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Comparative Summer Thermal and Moist-Air Responses of Glass-Enclosed Courtyards in Rural Housing: Implications for Sustainable Retrofit Screening

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Abstract

Glass-enclosed courtyards are common in self-built rural housing, but their summer retrofit value is uncertain because temperature attenuation may coexist with overheating or moisture accumulation. This study compared three south-facing brick-concrete dwellings with glass-enclosed courtyards in Qingdao, China, and integrated matched field measurements with a 64-household survey. Outdoor-normalized temperature offsets, sampled range differences, psychrometric variables, moist-air enthalpy, and courtyard-room temperature separation were analyzed. Mean courtyard–outdoor temperature differences across 18 observations were +1.34, +0.64, and −0.12 °C for Cases 1–3. On 15 July, Case 2 reduced the sampled courtyard temperature range to 0.9 °C compared with 7.9 °C outdoors, while its mean courtyard humidity ratio remained 2.86 g/kg higher than outdoors. This contrast shows that attenuation of dry-bulb temperature variation does not necessarily imply a reduction in absolute air-moisture content. The survey showed that 55.6% of valid respondents reported hot-side summer sensations, while 47.6% identified improved summer ventilation and cooling as a desired retrofit outcome. The survey provides complementary implementation context, while shading, courtyard ventilation, and courtyard–room air-exchange control are identified as candidate measures for future intervention testing rather than as validated retrofit solutions.

Keywords: rural housing; sustainable retrofit; glass-enclosed courtyard; climate-responsive design

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1. Introduction

Improving the thermal performance of existing rural housing is an important component of sustainable rural development because indoor environmental quality, cooling and heating demand, climate resilience, and household affordability are closely coupled. During hot and humid summer periods, insufficient passive control can increase heat exposure and encourage greater reliance on mechanical cooling, while retrofit strategies that are costly or difficult to operate may be poorly suited to self-built rural housing. A sustainability-oriented retrofit should therefore do more than reduce a single air-temperature metric: it should improve thermal conditions, avoid adverse moisture effects, remain adaptable to changing weather, and fit residents' practical constraints. Indoor thermal conditions are determined not only by air temperature but also by mean radiant temperature, humidity, air movement, clothing, metabolic activity, previous thermal experience, and the

availability of environmental controls [1–4]. Field studies have shown that occupants of naturally ventilated and mixed-mode buildings often accept wider temperature ranges than those predicted by static heat-balance models, partly because they can open windows, operate fans, adjust clothing, change activity, move between rooms, and intermittently use air conditioning [2–4]. These observations underpin the adaptive-comfort approach incorporated into contemporary thermal-environment standards [5] and reinforce the need to consider climate, building operation, and occupant agency together [6–8].

The relationship between thermal conditions and occupant responses is especially complex in rural housing. Compared with urban apartments, rural dwellings commonly differ in construction age, envelope quality, spatial organization, window type, heating and cooling systems, occupancy patterns, and household income. Detached and semi-detached rural houses are also more directly exposed to solar radiation, outdoor airflow, ground conditions, and surrounding vegetation. Consequently, findings obtained from offices or urban apartments cannot be transferred directly to rural dwellings. Reviews of thermal environments in Chinese residential and rural buildings have identified substantial differences among climatic regions in indoor temperature, acceptable temperature ranges, thermal expectations, and adaptive behavior [7,9]. Although the Chinese Thermal Comfort Dataset provides extensive evidence across multiple cities and climatic zones, its observations cover different building types and operating modes, and therefore cannot replace locally specific investigations of rural dwellings [8].

Field studies in different parts of China confirm this regional heterogeneity. Residents of traditional dwellings in Nanjing were found to tolerate relatively severe indoor conditions through behavioral and psychological adaptation [10]. Comparisons between urban and rural residents and among cities, towns, and villages have also revealed differences in thermal sensation, thermal expectations, adaptive behavior, and acceptable indoor temperatures [11,12]. Field studies conducted across different Chinese climate zones have shown that building-envelope performance, heating and cooling methods, clothing adjustment, age, and household practices can substantially affect both measured conditions and perceived comfort [13–17]. A year-long investigation of a traditional Chinese courtyard dwelling also demonstrated pronounced seasonal and spatial differences in thermal conditions and neutral temperatures, illustrating the importance of temporal context in the interpretation of courtyard-house measurements [18]. Coastal Shandong provides a particularly relevant setting for extending this evidence. Winter fieldwork in a coastal village of Qingdao revealed differences between the thermal expectations of residents and conventional comfort criteria and demonstrated the influence of heating practices, clothing, and dwelling characteristics [16]. More recent research involving low-income older households in rural Shandong showed that relatively high household energy use did not necessarily produce comfortable summer conditions, particularly in older dwellings with limited envelope performance [19]. Household composition, income, cooling practices, and building characteristics were found to influence both energy use and exposure to heat. These findings suggest that rural residential thermal conditions need to be interpreted through the combined effects of the physical building and household operation. The coastal location of Qingdao introduces additional complexity. Although Qingdao belongs to China's cold climatic region for building design, its summer environment is influenced by high humidity, variable cloud cover, solar exposure, and coastal airflow.

Recent rural-housing studies in Sustainability illustrate complementary pathways toward more sustainable housing improvement. Xie et al. examined how spatial configuration affected summer thermal conditions in three rural residential prototypes [20]; Cao et al. evaluated passive renovation measures for cold-region rural housing from energy, carbon, and economic perspectives [21]; and Yang and Misni compared vernacular and

modern rural dwellings by linking spatial form, courtyard configuration, thermal comfort, and energy use [22]. Together, these studies emphasize that sustainable rural housing depends on the interaction of spatial form, passive measures, occupant behavior, and implementation feasibility. However, the widespread practice of enclosing originally open courtyards with glazing remains insufficiently understood as a retrofit strategy, particularly under humid summer conditions and when household retrofit preferences are considered alongside measured environmental performance. Research on courtyards has shown that their thermal performance depends on geometry, orientation, solar exposure, shading, ventilation, surface properties, thermal mass, and the surrounding climatic conditions [23–27]. A courtyard can promote shading and ventilation under some conditions, but insufficient airflow or excessive solar exposure can also cause heat accumulation. A glass-enclosed courtyard also shares certain characteristics with attached sunspaces and glazed balconies. These spaces can act as thermal buffers and contribute to passive solar heating during cold periods, but their performance is strongly dependent on glazing characteristics, orientation, airtightness, ventilation, thermal storage, and operating strategy [28–31]. Reviews of sunspace applications identify summer overheating and night-time heat loss as two important limitations of poorly controlled designs [28]. Studies of glazed residential façades and balconies likewise show that additional glazing does not automatically improve thermal or energy performance and that solar-control and ventilation measures may remain necessary even in heating-dominated climates [29]. Research on rural sunspaces in cold and severe-cold regions has predominantly focused on winter heating, annual energy consumption, energy-saving retrofits, or simulated design optimization [30–32]. These studies provide useful physical explanations but do not establish that a glass-enclosed courtyard will always function as a thermal buffer during summer. Recent studies have begun to examine the dynamic performance of enclosed courtyards more explicitly. Field measurements and simulations of an enclosed single-story courtyard dwelling demonstrated that the courtyard's thermal effect changed with time and operating conditions [24]. Other experimental and numerical studies have confirmed that courtyard air temperature is governed by the balance among solar gains, convective exchange, heat storage, shading, and airflow [25–27,33]. These findings support treating the courtyard as a condition-dependent thermal space rather than assigning it a fixed role as either a passive-cooling element or a heat-gaining sunspace. Nevertheless, direct field evidence concerning glass-enclosed courtyards in rural housing remains limited, particularly in the humid summer conditions of coastal northern China. Evidence is also limited on how the courtyard–outdoor relationship changes among different weather conditions and how these changes relate to the temperatures and moisture states of adjoining occupied rooms.

