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Thermal–Spatial Strategies for Rural Dwellings: Environment–Behaviour nexus in Northern China

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Abstract
Rapid rural transformation in northern China poses challenges to thermal adaptation and residential satisfaction amid changing climatic conditions. This study investigates the interrelationships among spatial configuration, material properties, courtyard morphology, and occupants' adaptive behaviours in rural housing contexts. Based on survey data collected from 383 respondents and analysed using Partial Least Squares Structural Equation Modelling (PLS-SEM), the study evaluates the structural relationships linking dwelling typology, thermal comfort, and residential satisfaction. The findings reveal that dwelling typology significantly influences spatial organisation, courtyard performance, and perceived thermal comfort. Moreover, spatial configuration serves as a mediating factor in shaping residential satisfaction. These insights contribute to the formulation of climate-responsive rural housing strategies that integrate passive environmental design with occupant-driven adaptive behaviours.

Keywords: Thermal Comfort; Spatial Configuration; Rural Environment; Environment–Behaviour Studies

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1.0 Introduction

Rural revitalisation has become a significant development strategy in rapidly urbanising regions, particularly in northern China, where climatic variability strongly impacts residential environmental performance. Traditional rural settlements have evolved through long-term adaptations to local climate and socio-cultural conditions, resulting in vernacular courtyard dwellings that feature passive environmental regulation and spatial flexibility. These housing forms utilise thermal mass, shaded open spaces, and natural ventilation to moderate indoor thermal conditions while minimising energy consumption. Given buildings' substantial contribution to global energy use and carbon emissions, climate-responsive residential design has become increasingly vital for sustainable development (Aste et al., 2022).

However, contemporary rural reconstruction often replaces vernacular housing with standardised modern dwellings modelled on urban construction practices. Reinforced concrete structures and compact spatial layouts usually prioritise construction efficiency over environmental adaptability, leading to higher cooling demands and reduced thermal resilience in the face of changing climatic conditions (Ren et al., 2022). Northern China's hot-summer and cold-winter transitional climate further accentuates the importance of adaptive

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strategies, as indoor comfort relies not only on building performance but also on occupants' behavioural responses. Residents often adjust their thermal environments by opening windows and utilising courtyards, which significantly influence their perceived comfort (Du & Chen, 2024).

From an environment-behaviour perspective, housing satisfaction arises from the interactions between spatial environments and human perception. Spatial configurations mediate the behavioural opportunities and environmental experiences within residential settings. Despite the growing research on adaptive comfort and vernacular sustainability, empirical studies that integrate spatial configuration, behavioural adaptation, and housing satisfaction using structural modelling approaches remain limited in rural northern China.

This study aims to examine the interaction between environmental conditions and occupant behaviour in rural residential settings. Specifically, the study pursues three objectives:

(1) to compare the thermal performance of vernacular and contemporary rural dwellings;
(2) to assess the impact of courtyard morphology and material selection on indoor thermal conditions; and
(3) to establish structural relationships among spatial configuration, adaptive thermal comfort, and housing satisfaction.

2.0 Literature Review

2.1 Energy Transition and Thermal Performance in Residential Buildings

The building sector remains a primary contributor to global energy demand and associated carbon emissions, underscoring the urgency of improving residential thermal performance (Aste et al., 2022). Accelerated urbanisation, coupled with climate change, has intensified thermal stress in residential environments, particularly across rapidly developing regions in Asia (Ren et al., 2022). Inadequate building envelopes and construction methods that fail to account for climate factors increase cooling demand and operational energy use (Niza et al., 2022). Recent research highlights that combining spatial planning with passive design strategies can enhance thermal performance while promoting adaptive comfort in residential environments (Lee et al., 2025).

2.2 Vernacular Architecture and Passive Climate Adaptation

Vernacular architecture showcases climate adaptation strategies that have evolved. It incorporates passive features such as courtyards, shading, and thermal mass to help regulate indoor environments (Yang & Misni, 2025). Courtyard designs are particularly effective in reducing heat gain and enhancing ventilation, with their geometric configurations significantly influencing airflow and thermal stability. However, in contemporary rural housing, these climate-responsive designs are often replaced by standardised layouts that lack passive strategies. This shift results in decreased environmental satisfaction (Zhang et al., 2022). These findings emphasise the importance of reinterpreting traditional spatial principles in modern sustainable housing design.

