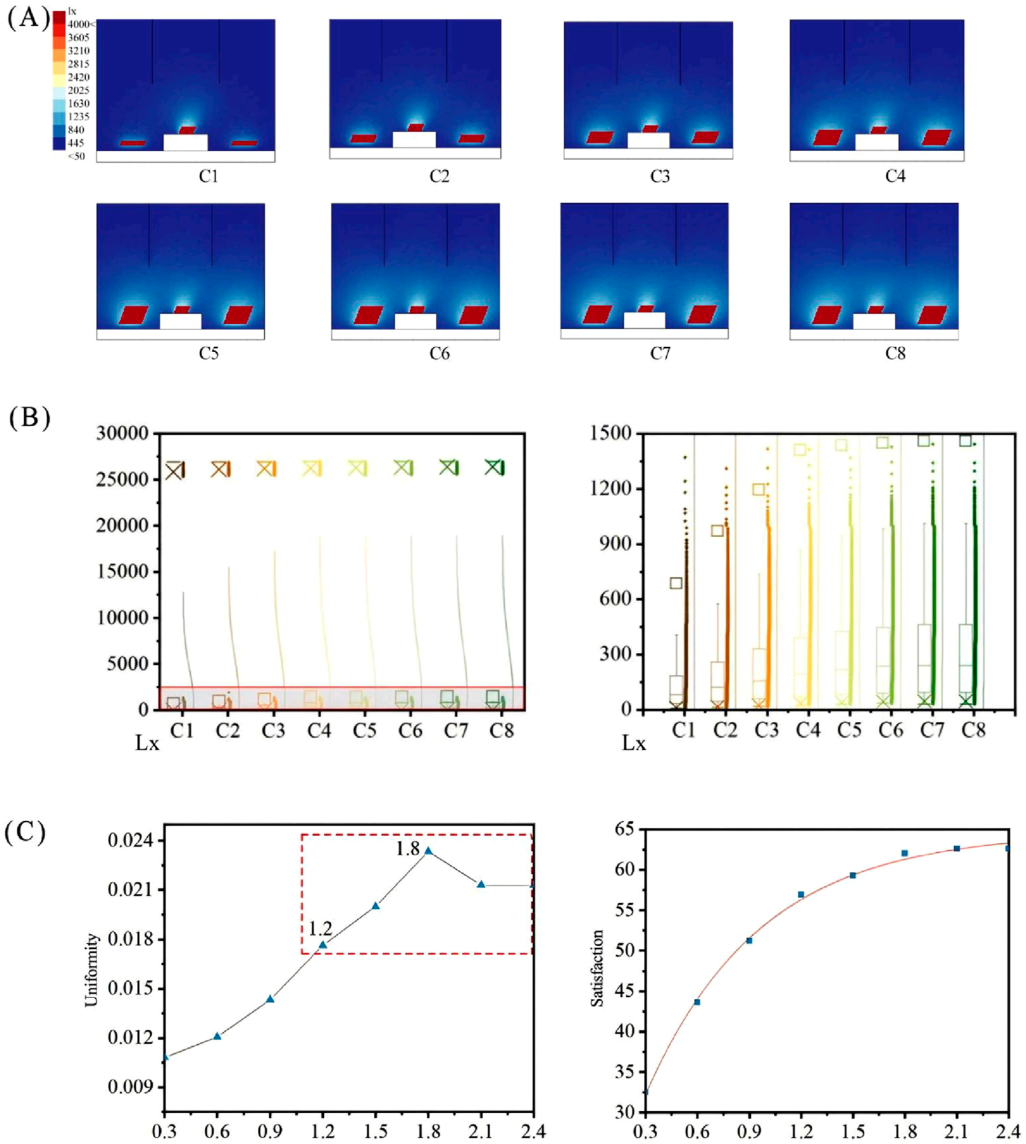


FIGURE 8
Different vertical dimensions of window sills **(A)** Simulation results of indoor lighting in residential buildings with different vertical dimensions of windows **(B)** Distribution of indoor light intensity in residential buildings with different vertical window dimensions **(C)** Satisfaction with indoor light intensity and uniformity as a function of window vertical dimensions.