Against this background, the present study examines whether the monitored glass-enclosed courtyards exhibited consistent or contrasting thermal responses under matched outdoor conditions, whether sampled temperature attenuation was accompanied by corresponding changes in moisture and moist-air state, and to what extent courtyard temperatures tracked those of adjoining occupied rooms. A separate household survey was used to characterize the local housing, thermal-perception, and retrofit implementation context rather than to statistically explain the measured environmental responses.

The incremental contribution of this study lies in three aspects. First, a common outdoor reference was used to compare multiple dwellings at matched measurement times, allowing cross-case differences to be identified without introducing different outdoor temperature and humidity series. Second, the analysis combines temperature offsets, sampled temperature-range responses, humidity ratio, moist-air enthalpy, and courtyard–room temperature separation, thereby extending the evaluation beyond dry-bulb temperature alone. Third, the physical observations are interpreted alongside local retrofit priorities

and implementation constraints to identify candidate directions for future retrofit testing. Given the limited number of dwellings and measurement days, the study is intended as an exploratory comparative field investigation rather than as a basis for establishing a general predictive model of courtyard performance.

2. Materials and Methods

2.1. Study Area and Case Selection

Qingdao is a coastal city located in the southeastern part of the Shandong Peninsula, China, between 35°35′–37°09′ N and 119°30′–121°00′ E. It borders the Yellow Sea to the east and south and has a temperate monsoon climate with pronounced maritime influences. According to the Chinese building climate classification, Qingdao belongs to the cold climate zone. The field investigation was conducted in Lijiacao Village, Chengyang District, Qingdao, during July 2026, in the local hot and humid summer season. Detailed environmental measurements used in this study were collected on 13, 14, and 15 July 2026. Three low-rise rural dwellings with glass-enclosed courtyards were selected for comparative field measurement. According to the case-information record, all three dwellings were constructed around 2000, used brick-concrete structural systems, and were south-facing. Figure 1 shows their three-dimensional forms and floor plans. Their overall plan dimensions were approximately 13.24 m × 10.24 m (Case 1), 14.24 m × 12.48 m (Case 2), and 15.20 m × 10.46 m (Case 3). The cases therefore share a broadly similar rural housing type while differing in plan geometry and courtyard configuration.

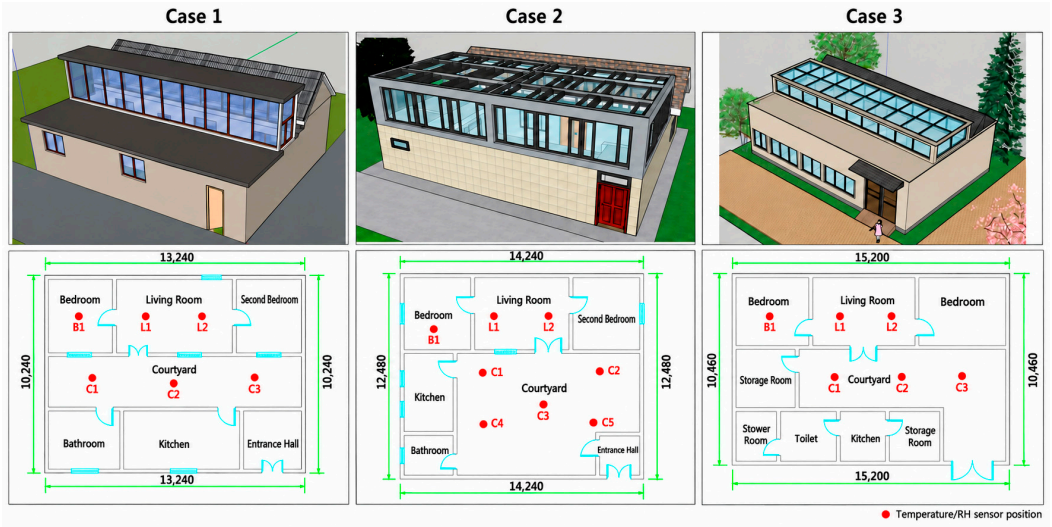


Figure 1. Three-dimensional representations and corresponding floor plans of the three investigated rural dwellings.

The selected cases align with several common characteristics observed in the household survey. Among classifiable survey responses, 76.2% of dwellings were brick-concrete, 88.9% were south-facing, and 87.3% fell within the questionnaire categories “before 1990” or “1990–2000”. The monitored dwellings, constructed around 2000, therefore correspond to common local structural and orientation characteristics.

Additional geometric, envelope, glazing, opening, and shading characteristics of the three monitored dwellings are summarized in Table 1.

Table 1. Descriptive envelope, glazing, opening, and shading characteristics of the monitored dwellings.

Parameter	Case 1	Case 2	Case 3
Plan dimensions (m)	13.24 × 10.24	14.24 × 12.48	15.20 × 10.46
Conventional windows (No.)	6	6	5
Total conventional-window opening area (m^2)	8.76	7.92	9
Net glazing area of conventional windows (m^2)	7.01	6.34	7.2
Maximum operable window area (m^2)	3.94	3.56	4.05
Courtyard-roof horizontal projected area (m^2)	≈33	≈75	≈36
Net translucent courtyard-roof area (m^2)	29.7	67.5	32.4
External wall construction	20 mm plaster + 240 mm Brick masonry + 20 mm plaster	Same as Case 1	Same as Case 1
Opaque roof construction	Pitched roofs in reinforced concrete structures	Same principle	Same principle
Translucent courtyard roof	Color-coated steel sheets	Glass window frame construction	Glass window frame construction
Main shading condition	Building self-shading, eaves, and front-roof shading	Building self-shading and partial shading by roof frame	Building self-shading, eaves, and entrance-canopy shading
Typical window configuration	Double-panel sliding window with one operable panel	Same as Case 1	Same as Case 1
Measurement-day door/window operation	Doors and windows were generally kept open when air conditioning was not in operation; this operating condition was observed/reported during the field investigation but was not continuously logged.	Same as Case 1	Same as Case 1
Occupancy during measurements	Not continuously recorded	Not continuously recorded	Not continuously recorded
Air-conditioning operation	Not continuously recorded at every scheduled measurement time	Same	Same

2.2. Field Measurement Protocol and Questionnaire Survey

Air temperature and relative humidity were measured using WSZY-1A temperature–relative-humidity data loggers (Beijing Tianjian Huayi Technology Development Co., Ltd., Beijing, China). The temperature measurement range was −40 to 100 °C, with a resolution of 0.1 °C and a stated instrumental uncertainty of ±0.5 °C. Relative humidity was recorded with a resolution of 0.1% RH and a stated instrumental uncertainty of ±3% RH. Each logger incorporated non-volatile storage with a capacity of 15,000 records. Outdoor air velocity was measured using a TSI vane anemometer (TSI Incorporated, Shoreview, MN, USA), with a measurement range of 0.25–30 m/s and a stated accuracy of ±1% of the reading or ±0.02 m/s, whichever was greater. No additional laboratory calibration was per-

formed specifically for this field campaign; therefore, the manufacturer-stated instrumental uncertainties were adopted in the uncertainty and sensitivity assessment.