2.3 Occupant Behaviour and Adaptive Thermal Comfort

Thermal comfort is increasingly understood as an adaptive process influenced by occupants' behaviours, such as adjusting windows, changing clothing, and modifying activity patterns, rather than being solely determined by fixed environmental conditions. Research on naturally ventilated homes indicates that behavioural adaptation plays a crucial role in maintaining acceptable comfort levels across different climates (Du & Chen, 2024; Chen & Misni, 2025). The theory of adaptive comfort emphasises the interaction between humans and their environment over reliance on mechanical conditioning. Additionally, vernacular courtyard designs promote flexibility, environmental resilience, and user control (Muqoffa et al., 2025).

2.4 Spatial Configuration, Environment–Behaviour Interaction and Housing Satisfaction

Research on the relationship between environment and behaviour indicates that housing satisfaction results from the interaction between spatial configuration and residents' perceptions. These interactions influence various factors, including environmental exposure, privacy, adaptive behaviour, comfort, and overall well-being. Post-occupancy studies further demonstrate that indoor environmental quality plays a significant role in satisfaction and psychological restoration, with courtyard designs promoting social interaction and enhancing perceived quality.

Studies using Structural Equation Modelling (SEM) suggest that spatial and environmental factors indirectly affect housing satisfaction, primarily through mediators such as perceived thermal comfort and behavioural adaptation (Yang & Misni, 2026). However, there is a notable research gap regarding the empirical application of Partial Least Squares SEM (PLS-SEM) in rural dwellings, particularly in northern China's transitional climate.

3.0 Methodology

3.1 Research Design Framework

A quantitative environment–behaviour framework is adopted to explore the interactions between spatial configuration, thermal conditions, and occupant adaptation in rural housing. The methodology combines physical environmental evaluation with human perception analysis to assess the residential experience within climate-responsive built environments. A conceptual analytical model was constructed to

examine the causal relationships among architectural variables and behavioural outcomes. This framework includes six latent constructs and eight hypotheses:
H1: Dwelling typology is associated with variations in spatial configuration.
H2: Dwelling type influences the selection and characteristics of building materials.
H3: Dwelling typology contributes to differences in courtyard configuration.
H4: Courtyard configuration affects the performance attributes of building materials.
H5: Spatial configuration plays a critical role in shaping material characteristics.
H6: Spatial configuration is expected to influence levels of housing satisfaction.
H7: Thermal comfort is hypothesised to affect the perception and utilisation of courtyard spaces.
H8: Thermal comfort is assumed to have a direct effect on housing satisfaction.

The proposed model indicates that dwelling typology influences environmental performance through the combined effects of spatial organisation and material characteristics, with thermal comfort acting as an intermediary factor shaping residential satisfaction.