3–5 lx. The maximum value of the illuminance under each working condition is not much different. The difference is not significant. Therefore, under the condition that other factors remain unchanged, increasing the height of windows with vertical dimensions less than 1.2 m can significantly improve the indoor light environment if the conditions permit, and increasing the height of windows with heights more than 1.2 m to improve the light environment has a general effect.

Therefore, considering indoor illuminance, satisfaction, and lighting uniformity, it can be concluded that when the vertical height of the window reaches at least 1.2 m, the interior daylighting conditions of the dwelling are significantly improved.

Indoor lighting intensity satisfaction and uniformity as a function of window vertical dimensions (Figure 8C). The uniformity of indoor lighting increases with the growth of window size, reaching a peak at 1.8 m before slowly decreasing. Under all conditions, the improvement in uniformity is not significant. In natural lighting conditions, the uniformity of indoor lighting in the traditional earthen dwellings of Laodong Village is very poor. Within the selected range, the uniformity of indoor lighting is best when the vertical window size is 1.8 m. Additionally, the relationship between the vertical size of dwelling windows and indoor lighting satisfaction follows an ExpDecl model (Equation 7), with a coefficient of determination $R^2$ = 0.99, and fits a polynomial model. The fitted equation of the curve is:

$$\mathrm{Sat} = -50.98 * \exp\left(-\frac{x}{0.66}\right) + 64.68 \tag{7}$$

where: Sat represents indoor lighting satisfaction, and x represents the vertical size of the dwelling windows.

Within the vertical window size range of 0.3–2.4 m, there is a significant positive correlation with satisfaction. Indoor lighting satisfaction increases with the height of the windowsill, but as the vertical window size increases, the increase in satisfaction per 0.3 m of height gradually decreases. Therefore, considering indoor illuminance, satisfaction, and uniformity, a window vertical height of at least 1.2 m ensures a good lighting environment in residential interiors.

## 4.3 Research on the optimization of eaves dimensions

Simulation results of indoor lighting in residential buildings with different eave overhang dimensions (Figure 9A) indicate that as the eave overhang dimension increases, the areas of light blue, yellow, and red in the indoor lighting significantly decrease. At a dimension of 0.6 m, the light blue area exceeds half of the indoor depth, and at 1.2 m, the light blue area only appears on the southern half of the depth. Additionally, the lightest-colored area in the indoor space near the northern side is the central location, i.e., the main hall, while the areas on either side of it are the regions with the poorest indoor lighting.

The simulation results of indoor light intensity of residential houses with different eave projection sizes show that (Figure 9B), with the increase of eave projection size, the average and maximum values of indoor light intensity decrease significantly, among which the average and maximum values are the highest at 0.6 m, which are 1731 lx and 48516 lx, respectively, and the smallest at 1.6 m, which are 702 lx and 26084 lx, respectively. In addition, for every 0.2 m increase in eave outreach size, the average light intensity decreases by 200–300 lx; for the decrease in maximum light intensity, the maximum value exceeds 47,472 lx for eave outreach sizes of 0.6–1.2 m, and for every 0.2 m increase in eave outreach size, the maximum light intensity decreases by 10 lx, and for every 0.4 m increase in eave outreach size, the maximum light intensity decreases by 10 lx. When the extension size increases from 1.2 m to 1.4 m, the maximum light intensity decreases by 21389 lx.

Accordingly, considering the survey results, the most common eaves projection size in the Raw Earth dwellings of Laodong Village is 1 m, which lies within a relatively optimal range for daylighting performance. Taking indoor lighting satisfaction, illumination uniformity, peak intensity, and mean illuminance as core evaluation metrics—and further considering the practical functional use of the eaves by residents—it is concluded that, from the perspective of the indoor light environment alone, an eave length between 0.8 and 1.2 m can be deemed a suitable and effective design range.

The results on indoor lighting satisfaction and uniformity under varying eave overhang sizes (Figure 9C) indicate that indoor light uniformity remained poor across all eave conditions, with the maximum value below 0.03. As the eave projection increases, the lighting uniformity improves significantly; however, once the eave projection reaches 1.4 m, no further improvement is observed. Field surveys indicate that traditional Raw Earth dwellings in Laodong Village commonly feature eaves extending about 1 m, at which point the lighting uniformity remains within an acceptable but moderate range. Additionally, when the eave projection ranges from 0.6 to 1.4 m, the relationship between the eave projection and indoor lighting satisfaction follows an ExpDecl model (Equation 8), with a coefficient of determination $R^2 = 0.93$, and fits a polynomial model. The fitted equation of the curve is:

$$\mathrm{Sat} = -18.38 * x + 1.70 * x^2 \tag{8}$$

where: Sat represents indoor lighting satisfaction, and x represents the eave projection.