The outdoor reference temperature and relative-humidity sensor was positioned in an open and naturally ventilated location near the monitored dwellings, approximately 1.5 m above the ground. The sensor was protected from direct solar radiation and precipitation using a ventilated radiation shield and was positioned away from building façades, windows, air-conditioning outdoor units, exhaust outlets, and other localized heat sources as far as practicable. The same outdoor reference location was used for all three dwellings at the corresponding measurement times to provide a common environmental boundary condition for the cross-case comparison. Air temperature and relative humidity were measured in the glass-enclosed courtyard, a selected bedroom, and the living room of each dwelling at six scheduled daytime measurement times on each measurement day: 09:00, 10:30, 12:00, 13:00, 15:00, and 16:30. Outdoor air temperature, outdoor relative humidity, and outdoor wind speed were recorded as common environmental reference variables. The same outdoor reference series was used for Cases 1–3 at corresponding measurement times, enabling matched cross-case comparison. Indoor sensors were positioned away from direct solar radiation, external doors and windows, air-conditioning outlets, and major localized heat sources as far as practicable. The sensors were positioned approximately 1.2 m above the floor. The same general positioning principle was applied across the three dwellings. The field campaign was designed primarily as a matched daytime cross-case comparison rather than as a continuous monitoring experiment. The six scheduled measurement times were selected to provide comparable morning, midday, and afternoon observations across the three occupied dwellings. Consequently, the measurements characterize sampled daytime states rather than complete diurnal thermal trajectories. Accordingly, nighttime heat release, overheating hours, degree-hours, and other full-diurnal performance metrics could not be derived from the present dataset.

A questionnaire survey was conducted with 64 adult respondents from 64 rural households in Lijiacao Village during the July 2026 field investigation. The households were randomly selected within the village, with one adult respondent representing each household. Approximately 90% of the surveyed dwellings had glass-enclosed courtyards, indicating that this enclosure form was common within the investigated village. The questionnaire collected descriptive information concerning respondent characteristics, dwelling age and construction, envelope characteristics, heating and cooling practices, perceived thermal conditions, overall thermal satisfaction, retrofit preferences, and acceptable household financial contributions.

The questionnaire was designed as a descriptive contextual survey rather than as a multi-item psychometric scale. Most questions addressed distinct factual or categorical domains and were not intended to measure a common latent construct. Accordingly, an overall internal-consistency coefficient such as Cronbach's alpha was not considered methodologically appropriate for the questionnaire as a whole. No formal psychometric validation or test–retest reliability assessment was performed, and the questionnaire findings are therefore interpreted as exploratory contextual evidence rather than as validated population-level estimates. Although the households were randomly selected within Lijiacao Village, the survey was limited to a single village and was therefore not intended to provide statistically representative estimates for the wider rural housing stock of Qingdao. The questionnaire was not designed to validate or statistically explain the monitored environmental responses. Its role in this study was limited to characterizing the local housing, thermal-perception, retrofit-priority, and implementation context. Questionnaire responses were summarized using counts and percentages. Percentages for individual items were calculated using the number of valid responses to that item. Missing, unclear, or

non-classifiable responses were excluded only from the affected item without imputation. For questions requiring a single response, multiply marked answers were excluded when a unique category could not be established. For multiple-response questions, each selected option was counted once per household. The questionnaire used in the household survey is provided as Supplementary File S1.

Participation in the questionnaire survey was voluntary. Before completing the questionnaire, all participants were informed of the purpose of the survey, the voluntary nature of participation, and that the information collected would be used solely for scientific research and analyzed anonymously. Verbal informed consent was obtained from all participants prior to participation. The survey was conducted with the prior permission and cooperation of the local village/community administration.

2.3. Environmental Data Processing and Comparative Indicators

For each case, measurement day, location, and scheduled time, air-temperature and relative-humidity data were checked for missing values and potential instrument-related anomalies. Mean, minimum, maximum, standard deviation, and sampled range were calculated. Atmospheric pressure P was set to 101.325 kPa for the psychrometric calculations. Saturation vapor pressure p_{ws}, vapor partial pressure p_v, humidity ratio w, and dew-point temperature T_d were estimated from the measured air temperature T and relative humidity RH as follows:

$$p_{ws} = 0.61078 \times exp[17.2694T/(T + 237.29)] \quad (1)$$

$$p_v = (RH/100) \times p_{ws} \quad (2)$$

$$w = 1000 \times 0.62198 p_v/(P - p_v) \quad (3)$$

$$\gamma = ln(RH/100) + 17.625T/(243.04 + T) \quad (4)$$

$$T_d = 243.04\gamma/(17.625 - \gamma) \quad (5)$$

where p_{ws} and p_v are expressed in kPa, w in g/kg dry air, and T and T_d in °C. Humidity ratio and dew-point temperature are calculated variables and should not be interpreted as directly measured quantities. Moist-air enthalpy was then calculated as:

$$h = 1.006T + w_{kg/kg}(2501 + 1.86T) \quad (6)$$

where h is in kJ/kg dry air and $w_{kg/kg}$ is the humidity ratio expressed in kg/kg dry air. Enthalpy is used here as a combined thermodynamic indicator of sensible and moisture-related air state, not as a direct measure of thermal comfort or building energy consumption. Because humidity ratio, dew-point temperature, and moist-air enthalpy were derived from measured air temperature and relative humidity rather than measured directly, their sensitivity to instrumental uncertainty was evaluated. Based on the stated uncertainties of the WSZY-1A data loggers (±0.5 °C for temperature and ±3% RH for relative humidity), each psychrometric variable was recalculated using combinations of $T \pm 0.5$ °C and RH ± 3%, while atmospheric pressure was maintained at 101.325 kPa. The resulting minimum and maximum values were used to characterize the uncertainty range of the derived psychrometric quantities. The use of a fixed atmospheric pressure represents an additional approximation and was considered when interpreting small differences between locations.

To remove the common outdoor temperature level from cross-case comparison, the outdoor-normalized zone temperature difference was calculated as:

$$\Delta T_{z-o,c,t} = T_{z,c,t} - T_{o,t} \quad (7)$$

where z denotes courtyard, bedroom, or living room; c is the case; and t is the matched measurement time. Positive values indicate that the zone was warmer than outdoors and negative values indicate that it was cooler. The sampled temperature range at each location was:

$$A_j = T_{j,max} - T_{j,min} \tag{8}$$

For the courtyard, the difference between its sampled range and the outdoor sampled range was used as the primary variability indicator:

$$\Delta A = A_c - A_o \tag{9}$$

A positive ΔA indicates amplification of sampled temperature variation relative to outdoors, while a negative value indicates attenuation. This difference metric was preferred to the range ratio as the primary comparison because a ratio can become disproportionately large when the outdoor sampled range is small. Courtyard–outdoor moisture and enthalpy offsets were calculated as $\Delta w_{C-O} = w_C - w_O$ and $\Delta h_{C-O} = h_C - h_O$. To quantify spatial separation between the courtyard and occupied rooms without cancelation of positive and negative differences, the mean absolute courtyard-room temperature separation was calculated as:

$$D_{i-c} = \frac{1}{n}\sum|T_{i,t} - T_{c,t}| \tag{10}$$

where i denotes the bedroom or living room.

