ANALYSIS OF INDOOR THERMAL ENVIRONMENT AND HUMAN THERMAL COMFORT IN RURAL RESIDENCES OF NORTHERN HENAN, CHINA

by

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To address inadequate winter indoor thermal comfort in rural areas of northern Henan, China, this study carried out field investigations in a representative village in Jiaozuo. The underlying factors contributing to low indoor temperatures in rural dwellings were analyzed, and neutral temperatures along with acceptable thermal comfort ranges for different age groups were determined based on thermal sensation votes. The results reveal that winter indoor temperatures in older houses are critically low, averaging 5.99 °C and 4.09 °C, which do not satisfy basic thermal comfort requirements. Both older and newly constructed residences experience substantial heat loss through exterior walls, with interior surface temperatures consistently lower than indoor air temperatures. Furthermore, neutral temperatures and the 90% acceptable thermal comfort ranges increase with age: 14.97 °C (13.73-16.11 °C) for youth, 15.57 °C (14.27-16.86 °C) for middle-aged adults, and elderly, 16.70 °C (15.30-18.12 °C) for the elderly. These findings underscore the importance of integrating age-specific thermal requirements into energy-efficient residential retrofit strategies to improve thermal comfort while reducing heating energy demand, providing a scientific basis for formulating local thermal environment standards and targeted renovation policies for rural housing in Northern Henan.

Keywords: *indoor thermal environment, rural residences, northern Henan province, thermal sensation vote, thermal comfort, thermal adaptability*

Introduction

Rural residential buildings in China have undergone substantial improvements in living standards over recent decades, accompanied by rising expectations for indoor thermal comfort. However, these improvements have also driven a steady increase in building energy consumption, intensifying the tension between enhanced thermal comfort and low-carbon development, particularly in rural areas. According to the Annual Development Research Report on Building Energy Efficiency in China, 2023, rural residential buildings consumed approximately 232 million tons of standard coal in 2021, accounting for 20.9% of total building energy use, with corresponding carbon emissions of about 490 million tons of CO_2 [1]. Balancing

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thermal comfort requirements with energy efficiency has therefore emerged as a critical issue for sustainable rural development. Field studies indicate that, despite substantial energy use, winter indoor thermal environments in many rural regions remain inadequate and often fail to meet occupants' comfort sneeds [2]. Given China's vast geographic extent and pronounced climatic diversity, rural indoor thermal conditions vary considerably among regions, underscoring the importance of region-specific assessments to support context appropriate, energy-efficient design and retrofit strategies for rural housing.

Currently, studies have examined indoor thermal environments and thermal comfort in rural dwellings through field measurements, questionnaire surveys, and on-site monitoring [3]. For instance, Wang *et al*. [4] conducted field monitoring in a typical rural dwelling in Tianjin and reported that primary activity areas frequently failed to achieve acceptable thermal comfort. Zhang *et al*. [5] investigated winter indoor thermal conditions in representative old and new dwellings in Xihaigu using combined measurements and surveys, identifying variations in thermal environments and their underlying causes. Based on research on existing rural housing in Xuzhou, He [6] developed a thermal comfort model for residents, analyzed key factors affecting comfort and energy consumption, and proposed an optimized, energy-efficient retrofit strategy, although its high implementation cost remains a limitation. Wu [7] focused on elderly residents in Xianjiangtou Village Guilin, and determined thermal neutral temperatures, preferred temperatures, and acceptable comfort ranges using integrated measurement and survey approaches. To address winter thermal discomfort and high energy use in Sanjia Village of northeast China, Wu [8] identified a thermal neutral temperature of 15.9 °C and a comfort range of 13.7-18.2 °C through field investigations. Shi [9] examined rural dwellings in Nantong and proposed an optimized retrofit scheme, that increased winter indoor temperatures by 7.07 °C while achieving an energy-saving rate of 57.41%, although retrofit costs remained high. The geographic distribution of these studies is summarized in fig. 1 and tab. 1. Although existing research provides valuable insights into rural indoor thermal environments, dwellings in the Central Plains of China, particularly in northern Henan, remain insufficiently represented. Moreover, residents' thermal comfort temperatures, especially age-related differences and differentiated comfort requirements, have not been comprehensively investigated.