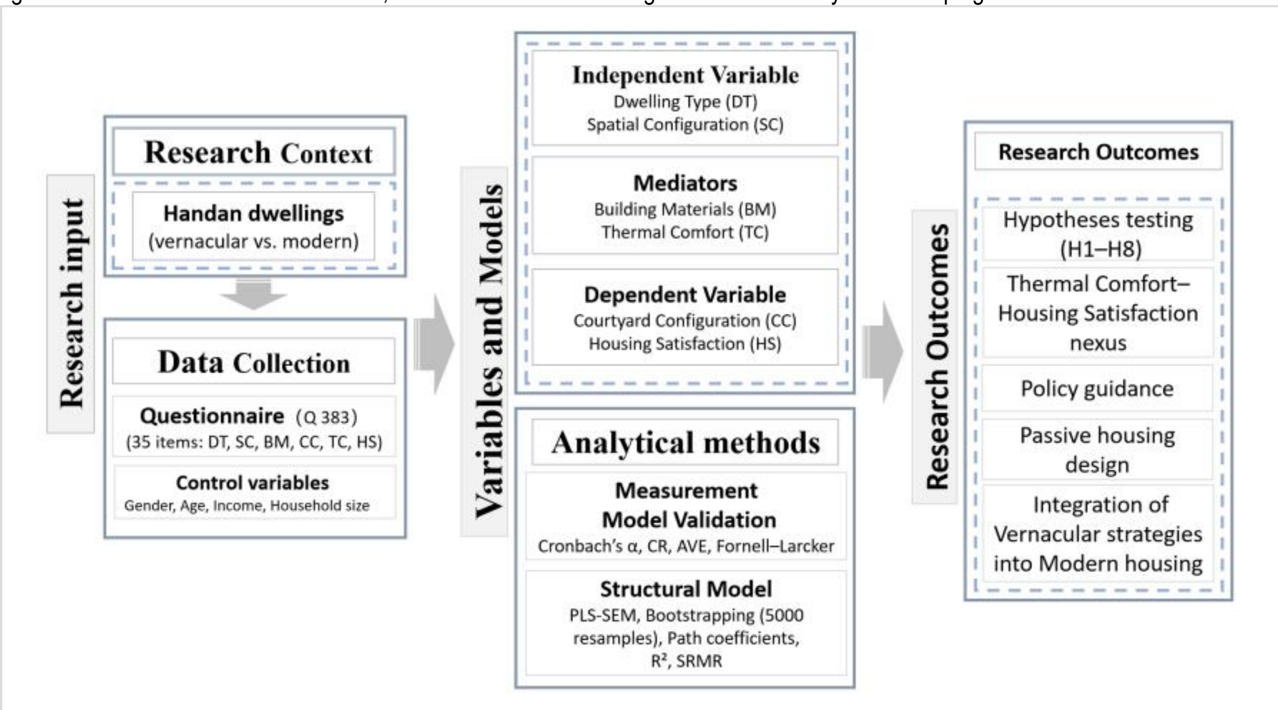

Figure 1. Framework for Understanding Environment-Behaviour Relationships

3.2 Study Area

Fig. 2: Study Area Location and the Condition of Houses in the Surveyed Village

The empirical investigation took place in Shatun Village, Handan City, located in the northern region of China, which experiences a hot-summer and cold-winter transitional climate. This area is characterised by high solar radiation intensity, significant diurnal temperature variations, and seasonal thermal stress, making it an ideal setting for evaluating climate adaptability in rural housing. The study examined two primary types of residential buildings:

i. Vernacular Courtyard Dwellings: These were built mainly before 2000, using brick masonry and designed with passive spatial layouts.

ii. Modern Rural Dwellings: Constructed after 2010, these houses utilise reinforced concrete systems and are influenced by urban housing models.

The coexistence of these two housing types allows for a comparative assessment of their thermal and spatial performance under similar climatic conditions.

3.3 Data Collection and Survey Procedure

A structured questionnaire survey was implemented between July and August 2025, a period characterised by peak summer conditions, to capture residents' thermal perceptions and corresponding behavioural responses. Through stratified household sampling, 383 valid questionnaires were successfully collected. The questionnaire was divided into four core sections: (i) demographic characteristics, (ii) spatial perception and dwelling attributes, (iii) thermal sensation and adaptive behaviours, and (iv) housing satisfaction assessment. Thermal perception indicators were measured using 5-point Likert scales adapted from existing research on adaptive thermal comfort. Behavioural adaptation variables included window operation frequency, courtyard utilisation, ventilation habits, and relocation of activities. All participants volunteered, and the Research Ethics Committee of Universiti Teknologi MARA granted ethical approval.

Table 1. Operation Definitions.

Latent variable	Content summary
DT (Dwelling Type)	Residential forms are categorised according to dwelling typology and key architectural characteristics.
SC (Spatial Configuration)	Spatial organisation is described in terms of layout structure, including the arrangement of openings, circulation patterns, and functional zoning.
BM (Building Materials)	The performance of primary construction materials and building envelopes is evaluated with respect to their thermal resistance, acoustic properties, and durability.
CC (Courtyard Configuration)	Courtyard spaces are characterised by their physical composition and functional roles, such as the integration of vegetation and shading elements.
TC (Thermal Comfort)	Indoor environmental quality is assessed through a combination of measured conditions and occupants' thermal perceptions.
HS (Housing Satisfaction)	The overall residential evaluation encompasses multiple dimensions, including comfort, privacy, daylighting, ventilation, and energy performance.

3.4 Measurement Model Development

All latent constructs were operationalised using multiple reflective indicators grounded in post-occupancy evaluation data and established environment–behaviour theoretical frameworks. The measurement model was rigorously evaluated in accordance with established Structural Equation Modelling (SEM) guidelines to ensure robust reliability and validity.

Reliability was assessed using Cronbach's alpha and composite reliability (CR), with acceptable thresholds set at 0.70. Convergent validity was determined using the average variance extracted (AVE), with values exceeding 0.50 considered satisfactory. Discriminant validity was further examined using the Fornell–Larcker criterion to confirm the distinctiveness of the constructs.

Overall, these validation procedures confirmed the adequacy of the measurement model, thereby providing a sound basis for subsequent structural model estimation.

