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Climate Adaptation Analysis and Comfort Optimization Strategies for Traditional Residential Buildings in Hot-Summer, Cold-Winter Regions: A Case Study in Xuzhou, China

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Abstract: Climate change and the energy crisis have catalyzed the architectural industry's consideration of green and energy-efficient buildings. With the continuous deepening and expansion of research, people have gradually realized the reference value of the passive design strategies embedded in traditional residential buildings for contemporary architectural design and renovation. This paper takes the traditional residential buildings on Hubu Mountain, Xuzhou, as its research object, and explores their thermal and wind environment characteristics through field investigations and software simulation analysis. It is found that Xuzhou's traditional houses have good temperature regulation, with fluctuations of about 5 °C indoors and 10 °C outdoors in summer and about 7 °C indoors and 12 °C outdoors in winter. Their form, material and structure are well adapted to the local climate. There is also a need to optimize the buildings' moisture resistance and ventilation for better comfort. Subsequently, this study analyzes the climate adaptability features in traditional building construction techniques and then extracts climate adaptability methods, proposing targeted optimization and renovation suggestions, aiming to contribute to the sustainable development of architecture and ecology.

Keywords: hot summer; cold winter; climate adaptability; optimization strategy; traditional residential building; Xuzhou

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1. Introduction

Since the first Industrial Revolution, society has developed rapidly, and now architecture has entered a period of rapid growth. The industrialization process was accompanied by significant energy consumption and environmental pollution. According to the data released by CAIT Climate Data Explorer, China is the world's largest emitter of greenhouse gas carbon dioxide emissions, accounting for 26.83% of the total global emissions; its emissions exceed those of the USA, which is ranked second and accounts for 12.47% of the global share [1]. Globally, the carbon emissions from the construction industry account for approximately 40% of total greenhouse gas emissions [2]. Compared with other countries and regions, China's construction industry makes up a large share of energy consumption and carbon emissions, accounting for 46.5% of the country's total energy consumption and 51.3% of total emissions [3,4]. At the United Nations General Assembly on September 22, 2020, the Chinese government officially proposed that China's carbon dioxide emissions will peak by 2030 and that by 2060, China will be carbon-neutral. The realization of this dual carbon goal requires the efforts of the whole society [5]. Exploring the road to green and low-carbon transformation of buildings is an important direction that cannot be ignored in reducing energy consumption and realizing sustainable development. In the achievement of this transformative process, the energy-saving potential and excellent passive design strategies demonstrated by traditional Chinese residential buildings deserve in-depth research and translation. This includes, but is not limited to, the siting and orientation of the building, the selection and combination of building materials, and the construction and practice of building details.

Xuzhou is located in eastern China and has a typical temperate monsoon climate (See Figure 1). In the summer, under the influence of the southeast monsoon, there is increased precipitation along with higher temperatures; meanwhile, in winter, under the influence of the northwest monsoon, there is reduced precipitation along with lower temperatures. This climate is mainly found in the eastern part of the Asian–European continent, including areas such as eastern China and northern Japan. In China, the hot-summer, cold-winter regions cover an area of about 1.8 million square kilometers, accounting for 18.8 percent of the total land area, while the population accounts for 40 percent of the total population and 48 percent of the country's gross national product [6,7]. These areas are densely populated and economically developed, but the ecological and climatic conditions are also more severely damaged [8]. Research into buildings in this type of region can not only improve indoor physical environments but also contribute to the promotion of sustainable development of the ecological environment [9]. In recent years, with the economic development of the Xuzhou area and the rapid improvement in people's standards of living, residents have generally installed their own heating and air-conditioning equipment. As a result of the lack of scientific design and adoption of corresponding technical measures, the energy consumption of buildings' heating equipment in winter and air-conditioning equipment in summer has risen sharply in the region, resulting in high energy losses [10], a substantial increase in residents' expenditures on energy, and no fundamental improvement in living conditions. However, as Xuzhou is a city with a rich history, there are many passive design strategies that can be translated from the traditional houses in the region. By scientifically analyzing the climate adaptability characteristics of traditional building techniques, we can better understand the unique spatial forms of local dwellings. At the same time, climate adaptability can be quantified through the screening of traditional building techniques, facilitating their future reuse. Improving the energy efficiency of buildings through the exploration of passive design principles and techniques for traditional buildings is one of the effective ways of achieving realizable development [11].

Figure 1. Geographic location of Xuzhou, Jiangsu, China.

2. Overview of State of the Art and Background Context

At present, the research results relating to passive energy-saving strategies for buildings in hot-summer, cold-winter areas are reasonably abundant. The main research content can be divided into the following three aspects in relation to hot-summer, cold-winter areas: research on building performance; energy-saving transformation methods for the buildings; and optimization strategies for the buildings. By studying the performance of buildings in this type of climate zone, researchers have explored the main factors affecting building comfort; on that basis, they have put forward suggestions for retrofitting and upgrading buildings in a targeted manner.