3. Results

3.1. Surveyed Housing, Thermal Demand, and Retrofit Context

A total of 64 household questionnaires were included, with one respondent per household. Respondents were predominantly older adults: 19/64 (29.7%) were aged 46–60 years and 30/64 (46.9%) were aged 61 years or older. The remaining respondents were aged 18–30 years (7/64, 10.9%) or 31–45 years (8/64, 12.5%). Farming was reported by 31 of the 63 respondents who answered the occupation item (49.2%). Of 63 classifiable construction-period responses, 35 (55.6%) indicated before 1990 and 20 (31.7%) indicated 1990–2000. Brick-concrete construction was the most common structural category (48/63, 76.2%), followed by brick-timber construction (10/63, 15.9%). Single-story dwellings accounted for 46/63 (73.0%), and two-story dwellings for 16/63 (25.4%). South-facing orientation was reported in 56/63 (88.9%).

All three monitored cases were brick-concrete, south-facing dwellings constructed around 2000. This agreement with common structural and orientation characteristics in the survey provides local context for case selection.

3.1.1. Building-Envelope Characteristics

Figure 2 summarizes the reported building-envelope characteristics. Solid clay brick alone was marked by 49/64 households (76.6%), while four households (6.3%) marked multiple wall materials and were retained as a separate category. Perforated brick alone, hollow block alone, earth alone, and other materials accounted for 7.8%, 3.1%, 4.7%, and 1.6%, respectively. Wall insulation was reported by 39/63 (61.9%), and roof insulation by 40/60 (66.7%). Flat roofs (33/63, 52.4%) and pitched roofs (30/63, 47.6%) were both common. Of 61 valid window responses, 59 (96.7%) indicated only single-glazed types. These self-reported envelope characteristics do not establish insulation continuity, airtightness, or measured thermal transmittance.

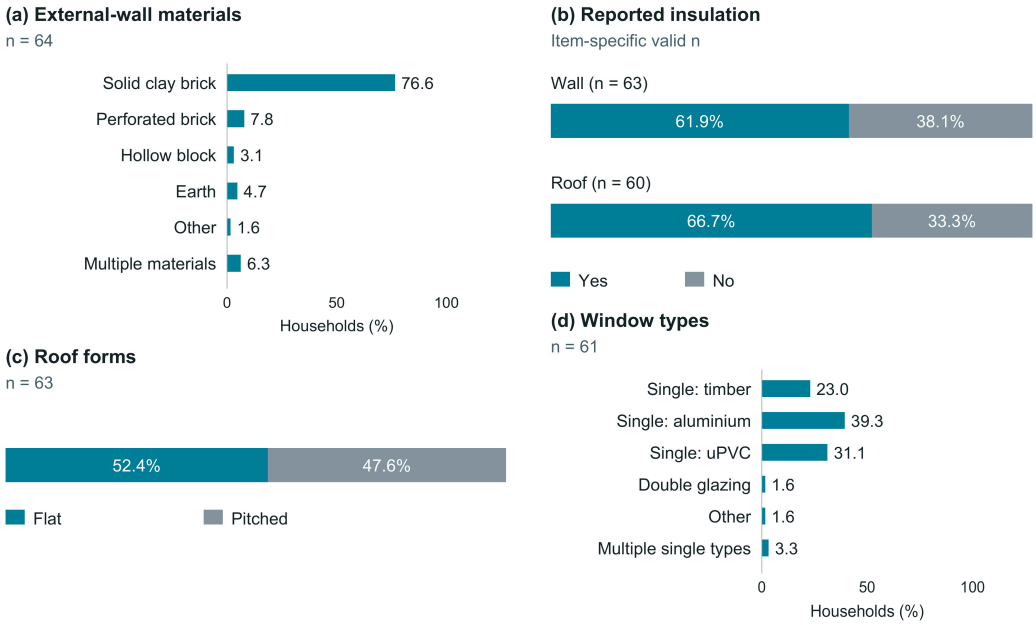


Figure 2. Building-envelope characteristics of the surveyed rural dwellings: (**a**) external-wall materials, (**b**) reported wall insulation and roof insulation, (**c**) roof forms, and (**d**) window types.

3.1.2. Summer Cooling, Thermal Perception, and Winter Conditions

Figure 3 presents summer cooling practices and subjective thermal responses. Among 62 households with a single classifiable primary cooling method, air conditioning was reported by 38/62 (61.3%), electric fans by 21/62 (33.9%), and natural ventilation by 3/62 (4.8%). Among 58 valid perceived-temperature responses, 24 households (41.4%) selected 24–26 °C, 24 (41.4%) selected 27–30 °C, and 6 (10.3%) selected the category labeled 30 °C and above. Thus, 30/58 respondents (51.7%) selected one of the two highest temperature categories. Of 63 valid summer thermal-sensation responses, 24/63 (38.1%) were neutral, while 35/63 (55.6%) were on the hot side of the scale: slightly hot (21), hot (13), or very hot (1).

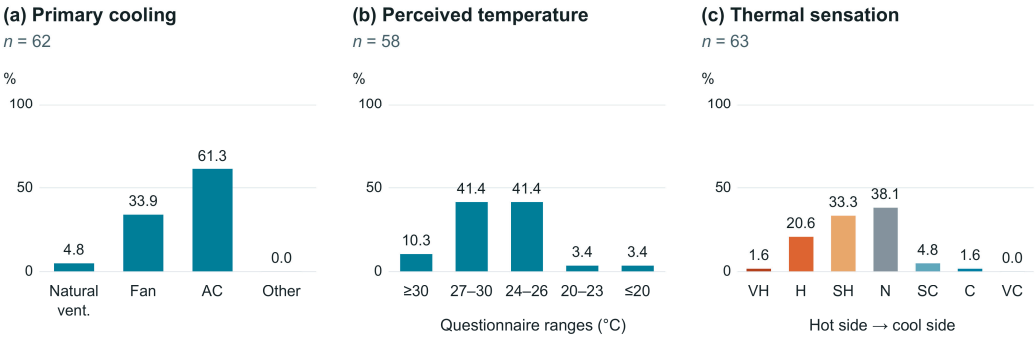


Figure 3. Summer cooling behavior and subjective thermal responses: (**a**) primary cooling method (*n* = 62), (**b**) perceived indoor temperature range (*n* = 58), and (**c**) summer thermal sensation (*n* = 63).

Figure 4 summarizes retrospectively reported winter heating methods and indoor environmental problems. Among 62 classifiable primary-method responses, coal-fired stoves or traditional household heating systems were the most common (40/62, 64.5%), followed by wall-mounted gas boilers (11/62, 17.7%), electric heaters or electric blankets (7/62, 11.3%), heat-pump air conditioning (3/62, 4.8%), and air-source heat pumps (1/62, 1.6%). All 64 households provided a classifiable answer to the multiple-response winter-problems item. High heating costs (24/64, 37.5%) and cold walls (23/64, 35.9%) were the two most frequently selected problems, followed by window draughts (14/64, 21.9%),

uneven indoor temperatures (8/64, 12.5%), and condensation or mold (6/64, 9.4%). Seven respondents explicitly reported no winter problem (10.9%).