3.5 Structural Equation Modelling (PLS-SEM)

In this study, Partial Least Squares Structural Equation Modelling (PLS-SEM) was implemented using SmartPLS 4.0. This method was selected for its proven efficacy in predictive analysis of intricate latent-variable relationships and its suitability for moderate sample sizes. PLS-SEM has become a widely adopted analytical tool in research on environment-behaviour interactions and built environment studies, primarily because it enables concurrent evaluation of measurement reliability and the causal associations between architectural and behavioural variables. To verify the statistical significance of the path coefficients, a bootstrapping procedure with 5,000 resamples was conducted, and the model fit and predictive performance were comprehensively evaluated by examining the significance of path coefficients (β), the coefficient of determination (R^2), predictive relevance (Q^2), and the Standardised Root Mean Square Residual (SRMR, with a threshold of < 0.08).

3.6 Research Validity and Analytical Procedure

To uphold the methodological rigour required for publication in line with E-BPJ standards, multicollinearity diagnostics were performed using Variance Inflation Factors (VIFs), all of which were confirmed to be below 5.0. Predictive capacity was further evaluated via blindfolding procedures. The entire analytical workflow was structured in five consecutive phases: questionnaire development, field survey implementation, measurement model validation, structural model testing, and interpretation of the interrelationships between environmental and behavioural variables.

4.0 Findings

4.1 Respondent Profile and Dwelling Characteristics

A total of 383 valid questionnaires were analysed to investigate thermal perception and residential satisfaction among rural occupants. The respondents were divided between two main types of dwellings: vernacular courtyard houses (51.7%) and modern rural homes (48.3%). Most participants had lived in their current homes for over ten years, providing a reliable basis for evaluating environmental performance after occupancy. Vernacular dwellings were primarily single-storey courtyard houses with brick masonry walls, high thermal mass, and semi-open transitional spaces. In contrast, modern houses are mainly reinforced concrete structures, characterised by larger window openings and compact internal layouts. Preliminary observational data suggest that residents of traditional vernacular homes experienced better natural ventilation and lower perceived summer overheating, whereas occupants of modern houses relied more on mechanical cooling systems.

4.2 Measurement Model Assessment

Before the formal hypothesis-testing phase, the measurement model was evaluated comprehensively to verify its reliability and validity. Internal consistency reliability was verified, as the Cronbach's Alpha and Composite Reliability (CR) values of all latent constructs exceeded the suggested critical value of 0.70.

Table 2. Measurement Model Reliability and Validity Results

Construct	Cronbach's α	Composite Reliability (CR)	AVE
BM	0.900	0.929	0.649
CC	0.714	0.901	0.623
DT	0.886	0.901	0.695
HS	0.777	0.873	0.402
SC	0.793	0.838	0.477
TC	0.806	0.891	0.527

Convergent validity was examined through the Average Variance Extracted (AVE) index, and the majority of constructs met the recommended 0.50 threshold. The AVE value for the Housing Satisfaction (HS) construct was 0.402, slightly below the suggested criterion, yet the construct was retained for subsequent analysis due to its CR value above 0.70. Existing scholarly research has established that AVE values below 0.50 can still be deemed acceptable when the corresponding Composite Reliability is sufficient (Fornell & Larcker, 1981; Hair et al., 2022), which signifies that the HS construct maintains acceptable internal consistency. This result is consistent with the PLS-SEM application guidelines for exploratory research in the field of environment-behaviour interactions. In addition, discriminant validity was assessed using the Fornell–Larcker criterion, which indicated that each construct had a higher variance share with its own observed indicators than with other latent constructs in the model. Collectively, the above results confirm that the measurement model has satisfactory reliability and validity, making it suitable for subsequent structural model analysis.