Showing a significant negative correlation. As the eave length increases, satisfaction with indoor lighting decreases. When the eave projection surpasses 1.4 m, satisfaction falls below 50%, whereas at 0.6 m, satisfaction peaks above 60%. Therefore, it is recommended that the eave overhang in Laodong Village's traditional Raw Earth dwellings should not exceed 1.4 m.

## 4.4 Passive daylighting technology

Before delving into the proposed passive daylighting technologies, it is crucial to understand the typical roof construction of traditional Raw Earth dwellings in Western Hunan, as this directly influences the feasibility and effectiveness of any roof-based interventions. These vernacular buildings commonly feature a timber-frame structure that serves as the primary support for the roof. The roof itself is typically constructed with a robust wooden rafter system, over which layers of small, dark grey tiles are laid. This traditional roofing method results in a relatively lightweight, non-load-bearing roof structure that is independent of the Raw Earth walls for vertical support. The inherent flexibility and modularity of this timber-tile system are advantageous for modifications. Specifically, the existing timber grid allows for the integration of new elements such as skylights or the replacement of opaque tiles with translucent ones, without compromising the overall structural integrity or requiring extensive structural reinforcement. This understanding underpins the viability of the proposed roof-based daylighting solutions.

Passive lighting technologies represent one of the most commonly employed approaches to improving indoor daylight conditions in traditional residential dwellings (Juffle et al., 2023). These techniques not only enhance indoor illuminance levels but also align with the residents' demand for cost-effective solutions. Field investigations indicate that certain Raw Earth dwellings in Laodong Village feature translucent roofing tiles; however, due to limitations in material availability and construction techniques, their adoption remains relatively limited. Beyond optimizing window positioning and dimensions, this study incorporates several established passive daylighting techniques and evaluates their applicability and effectiveness (Teo et al., 2023). In consideration of the architectural conservation requirements of Laodong Village's traditional Raw Earth dwellings, targeted passive lighting improvement strategies are proposed.

Light-guiding prism windows are typically installed on roofs or walls. Outdoor light is refracted into the interior through the prisms, effectively improving the lighting conditions in areas of the interior that are distant from windows (Huang et al., 2022). However, the cost is often relatively high. Reflective panels, on

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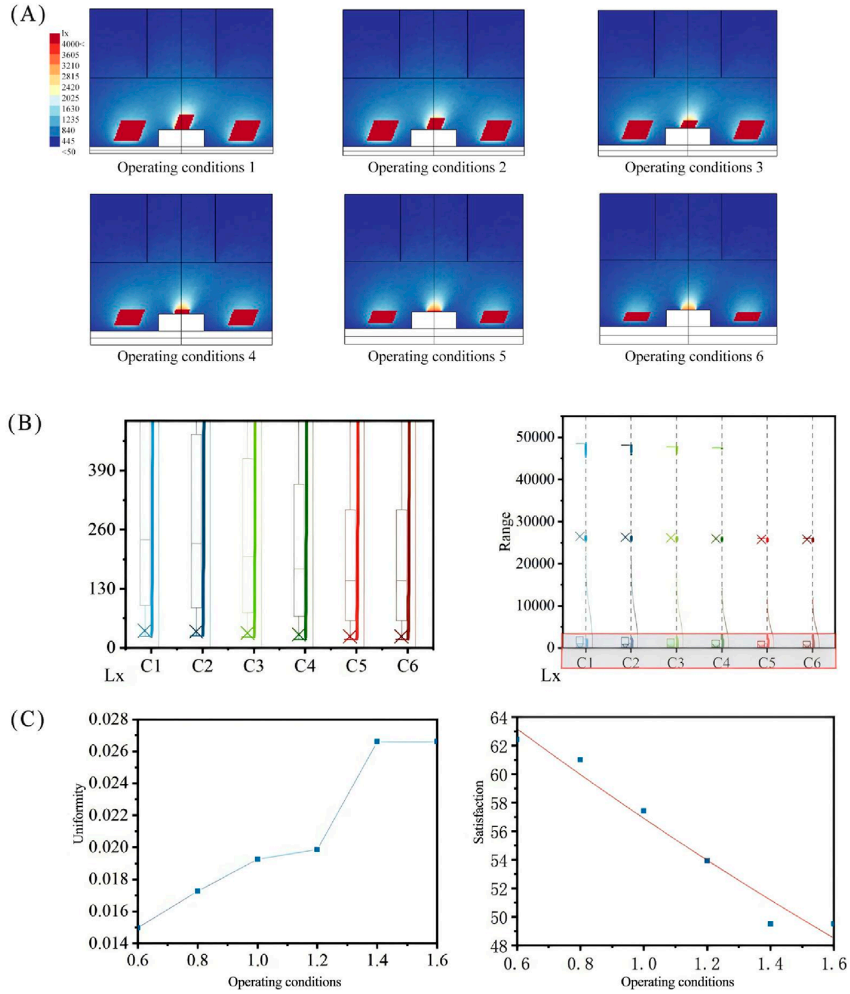