Northern Henan lies within a cold climate zone, where average outdoor temperatures during the coldest month range from –2~2 °C, indicating substantial winter heating demand. Unlike severe-cold regions with centralized heating, rural households in this area primarily rely on short-duration, intermittent heating using split-type air conditioners, leading to a persistent mismatch between heating demand and actual heating practices. Under these limited-heating conditions, age-related differences in thermal comfort have not been systematically quantified. In response, this study conducts a comprehensive field investigation of winter indoor thermal environments and thermal comfort in rural residences in northern Henan. By integrating questionnaire surveys, on-site thermal measurements, and thermal sensation experiments, age-specific thermal neutral temperatures and acceptable comfort ranges are quantified. The primary contributions of this study are twofold: first, it provides empirical evidence on winter indoor

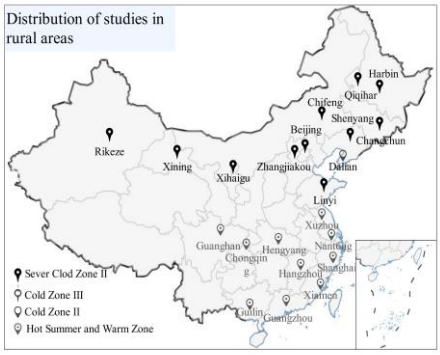

Figure 1. Distribution of studies in rural areas

thermal environments and thermal comfort in cold-climate rural housing of the Central Plains; second, it identifies pronounced age-dependent differences in thermal neutrality and comfort requirements, highlighting the heightened thermal vulnerability of elderly residents. These findings offer region-specific and age-sensitive guidance for energy-efficient retrofits and the development of adaptive thermal environment standards for rural housing in cold-climate regions.

Table 1. Research area distribution

References	Research area	Research content
[10]	Changchun	A field study was conducted to investigate thermal comfort and adaptive behaviors of rural residents in severe cold regions of Northeast China
[11]	Shenyang	A study was conducted using CFD simulation to investigate the passive regulation effect of newly-added sunspace on the indoor environment of rural residences
[12]	Harbin	The indoor air quality challenges brought about by the decentralized heating method of rural elderly people in cold regions of China were studied by using the method of field monitoring
[13]	Guanghan	The energy consumption pattern and indoor environment of rural families were studied by using the method of questionnaire survey
[14]	Chongqing	The influence of wheat straw addition on the heat and moisture absorption performance of rural residences, as well as the non-air-conditioned thermal environment and energy consumption of buildings was studied
[15]	Hengyang	The relationship between indoor and outdoor air temperature and relative humidity in rural areas with hot summer and cold winter was studied by using the method of field monitoring
[16]	Dalian	The optimal thermal parameters of the envelope structure and floor plan layout of rural residential buildings were studied by using the TRNSYS numerical simulation method
[17]	Yushu	The indoor environment of passive solar houses in rural areas of severe cold regions in China was studied by using the method of field investigation
[18]	Linyi	A thermal comfort model that combines physiological signals such as skin temperature, skin conductivity level and heart rate was developed by using machine learning technology
[19]	Harbin	The living patterns, heating methods, physical parameters and thermal sensations of the elderly in rural areas of Heilongjiang Province were studied by on-site monitoring

Field survey and monitoring in northern Henan rural areas

Household and dwelling characteristics survey

The study was conducted in Xishuiyun Village, Jiaozuo, northern Henan, China, with field investigations carried out between December 2024 and January 2025. To ensure data reliability, face-to-face interviews were adopted as the primary survey method. Information was collected through direct interactions with rural residents and documented using standardized questionnaires. In total, 83 households participated in the survey, accounting for 48.82% of all households in the village. Detailed characteristics of the surveyed households and dwellings are summarized in tab. 2.

Field measurements of indoor thermal environment

Field measurements were carried out during the winter heating season to evaluate indoor thermal conditions in representative rural dwellings, as shown in fig. 2. The monitoring

Table 2. Household and Dwelling Characteristics Survey

Category	Parameters
Household information	Name, education level, total household size, resident size, annual income, building energy efficiency awareness
Dwelling characteristics	Construction year, floor count, building height, orientation, floor area, building envelope composition, thermal insulation measures
Winter heating behavior	Heating equipment type, usage frequency, average daily operating hours, energy sources

focused on indoor air temperature and the interior surface temperatures of exterior walls in primary living areas, such as living rooms. Temperature sensors were installed at a height of 1.3 m above the floor, corresponding to the seated head level, in accordance with ISO 7726.