4.3 Structural Model Evaluation

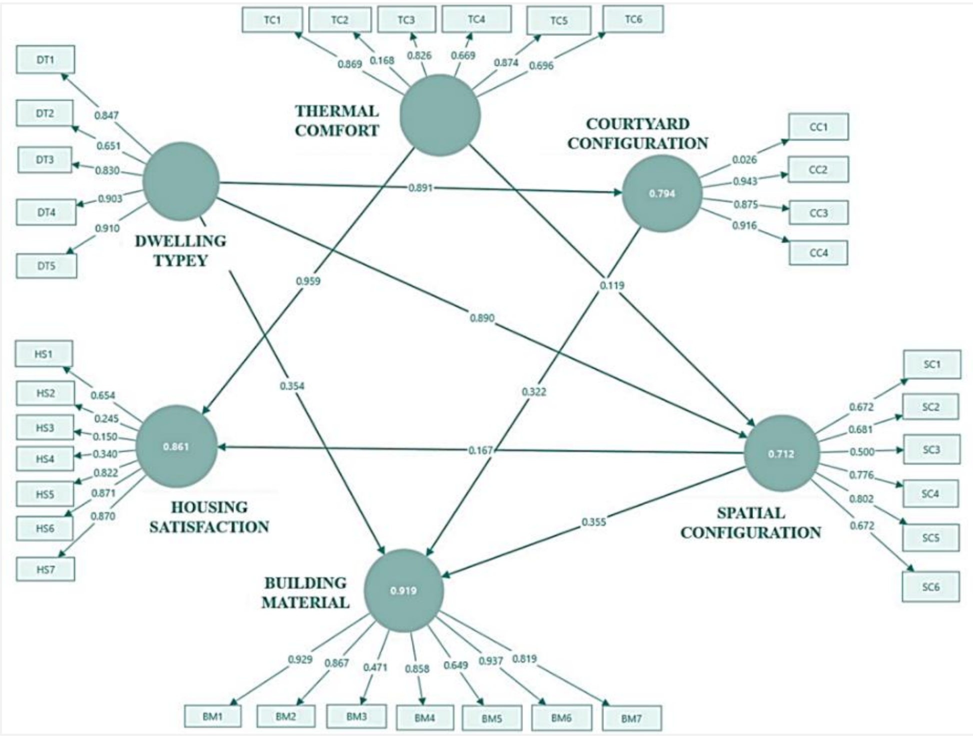

Fig. 2: Structural Equation Model with Path Coefficients

After the validation of the measurement model, the structural model was analysed via a bootstrapping approach with 5,000 resamples, and the results revealed significant causal linkages among architectural features, thermal comfort perceptions and housing satisfaction. Among all the studied variables, Dwelling Type exerted the most prominent effect within the model, significantly influencing Thermal Comfort ($\beta = 0.959$, $p < 0.001$), Courtyard Configuration ($\beta = 0.891$, $p < 0.001$), and Spatial Configuration ($\beta = 0.890$, $p < 0.001$). These results show that housing typology is a core determinant of environmental adaptability and spatial performance in rural residential contexts.

In addition, Building Materials was found to have a significant positive impact on Spatial Configuration ($\beta = 0.355$), suggesting that the properties of building envelopes shape spatial environmental behaviours through their thermal regulation performance. Courtyard Configuration also made a positive contribution to Spatial Configuration ($\beta = 0.322$), highlighting the climatic adaptability value of semi-open spatial systems. Moreover, Spatial Configuration had a significant positive effect on Housing Satisfaction ($\beta = 0.167$, $p < 0.05$), thereby verifying its mediating role between building physical attributes and occupants' experiential satisfaction.

4.4 Predictive Power of the Model

Coefficients of determination (R^2) were employed to assess the structural model's explanatory power, with Thermal Comfort and Spatial Configuration both exhibiting strong explanatory power—an outcome reflecting robust predictive correlations between residential morphological characteristics and occupants' environmental perceptions. Predictive relevance was further confirmed by Q^2 values, which indicated that the developed model exhibits favourable predictive performance for behavioural responses and housing satisfaction. While the Standardised Root Mean Square Residual (SRMR) value of 0.168 surpasses the generally recommended 0.08 threshold, this study adopts a PLS-SEM analytical approach that prioritises predictive capacity over stringent model fit requirements. Notably, existing scholarly research has highlighted the need for caution in interpreting SRMR values in PLS-SEM, particularly in exploratory research frameworks (Henseler et al., 2016). For this reason, the model evaluation in the present study emphasises R^2 and Q^2 values, which collectively demonstrate the model's satisfactory explanatory and predictive power. In line with PLS-SEM analytical norms, the model also achieves acceptable fit, and the integrated thermal-spatial analytical framework is thus proven to effectively account for occupants' environmental experience in rural residential settings.

Table 3. PLS-SEM Model Fit Indices.

Fit Criterion	Saturated Model	Estimated Model
SRMR	0.165	0.168
d_ULS	17.202	17.691
d_G	n/a	n/a

Chi-square	infinite	infinite
NFI	n/a	n/a

Table 4. R^2 Values for Endogenous Latent Constructs.