FIGURE 9
Different eave size sills **(A)** Simulation results of indoor lighting in residential buildings with different eaves overhang dimensions **(B)** Distribution of indoor light intensity in residential buildings with different eaves overhang dimensions **(C)** Satisfaction with indoor light intensity and uniformity as a function of eave projection size.

the other hand, use high-reflectivity materials to reflect outdoor light and improve indoor lighting conditions. Multiple reflective panels can be installed for multiple reflections, often requiring adjustment of the panels' angles to direct light to the desired areas (Ghafarpoor et al., 2025). This can effectively enhance indoor lighting uniformity and intensity. However, light manipulation is often complex, and improper handling may cause glare (Byun et al., 2018). If the wrong materials are selected, reflected light could pose a fire risk if it hits flammable items indoors. Light pipes operate on a principle like that of light prism windows, but light pipes can typically be adjusted to control the amount of light introduced. Active light pipes can also adjust based on the angle of the sun, though active light pipes are more expensive. Skylights are a common modern daylighting method, typically involving direct windows in the roof to introduce outdoor light (Bagdonas et al., 2022). However, they can cause glare. An improved version includes manual roller blinds to control the amount of light introduced, though this adds cost compared to standard skylights. Skylights are the most common passive daylighting method in residential buildings (Jia et al., 2023). Skylights are typically made of transparent materials such as glass and are installed on the rafters of residential buildings. They provide shelter from wind and rain while introducing natural light into the interior, improving insufficient indoor lighting. Their dimensions are typically 0.18 m × 0.3 m. They also exist in Raw Earth dwellings in Xiangxi region but are not widely used and are more commonly found in other types of residential buildings in Xiangxi. Combining traditional residential architectural style preservation, skylights and skylight passive daylighting technology can improve indoor lighting conditions while being cost-effective and not damaging the architectural style (Wu et al., 2024).

Translucent roof tiles and skylights are effective strategies for improving the indoor environment of traditional Raw Earth dwellings in Laodong Village. While enhancing indoor environmental quality, they also minimize disruptions to the original architectural appearance. Moreover, translucent tiles are commonly used in Xiangxi vernacular housing and are generally well accepted by local residents (Xu and He, 2013).

Skylights as a common form of modern daylighting, are highly efficient in introducing natural light into indoor spaces, though they are susceptible to causing glare (Kwong, 2020). The installation of manual blinds can help control light intensity; however, this solution increases overall construction costs. A skylight design placed between roof purlins significantly enhances full-day illumination while avoiding adverse impacts on the thermal insulation and envelope performance that could result from enlarging wall openings. Skylights are therefore most appropriate for primary spaces that require substantial and efficient improvements in lighting conditions (Stetsky et al., 2024). Additionally, their placement on the roof contributes to a more stable thermal indoor environment.