Figure 2. Typical dwellings

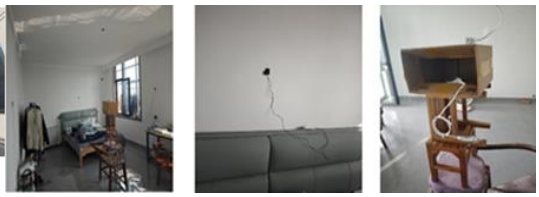

Figure 3. Schematic of indoor thermal environment monitoring

Indoor air temperature and wall surface temperature were recorded continuously at 10 minute intervals throughout the monitoring period, as illustrated in fig. 3. The sensors operated within a temperature range of −20-80 °C with an accuracy of ±0.1 °C. At the same time, relative humidity was measured over a range of 0%-99% with an accuracy of ±1.5%. All instruments were calibrated before installation to ensure data accuracy and reliability. The resulting dataset was used to characterize winter indoor thermal environments and to examine temperature differences between indoor air and building envelope surfaces.

Residential thermal comfort experiment

– Thermal sensation experiment

Thermal sensation experiments were conducted to examine residents' thermal responses under controlled indoor temperature conditions. A total of 110 local rural residents voluntarily participated in the study, fig. 4. All participants were healthy adults who had lived in the study area for more than 5 years and were therefore well adapted to the local climate. Using a random sampling approach, participants were stratified by age, with approximately 37 individuals assigned to each group: young adults (18-39 years), middle-aged adults (40-59 years), and older adults (≥60 years).

The experiments were performed in a test room where the indoor air temperature was maintained at four setpoints: 8 °C, 10 °C, 12 °C, and 14 °C. Each participant was exposed to all four temperature conditions within a single experimental session, with the order of exposure randomized to reduce potential sequence effects. Participants remained under each temperature condition for 30 minutes to allow thermal stabilization before completing the thermal sensation questionnaire.

– Thermal sensation vote and questionnaire

Thermal sensation was evaluated using the seven-point ASHRAE thermal sensation scale, which ranges from −3 (cold) to +3 (hot). Participants reported their thermal sensation immediately after each temperature exposure period. In total, 440 valid thermal sensation vote

Figure 4. Thermal comfort assessment set-up

(TSV) responses were obtained across all participants and temperature conditions. Objective environmental parameters, including air temperature, relative humidity, black globe temperature, and air velocity, were measured using the instruments listed in tab. 3.

In addition to TSV data, participants completed a brief questionnaire

Table 3. Instrumentation specifications

Instrument	Parameters	Range	Accuracy
QZWS-BX Data Logger	Air temperature	-20-80 °C	±0.1 °C
	Relative humidity	0-99 %RH	±1.5 %RH
JT2023 Anemometer	Air velocity	0-20 m/s	±0.03 m/s
TR50 Pt100 Thermometer	Globe temperature	-100-400 °C	±0.3 ℃

to collect basic demographic information, clothing insulation levels, and subjective thermal preferences. Based on the study by Li [20] on total clothing insulation across different climate zones in China, combined with calculations of actual garment insulation, the clothing insulation values for the different age groups were determined to be 1.45 clo for young adults, 1.55 clo for middle-aged adults, and 1.65 clo for older adults.

– Statistical methods

Thermal comfort was analyzed using the TSV approach based on the ASHRAE seven-point scale. To minimize data dispersion and enhance the robustness of the regression analysis, the binning method was applied to the TSV data. The operative temperature range was divided into 0.5 °C intervals. For each temperature bin *i,* the mean thermal sensation (MTS_i) was calculated using:

$$MTS_i = \frac{1}{n_i}\sum_{j=1}^{n_i} TSV_{ij} \tag{1}$$

where n_i is the number of TSV responses in bin i and TSV_{ij} – the j^{th} TSV within the bin. Linear regression analysis between MTS and operative temperature, T_{op}, was then performed for all participants and for each age group, as described in:

$$MTS = aT_{OP} + b \tag{2}$$

where a and b are the regression coefficients. The goodness of fit of the regression models was evaluated using the coefficient of determination, R^2, calculated by:

$$R^2 = 1 - \frac{\sum(y_i - \hat{y}_i)^2}{\sum(y_i - \bar{y})^2} \tag{3}$$

The thermal neutral temperature, T_n, was defined as the operative temperature at which the MTS equals zero. In accordance with the Evaluation Standard for Indoor Thermal Environment in Civil Buildings (GB/T 50785), the 90% acceptable thermal comfort range was defined by $-0.5 \leq MTS \leq +0.5$. Descriptive statistical methods were employed to summarize demographic characteristics, clothing insulation levels, and indoor environmental parameters.