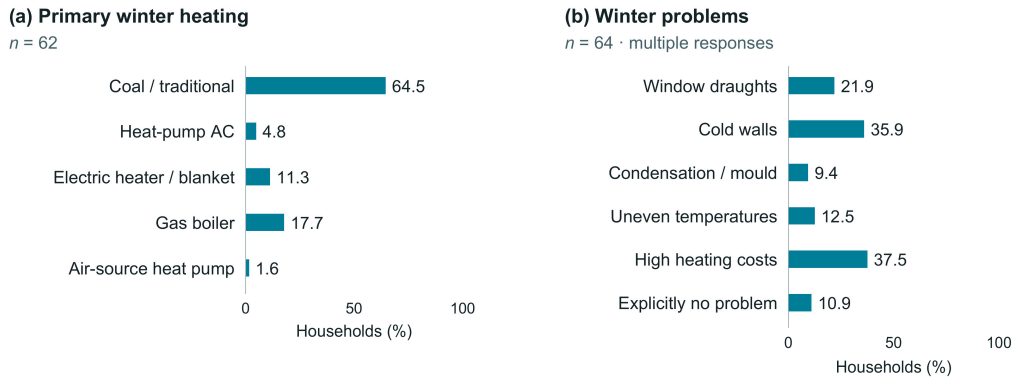


Figure 4. Retrospectively reported winter heating and indoor environmental problems: (**a**) primary heating method (n = 62) and (**b**) major winter problems (n = 64).

3.1.3. Thermal Satisfaction and Retrofit Preferences

Overall satisfaction with the residential thermal environment was positive for 44/64 respondents (68.8%), comprising 12 very satisfied and 32 somewhat satisfied respondents. The remaining 20/64 (31.3%) selected neutral; none selected either dissatisfaction category. Figure 5 summarizes desired improvements, retrofit attitudes, and acceptable household contributions. Among 63 respondents to the multiple-response improvement item, lower heating costs were most frequently selected (35/63, 55.6%), followed by better summer ventilation and cooling (30/63, 47.6%), warmer winter conditions (25/63, 39.7%), and additional wall or roof insulation (21/63, 33.3%). All 64 respondents answered the retrofit-attitude item: 28 (43.8%) strongly supported retrofitting, 20 (31.3%) supported it, 15 (23.4%) made their support conditional on government subsidies, and one (1.6%) opposed it. Among 63 classifiable contribution responses, 23 (36.5%) selected CNY 5000 and below, 10 (15.9%) selected CNY 5000–10,000, 7 (11.1%) selected CNY 10,000–20,000, 1 (1.6%) selected CNY 20,000 and above, and 22 (34.9%) did not accept a personal financial contribution.

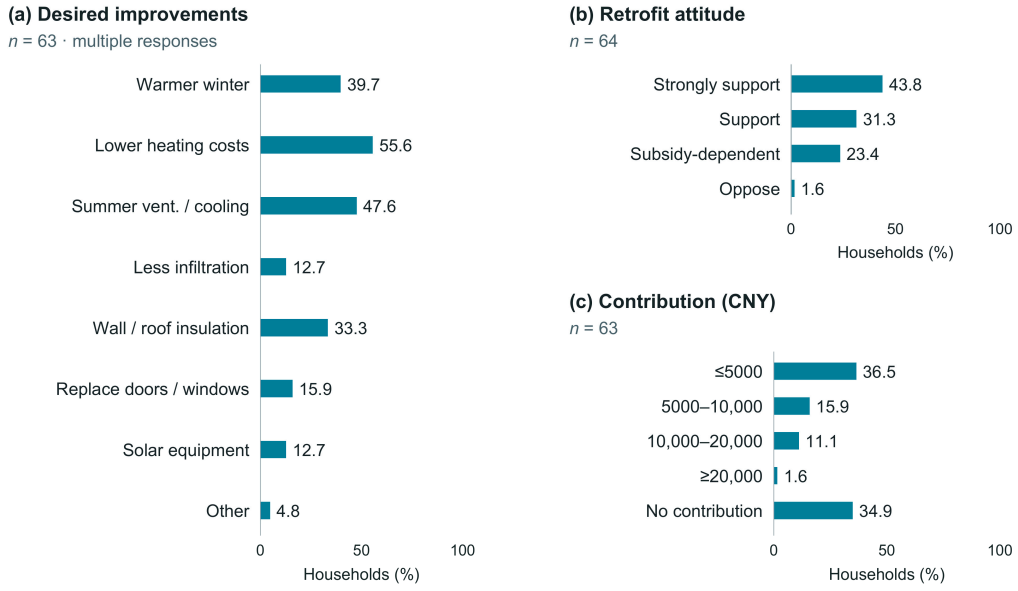


Figure 5. Residents' retrofit preferences: (**a**) desired improvements (n = 63), (**b**) attitudes towards energy-efficiency retrofits (n = 64), and (**c**) acceptable household financial contribution (n = 63).

3.2. Outdoor-Normalized Thermal Response Across the Three Cases

The three measurement days represented different sampled outdoor conditions. Outdoor temperature and relative humidity were comparatively stable and humid on 13 and 14 July, whereas 15 July exhibited a substantially larger daytime temperature range and lower relative humidity during part of the measurement period. Outdoor wind speed also varied among the three days. The day-specific outdoor temperature, relative-humidity, wind-speed, and field weather observations are summarized in Supplementary Table S3. These values represent the six scheduled daytime observations rather than full-day meteorological statistics; solar radiation was not measured. Using the common outdoor environment as the reference revealed cross-case differences that were less apparent from the raw temperature series alone. Figure 6 presents the outdoor-normalized temperature differences, expressed as $T_{zone} - T_{outdoor}$, for the courtyard, bedroom, and living room of the three cases at the corresponding measurement times. The figure provides an overview of both the magnitude and direction of the thermal deviations from the common outdoor reference and highlights the spatial and temporal differences among the three dwellings. Across all 18 matched observations per case, the mean courtyard–outdoor temperature differences were +1.34 °C for Case 1, +0.64 °C for Case 2, and −0.12 °C for Case 3. The corresponding standard deviations were 1.67, 1.79, and 2.48 °C, respectively, indicating that Case 3 had the widest variation in its offset from outdoors.