As a traditional passive daylighting method, translucent tiles serve both to shield from wind and rain and to introduce natural light. They have a basis of application in Xiangxi vernacular dwellings and are widely accepted by residents. Translucent tiles significantly improve indoor lighting; however, due to their small individual size, a large quantity (often more than 10 units) is required to meet the lighting demands of large spaces such as bedrooms or central halls. Moreover, the uncontrollable amount of incoming light may interfere with daily activities. It is therefore recommended that translucent tiles be prioritized for use in storage rooms, bathrooms, and utility spaces to improve localized illumination without compromising the main living spaces (Kononova et al., 2020).

# 5 Conclusion and suggestions

The 20th National Congress of the Communist Party of China proposed a national strategy to proactively address population aging (Zhan and Xizhe, 2020). Creating an age-friendly living environment has since become a critical societal challenge. Traditional raw-earth dwellings no longer meet the living needs of the older adult. Meanwhile, the rapid socio-economic development in rural Xiangxi has accelerated construction activities, exposing numerous issues including irrational planning, degradation of traditional village character, severe environmental pollution, excessive energy consumption, and outdated construction techniques (Havaei and Malekitabar, 2025).

This study explores the optimization of indoor lighting in Raw Earth dwellings in Western Hunan using window dimension sensitivity and passive daylighting techniques. The results demonstrate significant improvements in lighting uniformity and visual comfort for older adult residents, with implications for age-friendly housing design in rural areas.Through the quantitative evaluation of the optimization strategies, we found that adjusting window sizes can significantly improve the indoor daylighting performance of raw earth dwellings in Western Hunan. Specifically, under typical overcast conditions, the average illuminance of the optimized living room increased from a baseline of 50 lx–250 lx, far surpassing the minimum requirement of 150 lx for living rooms as specified in the Design Code for Buildings for the older adult. Moreover, illuminance uniformity improved, significantly enhancing the even distribution of light, which is crucial for daily activities such as reading and walking, particularly for older adult residents. These quantitative results strongly validate the effectiveness and feasibility of the strategies proposed in this study, providing a solid scientific foundation for the modernization of raw earth dwellings. The main conclusions are as follows:

1. Window position: Studies have shown that in the vertical position, the height of the windowsill can significantly affect the indoor lighting performance. When the height of the windowsill is 0.6–1.5 m, the satisfaction of indoor light is the highest (>50%), and the distribution of light intensity is good; after exceeding 1.5 m, the satisfaction tends to decrease linearly (<40%). In the horizontal position, the average indoor illuminance is optimal when the window is centered (1,411 lx), the offset is within the range of ±0.6 m, which has less influence on the lighting. It is recommended that the vertical height of the bay window of 0.6–1.5 m be preferred and combined with the horizontal centered layout to balance the comfort of the light environment and the need for traditional landscape protection.
2. Window size: The horizontal size of the windows is positively correlated with the light intensity in the room, with an increase of 0.3 m resulting in an increase of 150–200 lx in the average illumination; the uniformity of illumination is optimal at a horizontal size of 2.1 m, and the improvement tends to slow down after 3.3 m. The increase in vertical size significantly improves the light intensity in the north zone, but the marginal benefit decreases significantly after 1.2 m (increase <25 lx/0.3 m). The increase in vertical dimension significantly improves the lighting in the north area, but the marginal benefit decreases significantly after 1.2 m (<25 lx/0.3 m). Combining economy and light efficiency, it is recommended that the horizontal dimension be controlled at 2.1–3.3 m and the vertical height not less than 1.2 m, to balance the lighting efficiency and construction feasibility.
3. Eave Size: Increasing eave projection reduces indoor illumination significantly. Each 0.2 m increase lowers average illuminance by 200–300 lx, with the maximum drop reaching 21389 lx (in the 1.2–1.4 m range). Lighting satisfaction negatively correlates with eave length ($R^2 = 0.962$); it falls below 50% at 1.4 m. A range of 0.8–1.2 m is recommended to ensure shading while preserving adequate lighting (average >700 lx).
4. Passive lighting technology: Tiles and skylights are the most suitable passive technology for traditional houses. Skylight lighting efficiency is 3 times that of side windows, which can significantly increase the area above 300 lx (about 100%), but need to avoid the problem of glare; open tiles are suitable for local areas (e.g., storage rooms), and a single size of 0.18 m × 0.3 m requires ≥10 tiles to satisfy the functional requirements. It is recommended to give priority to the use of skylights combined with adjustable sun shading devices and supplemented with bright tiles in non-main activity areas to optimize the light environment at a low cost, while retaining the traditional architectural style to the maximum extent possible.
5. Limitations and Outlook: Seasonal variations (e.g., winter solstice angles) and long-term material degradation were not fully modeled. Further studies should incorporate subjective feedback (e.g., skylight acceptance) and thermal-light interaction analysis. Future work will include occupant behavior mechanisms and improved multi-objective