– Ethics statement

All participants gave informed consent before participating in the study, and all procedures were conducted in accordance with applicable ethical guidelines.

Analysis of indoor thermal environments

Household and dwelling characteristics

– Household demographics

In Xishuiyun Village, the dominant household structures consist of *middle-aged and elderly* families and elderly couples. As illustrated in fig. 5(a), households with two to four permanent residents constitute the largest share, accounting for 59.6% of the total. Regarding economic conditions, 70.2% of households report annual incomes exceeding 50000 CNY, while 29.8% fall below this level, fig. 5(b), indicating generally improved economic circumstances in the study area. Winter heating practices are strongly influenced by local coal-ban policies. As a result, residents rely solely on split-type air conditioners for space heating. However, high electricity costs and limited heating alternatives lead most households to use air conditioners intermittently and for short periods, resulting in constrained heating throughout the winter season.

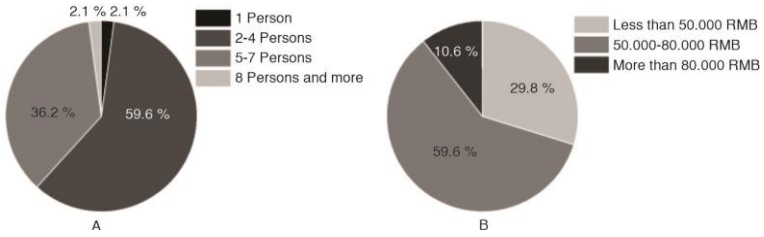

Figure 5. Distribution of permanent residents per household and annual household income

– Building envelope performance

Table 4 provides a quantitative assessment of the building envelope characteristics of rural dwellings in Xishuiyun Village. The findings reveal a high level of uniformity in envelope construction materials. All exterior walls are built with 240 mm solid clay bricks. Roof structures are predominantly composed of precast concrete slabs (91.5%), with a smaller share (8.5%) using cast-in-place concrete.

Table 4. Building envelope composition [%]

Component	Material	Proportion
External wall	240 mm solid clay brick	100%
Floor	Ceramic tiles	80.2%
	Cement screed	7.6%
	Wood flooring	13.2%
Roof	Precast concrete slabs	91.5%
	Cast-in-place concrete	8.5%
Doors	Aluminum alloy doors	73.0%
	Wood-framed doors	27.0%
Windows	Single-glazed aluminum windows	60.0%
	Wood-framed windows	22.3%
	PVC-steel windows	8.1%
	Double-glazed thermally broken windows	9.6%

Regarding floor finishes, ceramic tiles are the most prevalent material, accounting for 80.2%, followed by wood flooring (13.2%), and cement screed (7.6%). Regarding window systems, 60.0% of dwellings are fitted with single-glazed aluminum windows, 22.3% with wood-framed windows, 8.1% with PVC-framed windows, and only 9.6% with double-glazed, thermally broken aluminum windows. None of the surveyed residences incorporates additional thermal insulation measures.

As a result, the building envelope components show relatively high heat transfer coefficients (*U*-values), particularly for the brick walls, which range from 2.0-2.3 W/m^{2}K. The poor thermal performance of the envelope substantially increases operational energy demand during both winter heating and summer cooling periods.

Analysis of indoor thermal environments in winter for typical dwellings

Figures 6-8 present the temporal variations in indoor air temperature and interior wall surface temperature measured in Dwellings A, B, and C. The monitoring results demonstrate clear differences in thermal performance and corresponding indoor comfort conditions among the three dwellings.