Endogenous Latent Construct	R^2	Adjusted R^2
Building Materials (BM)	0.919	0.919
Courtyard Configuration (CC)	0.794	0.794
Housing Satisfaction (HS)	0.861	0.860
Spatial Configuration (SC)	0.712	0.711

4.5 Environment–Behaviour Mediation Effects

Further analysis reveals that Spatial Configuration serves as a vital link between dwelling characteristics and housing satisfaction. Instead of directly impacting satisfaction, architectural features influence behavioural opportunities that allow occupants to adapt to thermal conditions. Courtyard spaces, for instance, encourage adaptive behaviours such as spending time outdoors, adjusting ventilation, and shifting activities over time. These adaptations enhance perceived comfort without increasing energy consumption. This finding supports the Environment-Behaviour hypothesis, which posits that environmental quality arises from the interaction between spatial affordances and human adaptation processes. The results confirm that passive spatial design strategies improve both environmental performance and subjective well-being in rural residential settings.

5.0 Discussion

5.1 Thermal–Spatial Interaction in Rural Residential Environments

The findings suggest that the thermal performance of rural dwellings is mainly influenced by the interaction between spatial configuration and occupants' behavioural adaptations, rather than by building materials alone (Xu et al., 2020; Ibrahim et al., 2020). The notable impact of dwelling type on thermal comfort indicates that vernacular courtyard houses incorporate climate-responsive spatial strategies developed through long-term environmental adaptation. In contrast to modern rural housing, vernacular dwellings manage indoor conditions through spatial buffering, shaded transitional areas, and natural ventilation mechanisms. The design of courtyard spaces serves as a microclimatic regulator by reducing solar heat gain while facilitating airflow and outdoor activities. These results indicate that sustainable rural housing should revisit and adapt vernacular spatial principles rather than rely on standardised construction models that undermine passive environmental regulation. From an Environment–Behaviour perspective, architectural space functions as an adaptive system that allows occupants to respond dynamically to thermal conditions through their daily use of space (Huang et al., 2015).

5.2 Behavioural Adaptation as a Mediating Mechanism

A key contribution of this study is identifying spatial configuration as a crucial link between environmental performance and housing satisfaction. The findings indicate that occupants actively adapt to thermal conditions by engaging in behaviours such as opening windows, using courtyards, and relocating activities. In line with adaptive thermal comfort theory, comfort arises from the interaction between humans and their environment rather than from fixed indoor temperature settings (De et al., 2020). Courtyard spaces enhance behavioural flexibility by providing semi-outdoor environments that support both seasonal and temporal adaptations. This mediation effect suggests that improving spatial adaptability can lead to greater residential satisfaction while reducing reliance on mechanical cooling. Consequently, it presents a viable pathway toward achieving low-carbon rural living environments.

5.3 Implications for Climate-Responsive Rural Housing Design

The shift towards modern rural housing has changed traditional environmental behaviour patterns by limiting spatial adaptability and the connection between indoor and outdoor spaces. The structural model shows that restricted adaptive spaces hinder occupants' ability to manage their thermal conditions naturally. The findings suggest several key design implications:

1. Reintegration of courtyard systems as passive regulators of microclimates.
2. Creation of shaded semi-open transitional areas that support behavioural adaptation.
3. Climate-responsive envelope designs that combine thermal mass with controlled ventilation.
4. Design approaches focused on human behaviour that prioritise spatial interaction rather than relying on technology.

These strategies emphasise a human-centred approach to environmental design, moving beyond conventional energy-efficiency optimisation.

6.0 Conclusion

This study employed empirical modelling approaches within an Environment-Behaviour framework to investigate the correlations between thermal conditions and spatial attributes in rural residential buildings. The key conclusions derived from the research are as follows:

1. Dwelling type serves as the dominant factor that impacts the environmental performance of rural dwellings.
2. Spatial configuration acts as a crucial mediator in the relationship between architectural design elements and residents' housing satisfaction.
3. Courtyard layout and design features can significantly promote the level of adaptive thermal comfort for occupants.
4. Residents' behavioural adaptation can effectively enhance the efficiency of passive design strategies applied in rural housing.

7.0 Recommendations

For future rural development policies, priority should be given to climate-responsive planning strategies rather than to standardised construction methods. Furthermore, extending future research to cover diverse climatic regions and different seasonal conditions will improve the generalizability of the conclusions. Incorporating human behaviour research into architectural design offers a feasible way to build resilient, sustainable rural living environments across Asia.

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