optimization models.n this study, a one-factor-at-a-time approach was primarily employed, whereby only a single factor was examined at a time. As a result, potential interactions among different variables could not be fully revealed. To overcome this limitation, future research will incorporate multi-factor experimental designs, focusing on the interactions among key parameters such as window height and eave depth. This methodological enhancement will enable a more systematic assessment of the synergistic effects of multiple factors on the indoor lighting environment, thereby providing a more scientifically robust and comprehensive basis for optimizing daylighting performance in residential spaces.

Through parametric simulations, this study systematically reveals the sensitivity of indoor daylighting performance to window geometric parameters in raw earth dwellings. As window height increases, the indoor average illuminance shows a significant linear increase, while uniformity reaches an optimal level within a specific range. For example, when the window height increases from 0.8 m to 1.6m, the average illuminance rises from 50 lx to 200 lx, thus improving the indoor daylighting level to better meet the minimum illuminance requirements for older adult living spaces as specified in the Design Code for Buildings for the older adult (e.g., 100 lx for bedrooms and 150 lx for living rooms). Additionally, we found that windowsill height has a critical impact on indoor daylighting uniformity. A windowsill that is too high prevents light from penetrating deeply into the room, creating stark light-dark contrasts. However, controlling the windowsill height between 0.6 m and 0.9 m effectively enhances light penetration depth and distribution uniformity, which is crucial for preventing falls and reducing visual fatigue in older adult residents. Furthermore, there is a complex interaction between eave depth and window height. Excessive eave depth significantly weakens the daylighting benefits brought by high windows. Therefore, both factors must be considered together in design to avoid excessive shading. These findings not only provide specific optimization parameters but also reveal key design strategies for improving age-friendly daylighting performance in raw earth dwellings. They offer quantitative evidence for the protection and development of traditional villages in the context of rural revitalization.

The daylighting improvement strategies proposed in this study aim not only to enhance residential comfort but also align closely with the national “Rural Revitalization Strategy” and the goal of creating livable villages, which emphasize “views of mountains and rivers and retaining the village’s cultural memory.” When implementing these modifications, careful consideration must be given to balancing the enhancement of daylight performance with heritage preservation, thermal performance, construction feasibility, and socio-economic impacts. While increasing window sizes can significantly improve daylighting, it may also lead to higher winter heat losses and overheating from solar radiation in the summer. To address this, it is recommended to use double-glazed or low-emissivity glass in combination with traditional adjustable shading elements (such as external louvers and deep eaves) to balance daylighting with thermal performance. Furthermore, the introduction of skylights and translucent tiles can effectively improve lighting in deeper parts of the room, but in humid climates, their durability, waterproofing, and maintenance costs must be considered. All retrofit solutions should prioritize locally available materials and techniques compatible with raw earth construction, while fully respecting the preferences and traditional building wisdom of local residents, ensuring the sustainability of the retrofit and the endogenous development of the community. Future research should explore multi-objective optimization methods to quantitatively assess the best design solutions under multiple goals, including daylighting, thermal performance, structural safety, and heritage value, and incorporate national standards such as the Building Daylighting Design Code and the Design Code for Buildings for the older adult, providing more comprehensive technical guidance for age-friendly retrofits of raw earth dwellings.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Author contributions

LS: Supervision, Investigation, Writing – review and editing, Formal Analysis, Data curation, Software, Writing – original draft, Methodology, Conceptualization. ZZ: Conceptualization, Data curation, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review and editing. FZ: Resources, Validation, Formal Analysis, Writing – review and editing, Supervision. SL: Formal Analysis, Methodology, Supervision, Writing – review and editing. YC: Investigation, Methodology, Visualization, Writing – original draft.

## Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This work was supported by the (China National Key Research and Development Program Project), under Grant (2024YFD1600405-5) and (China National Key Research and Development Project), under Grant (2024YFD1600401-04).

## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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