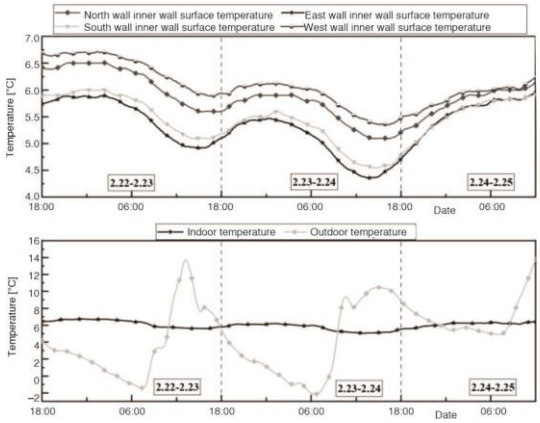

Figure 6. Temperature profiles in dwelling A

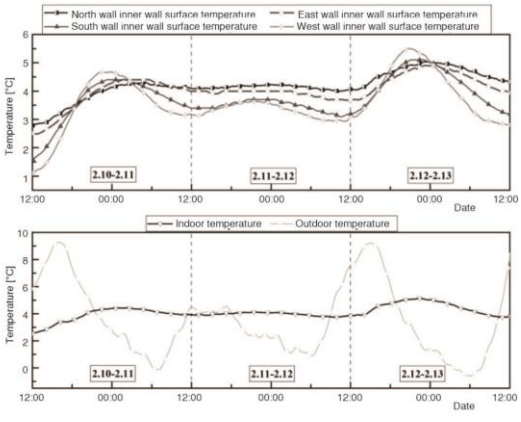

Figure 7. Temperature profiles in dwelling B

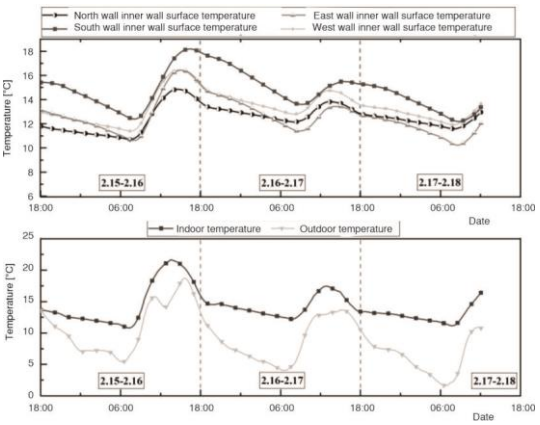

Figure 8. Temperature profiles in dwelling C

During the observation period, indoor air temperatures in dwelling A ranged from 5.03-7.06 °C, significantly below the minimum requirements specified in the Design Standard for Energy Efficiency of Rural Residential Buildings [21]. Dwelling B demonstrated even poorer thermal conditions, with an average indoor air temperature of only 4.09 °C, approximately 8.80-11.49 °C below the standard. In comparison, dwelling C achieved a substantially higher mean indoor air temperature of 14.07 °C, approaching the lower comfort threshold.

Further analysis of building envelope performance shows that in both dwellings A

and B, the interior surface temperatures of most exterior walls were consistently lower than the corresponding indoor air temperatures. This temperature disparity increases radiant heat loss, intensifies cold radiant discomfort, and exacerbates thermal bridging, resulting in considerable winter heat loss. Although dwelling C maintained relatively higher indoor air temperatures, the interior surface temperatures of the east, north, and west walls remained persistently below the room-average air temperature. Such low wall surface temperatures reduce the mean radiant temperature (MRT) and heighten occupants' sensation of cold, even when air temperature conditions are improved. This cold radiant asymmetry, primarily due to the absence of external wall insulation, is a major factor contributing to winter heat loss and inadequate thermal comfort in rural dwellings in Northern Henan. Therefore, enhancing the thermal performance of building envelopes is critical not only for lowering heating energy demand but also for improving perceived indoor thermal comfort.

Analysis of winter thermal comfort for rural residents in northern Henan

Thermal sensation vote

As illustrated in fig. 9, the distribution of TSV among rural residents in northern Henan is primarily concentrated in the *Cold* and *Slightly Cold* categories. The most frequently reported sensation was *Slightly Cold*, representing 48.93% of all TSV responses. Thermal acceptability was assessed based on TSV values, with responses in the range of $-1 \leq \text{TSV} \leq +1$ defined as within the *acceptable zone*. According to this criterion, approximately 57.44% of the votes were deemed acceptable, whereas about 42.55% fell within the *unacceptable zone*, broadly corresponding to the *Cold* category. These findings indicate that nearly half of the respondents perceived the winter indoor thermal environment as unacceptable. Despite wearing clothing with relatively high insulation levels, many residents continued to experience thermal discomfort because indoor temperatures remained below their physiological comfort thresholds. This outcome further highlights the inadequacy of current winter indoor thermal conditions in rural dwellings of Northern Henan.