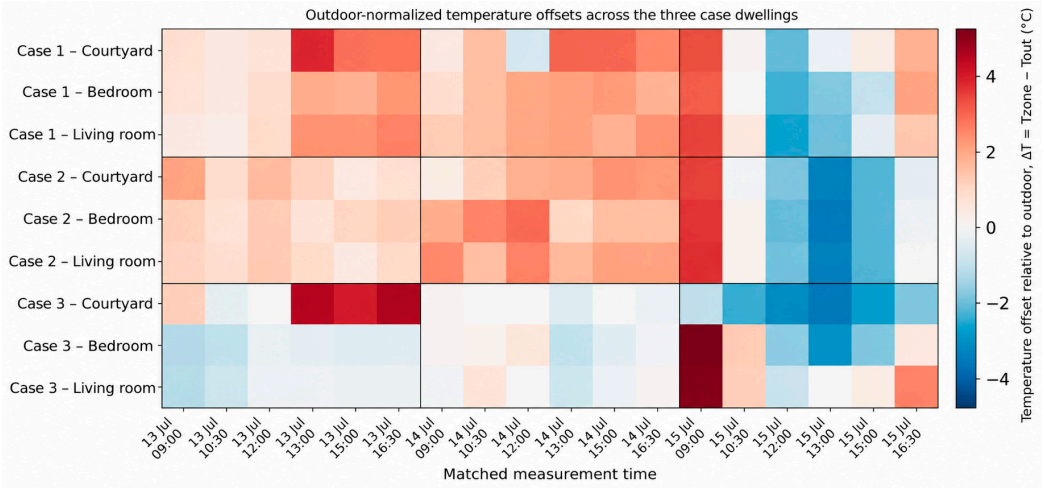


Figure 6. Outdoor-normalized temperature offsets ($T_{zone} - T_{outdoor}$) for the courtyard, bedroom, and living room in the three cases at the matched measurement times.

The overall cross-case thermal and moist-air indicators are summarized in Table S1, providing an integrated comparison of courtyard temperature offsets and moisture-related differences across the three dwellings.

The response also changed by day. On 13 July, the three courtyards were warmer than outdoors on average, with daily mean ΔT_{C-O} values of +1.87, +1.12, and +2.35 °C for Cases 1–3, while their sampled range differences ΔA were +3.2, +1.0, and +4.4 °C. On 14 July, Cases 1 and 2 remained warmer than outdoors on average (+1.65 and +1.60 °C) and showed larger sampled variations than outdoors, whereas Case 3 approximately tracked outdoors (mean $\Delta T_{C-O} = -0.10$ °C; $\Delta A = 0$). On 15 July, all three courtyards attenuated the large outdoor sampled variation of 7.9 °C. Case 2 showed the strongest attenuation, with a courtyard range of only 0.9 °C ($\Delta A = -7.0$ °C) and a mean courtyard–outdoor difference of −0.80 °C. Case 3 was still cooler on average (−2.62 °C) but had a wider courtyard range of 5.4 °C.

The combined effects of mean thermal bias and variation amplification or attenuation are summarized in Figure 7. By plotting the daily mean courtyard–outdoor temperature

difference against the difference between the courtyard and outdoor sampled temperature ranges, the figure distinguishes four thermal-response patterns: warmer with amplified variation, warmer with attenuated variation, cooler with amplified variation, and cooler with attenuated variation. The distribution of the nine case-day observations shows that the sampled courtyard response was not uniform across the investigated dwellings and measurement days.

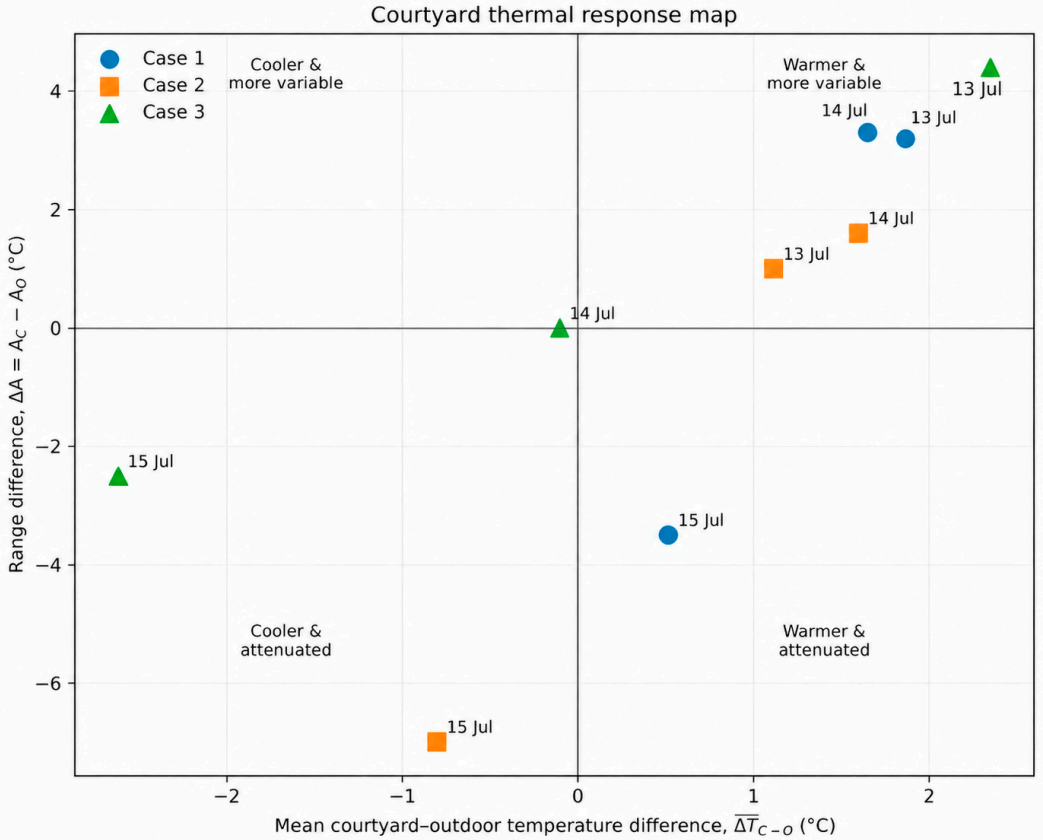


Figure 7. Courtyard thermal-response map based on the daily mean courtyard–outdoor temperature difference and the courtyard-minus-outdoor sampled range difference.

The occupied rooms did not respond uniformly to courtyard conditions. Across all observations, the mean absolute bedroom–courtyard and living-room–courtyard temperature separations were 0.73 and 0.72 °C in Case 1, 0.59 and 0.38 °C in Case 2, and 2.04 and 2.42 °C in Case 3. Case 3 therefore exhibited the strongest thermal decoupling between the courtyard and occupied rooms. The sign of the difference also reversed between measurement days: on 13 July, its bedroom and living room were on average 3.07 and 2.90 °C cooler than the courtyard, whereas on 15 July they were 2.73 and 4.05 °C warmer than the courtyard. These reversals demonstrate that courtyard temperature alone cannot be used as a proxy for the thermal state of the adjoining occupied rooms.

3.3. Moist-Air Response

The moisture and enthalpy analysis change the interpretation obtained from air temperature alone. Across all 18 observations, mean courtyard–outdoor humidity-ratio differences were +0.50, +0.03, and −0.27 g/kg dry air for Cases 1–3, respectively, while corresponding mean enthalpy differences were +2.67, +0.75, and −0.80 kJ/kg dry air. The sign and magnitude of these offsets changed by day, indicating that temperature and moisture responses were not tightly coupled. These overall and daily moist-air indicators are summarized in Table S2.