2.1. Research on Building Performance in Hot-Summer, Cold-Winter Areas

The maintenance structure of a building is the main factor affecting its comfort. Scholars have studied the doors, windows, external walls, and roofs of buildings in hot-summer, cold-winter regions through field research, to assess their performance in heat preservation, ventilation, and moisture protection. This is a process of identifying problems, which subsequently provide a research direction and scientific basis for how to improve the thermal comfort of buildings subsequently.

For example, Gong et al. (2023) [12] took five different types of public buildings in the hot-summer, cold-winter region of the east coast of China as their research object, collected data, measured over 10 years, of 2000 buildings and analyzed the energy-saving potential (ESP) and the impact of each influencing factor on the energy consumption of the buildings. The study laid the foundation for the development of building energy performance assessment and diagnostic tools. Pozas et al. (2016) [13] analyzed the hygrothermal behavior of the interior of vernacular buildings in a hot-summer, cold-winter region in Spain. The results suggested that during the hot period, indoor conditions were comfortable without the need for an additional energy supply. Nevertheless, in the cold period, indoor conditions were warmer than outdoor conditions, but an additional external energy supply would be required to achieve the comfort zone. Tokbolat et al. (2020) [14] investigated various types of façades used in residential buildings in Kazakhstan and evaluated their performance in terms of their impact on the buildings' energy consumption. Lamrhari et al. (2018) [15] evaluated the optimal combination of all the studied energy-efficiency measures in a variety of climatic conditions, including a hot summer and cold winter, through the study of the envelope insulation, orientation, and absorption coefficients of roofs and façades of apartment buildings. Luka et al. (2022) [16] studied the relevance of passive design measures selected for heating and cooling energy utilization in single-family detached buildings at five sites in Europe. It was found that apart from effective shading, the most relevant parameter affecting cooling energy consumption was the window-to-ground ratio. Zhong et al. (2023) [17] simulated the indoor thermal environment of the house using Phoenics 2016 software, and found that enlarging the horizontal windows and roof windows could significantly improve the indoor air flow. Shi et al. (2016) [18] took the experimental building extension of Huazhong University of Science and Technology as the research object. The thermal environment parameters and building energy consumption of the experimental building were monitored. Wei et al. (2022) [19] conducted a one-year field study on residential buildings in Xi'an, China, identifying the acceptable temperature ranges for 80% and 90% of the seasons, as well as adaptive thermal comfort models and thermal comfort zones. These studies have provided a scientific basis for the energy-efficiency retrofitting of local buildings.

2.2. Energy-Saving Retrofit Methods for Buildings in Hot-Summer, Cold-Winter Areas

In response to the problems identified in the building performance studies, researchers have proposed and trialed many more feasible suggestions.

Among them, the architectural practice of Malaysian architect Ken Yeang is highly representative of the field of bioclimatic architecture [20]. He has proposed minimal impact on the natural environment during construction and has aimed to integrate the built environment with the ecosystem of the biosphere. Lamberti et al. (2024) [21] explored climate adaptation methods using Le Corbusier's modern building renovations as an example. It is argued that adaptive strategies can complement traditional retrofitting when responding to current and future climatic conditions. Building upon previous research, Harkouss et al. (2018) [22] have conducted comprehensive studies on passive optimization design for residential buildings, and suggested implementing suitable passive cooling strategies, such as louvers and natural ventilation, to reduce building energy demands (cooling and heating) and life cycle costs (LCCs), exploring the optimal passive solutions for architecture. Based on the three pillars of sustainability, Van Ellen et al. (2021) [23] developed an adaptive building framework that incorporated systems thinking. The study, which considered the building and its components to meet the changing requirements for user comfort and energy saving, recommended a rhythm-based architectural strategy for future adaptive designs. Figueirdo redesigned a passive house in Portugal and realized reductions of 62% and 72% in the heating and cooling demand, respectively [24]. Hao et al. (2023) [25] explored the optimal thickness of exterior wall insulation incorporating the effect of indoor wet buffering in hot-summer, cold-winter regions. Jiang et al. (2018) [26] studied the effect of external window performance on the energy consumption of residential buildings in hot-summer, cold-winter areas. The results showed that reducing the heat transfer coefficient and shading coefficient of external windows can significantly reduce the buildings' energy consumption. The results of these studies provide an informative basis for improvements in building energy efficiency in hot-summer, cold-winter regions.

2.3. Building Optimization Strategies for Hot-Summer, Cold-Winter Regions

In addition to the above explorations of green and energy-efficient buildings, there are also architects who have tried to identify valuable experiences, techniques, and inspirations from traditional architecture and then further develop and improve them to form a unique eco-design approach.