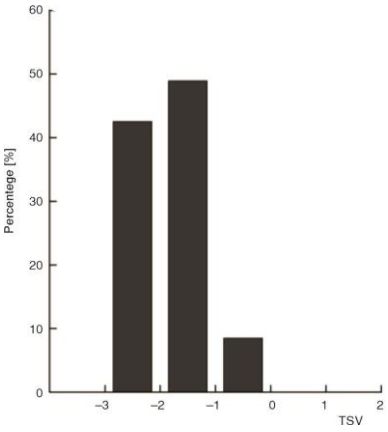

Figure 9. Frequency distribution of the TSV

Comfort and acceptable temperature

Based on the TSV and the corresponding operative temperatures, T_{OP}, the neutral temperature and acceptable temperature ranges were estimated, with the raw data distribution shown in fig. 10(a). The regression relationship between MTS and operative temperature for the binned dataset is illustrated in fig. 10(b). The coefficient of determination, R^2, of 0.92 indicates a strong linear correlation and a high level of model fit. As expected, the R^2 value obtained from the binned data is higher than that derived from the raw data, while the slopes and intercepts of the two regression equations remain highly consistent. Using the fitted regression model, the neutral temperature, defined as the operative temperature at which MTS equals zero, was calculated. The resulting value of 16.45 °C represents the thermal neutral temperature for the overall rural population in the study area.

According to the Evaluation Standard for Indoor Thermal Environment in Civil Buildings (GB/T 50785) [22], when the assessment level is Grade I (PPD ≤ 10%), the

acceptable thermal sensation range is defined as $-0.5 \leq \text{PMV} \leq +0.5$. By analogy, the 90% acceptable temperature range in this study was determined as the operative temperature interval corresponding to $-0.5 \leq \text{MTS} \leq +0.5$, yielding a range of 14.96-17.93 °C. This interval reflects thermal conditions under which the majority of occupants reported acceptable sensations. However, thermal neutrality and acceptable temperature ranges may differ significantly across age groups, an issue examined in the following subsection.

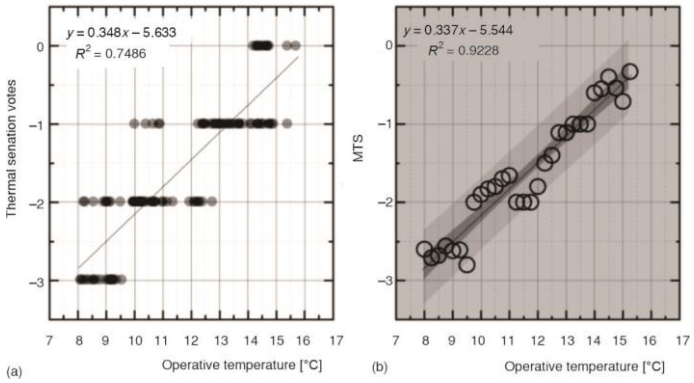

Figure 10. The operative temperature and TSV; (a) raw data and (b) binned data

Correlation analysis of age and mean thermal sensation

Thermal comfort requirements can differ across age groups due to age-related physiological characteristics and variations in clothing insulation. The participants ranged in age from 18 to 83 years, with an average age of 49.5 years. In line with the classification criteria outlined in section *Residential thermal comfort experiment*, participants were divided into three age categories: youth (18-39 years), middle-aged adults (40-59 years), and elderly adults (≥60 years). For each age group, linear regression analyses were conducted to examine the relationship between MTS and operative temperature. The resulting regression relationships are presented in fig. 11. Based on the fitted equations, the neutral temperature ($MTS = 0$) and the corresponding 90% acceptable temperature range ($-0.5 \leq MTS \leq +0.5$) were determined for each age group, summarized in tab. 5.