Figure 8 summarizes the daily moist-air responses of the three courtyards by plotting the mean courtyard–outdoor humidity-ratio difference against the corresponding mean enthalpy difference. The distribution of the nine case-day observations shows that the direction and magnitude of the moisture-related responses varied among both cases and measurement days. The clearest contrast occurred on 15 July. Case 2 had a cooler and much less variable courtyard than outdoors (mean ΔT_{C-O} = −0.80 °C; courtyard range = 0.9 °C versus 7.9 °C outdoors), while its nominal mean humidity-ratio and enthalpy differences were +2.86 g/kg and +6.46 kJ/kg, respectively. Under the conservative uncertainty analysis based on the stated instrumental uncertainties of ±0.5 °C and ±3% RH, the positive humidity-ratio difference remained directionally consistent, whereas the sign of the enthalpy difference was not robust. Accordingly, the comparison indicates more reliably that attenuation of dry-bulb temperature variation did not necessarily coincide with a reduction in absolute air-moisture content, while the enthalpy contrast should be interpreted with greater caution. Case 1 on the same day showed nominal humidity-ratio and enthalpy differences of +3.90 g/kg and +10.50 kJ/kg, whereas Case 3 showed −0.95 g/kg and −5.14 kJ/kg.

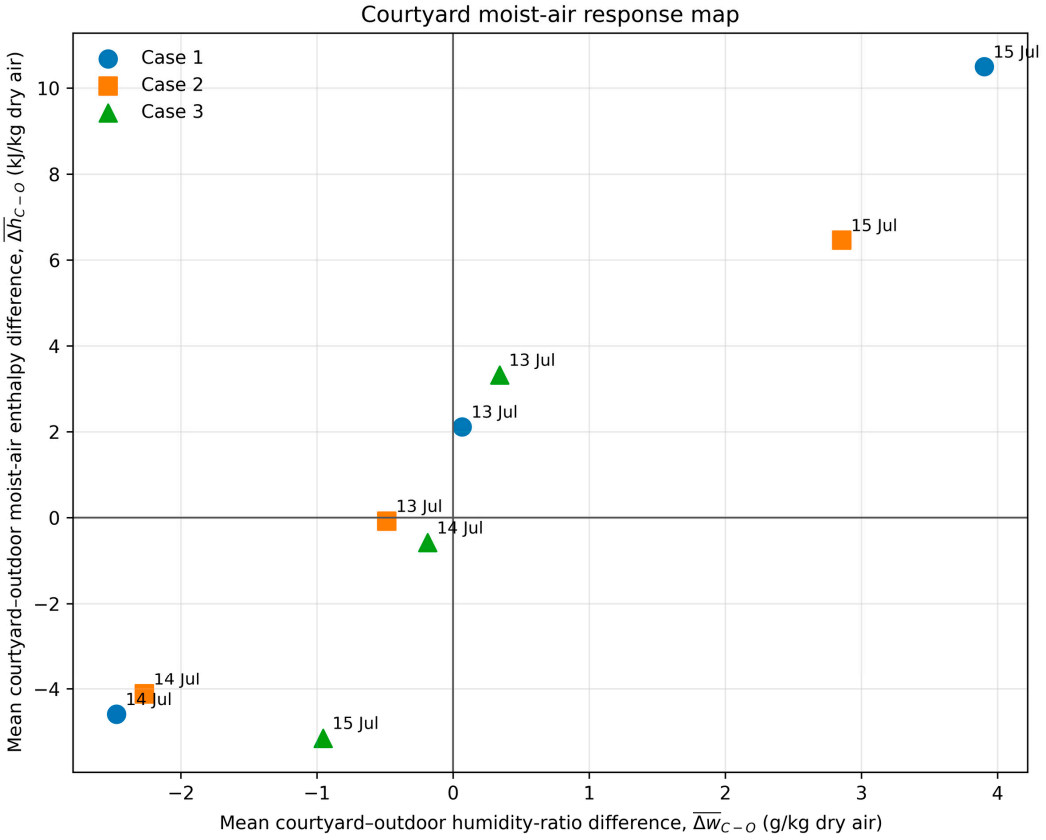


Figure 8. Courtyard moist-air response map showing the daily mean courtyard–outdoor differences in humidity ratio and moist-air enthalpy.

The household survey was not paired with the monitored dwellings and was therefore not used to validate or statistically explain the measured thermal responses. Instead, it provides supplementary context regarding local housing characteristics, thermal perceptions, and retrofit priorities. Among valid responses, 51.7% of respondents selected perceived summer indoor temperatures of 27 °C or above, 55.6% reported hot-side thermal sensations, and 47.6% identified improved summer ventilation and cooling as a desired retrofit outcome. These survey results are interpreted independently of the field measurements and are used only to characterize the local implementation context for future retrofit studies.

4. Discussion

Within the limited sampled dataset, substantial variation was observed both among measurement days and among the three monitored dwellings. The matched outdoor reference strengthens the descriptive comparison because the cases were evaluated against the same outdoor temperature and humidity series at corresponding measurement times. However, the observations should not be interpreted as establishing a general weather-dependent model of glass-enclosed courtyard behavior. The dataset demonstrates only that the sampled thermal responses were not uniform across the investigated dwellings and days.

Differences in glazing area, enclosure geometry, roof construction, solar exposure, shading, thermal storage, infiltration, opening status, and household operation may have contributed to the observed cross-case variation. Some additional enclosure descriptors are now reported in Table 1; however, several control variables were not measured continuously or consistently. The present study therefore does not attribute the observed differences causally to any individual building or operational parameter.

4.1. Temperature Attenuation Does Not Necessarily Imply a Favorable Moist-Air State

The combined temperature–humidity analysis shows why dry-bulb temperature or relative humidity should not be interpreted in isolation in the humid summer context of coastal Qingdao. A courtyard can be cooler than outdoors while still containing more water vapor. Case 2 on 15 July is particularly instructive: despite a mean temperature offset of $-0.80\ ^{\circ}C$ and strong attenuation of the sampled outdoor temperature range, its nominal mean courtyard humidity ratio was 2.86 g/kg higher than outdoors. The conservative uncertainty analysis indicated that the direction of this humidity-ratio difference remained positive, whereas the sign of the corresponding enthalpy difference was not robust. The more reliable interpretation is therefore that attenuation of dry-bulb temperature variation did not necessarily coincide with a reduction in absolute air-moisture content. Enthalpy differences should be interpreted more cautiously because they inherit uncertainty from both temperature and relative-humidity measurements.

4.2. The Occupied Rooms Must Be Analyzed Together with the Courtyard

The cross-case comparison strengthens the conclusion that courtyard conditions alone cannot represent dwelling-level thermal exposure. Case 3 exhibited the largest mean absolute courtyard-room temperature separation and a clear reversal between 13 and 15 July. On the first day, the overheated courtyard coexisted with cooler occupied rooms; on the third day, the courtyard was substantially cooler than the living room. This behavior is consistent with thermal decoupling created by partition walls, openings, room orientation, local heat storage, and intermittent mechanical cooling, although the present measurements do not isolate their individual effects. Retrofit design should therefore treat the courtyard and adjacent rooms as a coupled spatial system rather than optimize the courtyard in isolation.