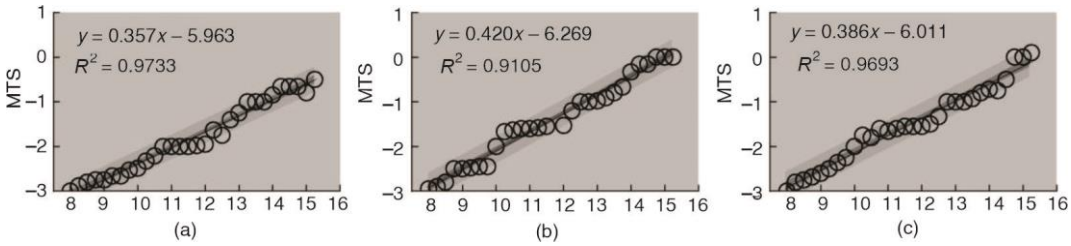

Figure 11. Relationships between the MTS and operative temperature in the three age groups; (a) Youth group, (b) middle age group, and (c) elderly group

As shown in tab. 5, the elderly group showed the highest neutral temperature at 16.70 °C, followed by the middle-aged group at 15.57 °C and the young group at 14.97 °C.

Pronounced differences in thermal neutrality were evident among the three age categories, with an average intergroup difference of approximately 0.87 °C. Within the 90% acceptable temperature range, the lower bounds for the young and middle-aged groups were relatively similar, whereas a larger gap was observed between the young and elderly groups. The upper limit of the acceptable temperature range increased progressively from the young group to the elderly group. These findings indicate that elderly residents require higher indoor temperatures to achieve thermal neutrality, followed by middle-aged and younger residents. Such age-related differences in thermal comfort requirements are likely attributable to physiological changes associated with aging, including reduced metabolic rates and diminished thermoregulatory capacity, which heighten sensitivity to cold conditions and increase thermal discomfort at lower indoor temperatures.

Table 5. Summary of the relevant parameters for the three age groups

Age groups	Mean clothing thermal resistance	Neutral temperature	90% acceptable temperature range
Youth	1.45 clo	14.97 ℃	[13.73 ℃,16.11 ℃]
Middle age	1.55 clo	15.57 ℃	[14.27 ℃,16.86 ℃]
Elderly	1.65 clo	16.70 ℃	[15.30 ℃,18.12 ℃]

Discussion

Comparison with other regions

As shown in fig. 12, comparisons with previous studies demonstrate substantial regional variability in thermal neutral temperatures. In cities such as Beijing and Harbin, where the winter heating season is longer and heating supply systems are more stable, higher thermal neutral temperatures have been reported, at approximately 18.6 °C and 21.6 °C, respectively. In comparison, Nanjing shows a considerably lower thermal neutral temperature of 14.44 °C [23]. In Turpan, which is characterized by pronounced seasonal temperature extremes, the reported thermal neutral temperature is approximately 19.3 °C [24]. Compared with these regions, rural residents in Northern Henan have a comparatively low thermal neutral temperature of 16.45 °C.

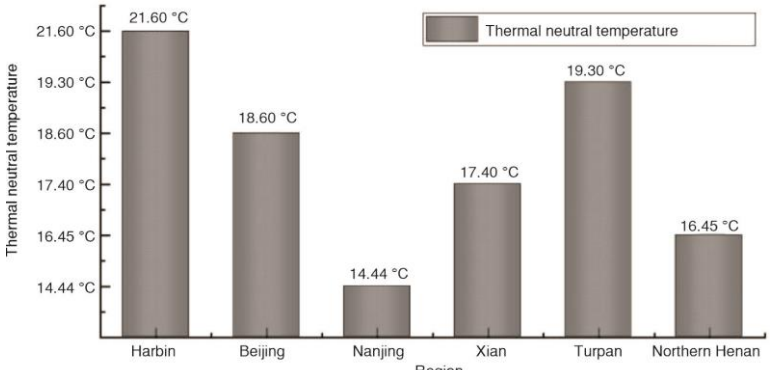

Figure 12. Indoor thermal comfort temperatures in different regions

These interregional comparisons highlight the need to establish region-specific, context-sensitive thermal comfort benchmarks rather than relying on uniform thermal standards across rural areas that differ significantly in climate, heating practices, and occupants' behavioral adaptations.

Prioritization of retrofit measures under cost constraints

– Cost-oriented retrofit measures

Previous research suggests that the persistently low indoor temperatures in rural dwellings in northern Henan are primarily due to constrained heating practices and significant indoor heat loss. Given prevailing economic constraints, retrofit strategies should prioritize improvements to the thermal insulation of the building envelope to reduce heat loss. As illustrated in fig. 13, recommended retrofit measures are classified by cost level. Low-cost interventions should focus on improving the airtightness of doors and windows, installing insulated curtains, and sealing air leakage paths to reduce indoor heat loss. Medium-cost retrofits should focus on improving the thermal performance of key envelope components, particularly exterior walls and roofs. High-cost measures should be adopted selectively and implemented in stages, with careful consideration of household financial capacity and the availability of sustained policy support.

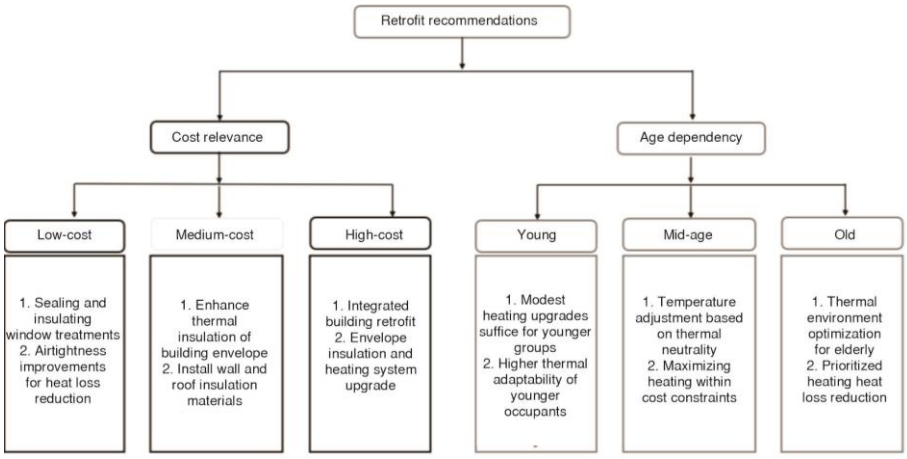

Figure 13. Age and cost sensitive retrofit recommendations

– Age-related retrofit measures

The age-related differences in thermal comfort identified in this study indicate that elderly residents are particularly vulnerable to low indoor temperatures. As a result, as shown in fig. 13, retrofit strategies should extend beyond a uniform thermal target and adopt an age-sensitive approach. For households with elderly occupants, retrofit measures should prioritize frequently used spaces, especially bedrooms. Enhancing wall and window insulation to raise the MRT is more effective in improving thermal comfort for elderly residents than simply increasing indoor air temperature. Targeted and localized retrofit interventions can therefore deliver substantial comfort gains while maintaining cost efficiency.

In comparison, younger residents demonstrate greater thermal adaptability and lower thermal neutral temperatures. As a result, moderate heating improvements may be sufficient to satisfy their comfort needs, supporting the formulation of flexible retrofit standards that account for household demographic composition.

Conclusions

This study conducted a comprehensive field investigation of winter indoor thermal environments and thermal comfort in rural residences of northern Henan, China. Field measurements revealed persistently low indoor air temperatures and pronounced wall surface temperature deficits, confirming that insufficient envelope thermal performance is a dominant contributor to poor winter indoor conditions. Thermal sensitivity analysis further indicates that, unlike other regions, rural residents in the northern Henan exhibit significant thermal adaptability, with a thermal neutral temperature of 16.45 °C, which is lower than that in the severe cold regions of the north and the extreme climate regions of the northwest, showing distinct regional characteristics. Obvious age-related differences were found. Elderly people require a higher neutral temperature and have a narrower tolerance range for thermal comfort.

The principal contributions of this study include providing a systematic dataset on rural thermal environments in northern Henan, quantifying age-specific thermal comfort characteristics under real living conditions, and translating these findings into cost-conscious, age-sensitive retrofit and policy recommendations. The results underscore the importance of adopting region-specific and demographically responsive thermal comfort benchmarks for rural housing. Integrating adaptive thermal comfort criteria, improving building envelope performance, and targeted policy support can enable cost-effective, energy-efficient retrofits, enhance living conditions for vulnerable populations, and promote low-carbon development in cold-climate rural regions of China.

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