4.3. Implications and Candidate Measures for Future Retrofit Testing

The combined field and survey evidence suggest that sustainable rural retrofit should be approached as a staged decision process rather than as a single fixed envelope package. Among valid survey responses, 59/61 households (96.7%) reported only single-glazed window types, while 61.9% reported wall insulation and 66.7% reported roof insulation. At the same time, high heating costs, cold walls, and window draughts remained common winter concerns. Household preferences also favor a staged approach. Reducing heating costs (55.6%) and improving summer ventilation and cooling (47.6%) were both prominent objectives. Although 75.0% of respondents supported retrofitting without selecting the

subsidy-dependent category, 34.9% of classifiable respondents declined a personal financial contribution and 52.4% selected one of the two lowest monetary contribution bands. These findings support evaluating lower-cost, reversible, and controllable measures first.

Based on the observed thermal and moisture-related responses, adjustable shading, controllable courtyard ventilation, and coordinated courtyard–room air exchange are considered candidate measures for future intervention testing rather than validated retrofit solutions. The present study does not demonstrate the effectiveness of shading, controlled ventilation, or courtyard–room air-exchange interventions because these measures were not experimentally manipulated. Their physical rationale is supported by previous studies of solar gain and ventilation in glazed intermediate spaces, whereas the present measurements identify the types of thermal and moisture responses that such future interventions should seek to address. Targeted window sealing or replacement may offer cross-season benefits where inspection confirms leakage or poor glazing performance. Table 2 summarizes candidate retrofit measures and the corresponding validation requirements for future intervention studies.

Table 2. Candidate retrofit measures and validation requirements.

Observed Issue/Evidence	Candidate Intervention for Future Testing	Required Validation
Courtyard thermal regimes changed by day; all three cases were warmer than outdoors on 13 July, and temperature attenuation did not always coincide with lower absolute moisture content.	Adjustable shading and condition-based opening of courtyard vents.	Continuous solar radiation, opening status, air-change rate, and before-after temperature, humidity-ratio, and enthalpy monitoring.
Case 3 showed mean absolute courtyard-room separations of 2.04 °C (bedroom) and 2.42 °C (living room), with sign reversals between days.	Coordinate doors/windows between courtyard and occupied rooms; avoid uncontrolled transfer during adverse courtyard conditions.	Airflow direction/rate, room thermal conditions, occupant operation, and air-conditioner status.
96.7% of valid window responses indicated only single glazing; winter surveys also identified cold walls and window draughts.	Inspect seals, frames, glazing, and local envelope defects; apply targeted sealing or window upgrades where justified.	U-value/infiltration measurements, condensation risk, winter-summer monitoring, and installed cost.
Retrofit support was high, but 34.9% declined personal contribution and 52.4% selected the two lowest contribution bands.	Combine operational and envelope measures only where household priorities, subsidies, and dwelling condition support a larger package.	Seasonal energy use, life-cycle cost, household affordability, comfort, moisture performance, and before-after verification.

4.4. Limitations and Future Work

Several limitations constrain the interpretation and generalizability of the present findings. First, the environmental dataset comprises three dwellings monitored at six scheduled daytime times over three summer days. It therefore provides an exploratory matched-condition comparison rather than a complete characterization of courtyard performance. In particular, the absence of nighttime monitoring means that nocturnal heat release, night-ventilation potential, delayed thermal response, overnight moisture behavior, and full 24 h overheating exposure cannot be evaluated. The terms “amplification” and “attenuation” used in this study refer strictly to differences in the sampled daytime temperature ranges and not to full-diurnal thermal performance. Second, although additional glazing, opening, construction, and shading characteristics have been documented, several important control variables—including solar radiation, infiltration/air-change rate, measurement-time opening status, detailed thermal properties, and air-conditioning operation—were not continuously quantified. Consequently, the study identifies observed differences but cannot establish the physical causes of those differences. Third, the household survey was

based on a locally recruited exploratory sample and was not paired with the monitored dwellings at the household level. It therefore provides implementation context rather than statistical validation of the measured thermal responses. No formal psychometric validation or test–retest reliability assessment was performed.

Future research should proceed in four complementary directions. Round-the-clock continuous monitoring across representative summer and winter periods is needed to characterize complete diurnal heat and moisture dynamics. Controlled before-and-after intervention experiments should directly test adjustable shading, courtyard ventilation, and courtyard–room air-exchange strategies. Larger multi-dwelling field campaigns should cover a broader range of courtyard geometries, glazing configurations, and household operating patterns. Finally, environmental monitoring should be coupled with measured energy consumption, retrofit cost, life-cycle economic assessment, and household affordability to evaluate the actual energy and techno-economic performance of candidate retrofit strategies.

5. Conclusions

This exploratory field study compared the summer thermal and moist-air responses of glass-enclosed courtyards in three rural dwellings using a common outdoor reference at matched measurement times. The results showed substantial variation among the sampled days and dwellings, but the limited monitoring duration and number of cases do not support generalization to a universal weather-dependent or condition-dependent model of courtyard performance.

Across all matched observations, the mean courtyard–outdoor temperature differences were +1.34, +0.64, and −0.12 °C for Cases 1–3, respectively. The daily comparisons further showed that the sampled courtyard temperature response was not uniform across the three dwellings or measurement days. On 15 July, Case 2 reduced the sampled courtyard temperature range to 0.9 °C compared with 7.9 °C outdoors, while its mean humidity ratio remained 2.86 g/kg higher than outdoors. This result indicates that attenuation of dry-bulb temperature variation did not necessarily coincide with a reduction in absolute air-moisture content. The enthalpy differences derived from temperature and relative humidity were more sensitive to instrumental uncertainty and should therefore be interpreted with greater caution.

The relationship between courtyard and occupied-room temperatures also differed among the monitored dwellings. Case 3 showed mean absolute courtyard–room temperature separations of 2.04 °C for the bedroom and 2.42 °C for the living room, with the direction of the temperature difference reversing between measurement days. These observations indicate that courtyard temperature alone should not be used as a proxy for the thermal conditions of adjoining occupied rooms.

The household questionnaire provides supplementary information on local housing conditions, thermal perceptions, retrofit preferences, and implementation constraints, but it was not statistically linked to the monitored environmental data and should not be interpreted as validation of the field measurements. Similarly, the present study did not experimentally test the effectiveness of shading, controlled ventilation, or courtyard–room air-exchange strategies. These measures are therefore proposed only as candidate interventions for future testing.

Overall, the study provides an exploratory comparative evidence base for identifying thermal and moisture-related issues that warrant further investigation in glass-enclosed rural courtyards. Future research should use round-the-clock continuous monitoring, larger multi-dwelling samples, controlled pre–post retrofit experiments, and direct energy and

techno-economic measurements to determine the mechanisms underlying the observed differences and to verify the actual effectiveness of candidate retrofit strategies.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su182111286/s1: Table S1: Overall cross-case thermal and moist-air indicators; Table S2: Daily courtyard response indicators and conservative uncertainty ranges for the derived moist-air differences; Table S3: Day-specific outdoor environmental conditions during the field measurements; Supplementary File S1: Household questionnaire; Supplementary Data S1: Measured temperature and relative-humidity series for the three monitored dwellings.

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Data Availability Statement: The measured temperature and relative-humidity series supporting the findings of this study are provided in Supplementary Data S1. Additional de-identified supporting data are available from the corresponding author upon reasonable request. Individual-level questionnaire records are not publicly available to protect participant privacy.

Conflicts of Interest: The authors declare no conflicts of interest.

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