In "Guangdong Folk Houses", edited by Lu Yuanding and Wei Yanjun, a comprehensive analysis was undertaken of the integration of architecture, regional topography, and climatic conditions, and corresponding strategies were proposed for the ventilation, shading, and thermal insulation treatment of Guangdong folk houses in their specific climatic environment, providing valuable references for the ecological study of traditional Chinese folk houses [27]. Huo et al. (2024) [28] proposed a new multi-objective optimization model based on Latin hypercube sampling (LHS). The model combined combines a genetic algorithm (GA) with an artificial neural network (ANN) to evaluate and optimize the technology used for retrofitting projects, aiming to provide solutions for the energy-saving renovation of existing buildings. Zeng et al. (2017) [29] analyzed the local climate of traditional villages in the Lingnan area on the basis of numerical simulations. The results showed that the traditional grid layout has a significant impact on the microclimate of residential streets. In the summer, the areas near the entrance to shady alleys and the edges of residential buildings offer relatively pleasant wind conditions, while the living spaces within the traditional architectural layout maintain good thermal comfort environments owing to the insulation provided by the street space. Min et al. (2016) [30] provided a detailed interpretation of the responsive measures and passive design strategies formed by the opening of residential interfaces in Suzhou during the process of long-term adaption to regional climates. Meanwhile, using bioclimatic diagrams and climate factor decomposition analyses, the regional climate response model of interface openness and its relationship with thermal comfort environments were studied. Xu et al. (2019) [31] analyzed the characteristics of traditional residential buildings in the Qinba mountain region that are adapted to the climate environment. The advantages and disadvantages of the physical environment of housing in response to climate characteristics were summarized, and effective climate adaption strategies, such as natural ventilation, thermal insulation, and buffering spaces, were proposed for the traditional earthen residential buildings. Amin et al. (2018) [32] conducted a study on climate-responsive solutions for traditional dwellings in a southwestern Iranian city, comparing them with modern buildings and analyzing their impact in terms of thermal comfort and energy consumption. Indraganti conducted a study on climate adaptation in typical traditional settlements in India [33]. The interrelationship between settlements and climate was discussed in terms of layout of living space, courtyard patterns, and choice of building materials. At the same time, the cooling effect of the use of centralized layout and narrow, high-density streets at lower temperatures was analyzed.

2.4. Research Review

To summarize, scholars have made many useful suggestions on energy-saving building renovation and design methods in hot-summer, cold-winter regions according to the social living habits and economic development level of different regions. Architects have transitioned from focusing on the defects of housing performance to the importance of innovation in building materials and construction methods, which is a process from finding problems to solving them. After reaching the bottleneck of technological means, architects have found that in regions with varying climate characteristics ranging from −10 °C to 40 °C, built environments have been created that do not rely on fossil fuels to meet human habitation needs. In today's context of environmental crises and increasingly pressing energy issues, there is a need to further explore, learn from, and transform the low energy consumption and appropriate technology experiences derived from traditional dwellings in order to achieve the sustainability of buildings in terms of both the environment and social culture [34]. Exploring regional design strategies that have been applied to traditional dwellings and applying them to the renovation of existing and new dwellings will provide inspiration for dwelling construction in other regions and contribute to energy efficiency and sustainable development in the country as a whole.

3. Methodology

This paper used a combination of qualitative and quantitative analytical methods, including field measurement and software simulation. By exploring the indoor and outdoor physical environments of traditional buildings, it is possible to more accurately distill the passive strategies involved in responding to climate. In addition, recommendations for optimization and retrofitting can be targeted [35,36].

The field measurement work was conducted as follows:

Firstly, based on the field research, different individual buildings (preservation status and representative architectural style) were examined and screened to determine the location of the measurement points; then, data on indoor and outdoor air temperature, humidity, and wind speed of different buildings were collected under two extreme weather conditions in summer and winter; finally, the collected data were utilized to perform comparative analyses. The field measurements of the indoor thermal environment were obtained to investigate the effects of climate responsive strategies.

The software simulation works comprised the following steps:

In the thermal environment simulation, the first step was to use the Weather Tool climate analysis software that is part of the Ecotect ecological building analysis software. The Weather Tool visualizes annotated climate data, characterizes climate data, and facilitates the analysis of the effectiveness of reactive strategies, focusing on the macro level. The thermal environment of the building is then analyzed, and the main factors affecting that environment are evaluated.

Phoenics software was chosen for the wind environment simulation. Phoenics is powerful and easy to use, with full functionality within the software and direct access to PLANT and INFORM functions, eliminating the need to write FORTRAN source code. The simulation results can be used for the targeted improvement of the indoor wind environment in buildings [37].

Measurements and simulations can be mutually verified with each other to enhance the accuracy of the study conclusions. To facilitate understanding of the methodology, Figure 2 illustrates the framework of this study.

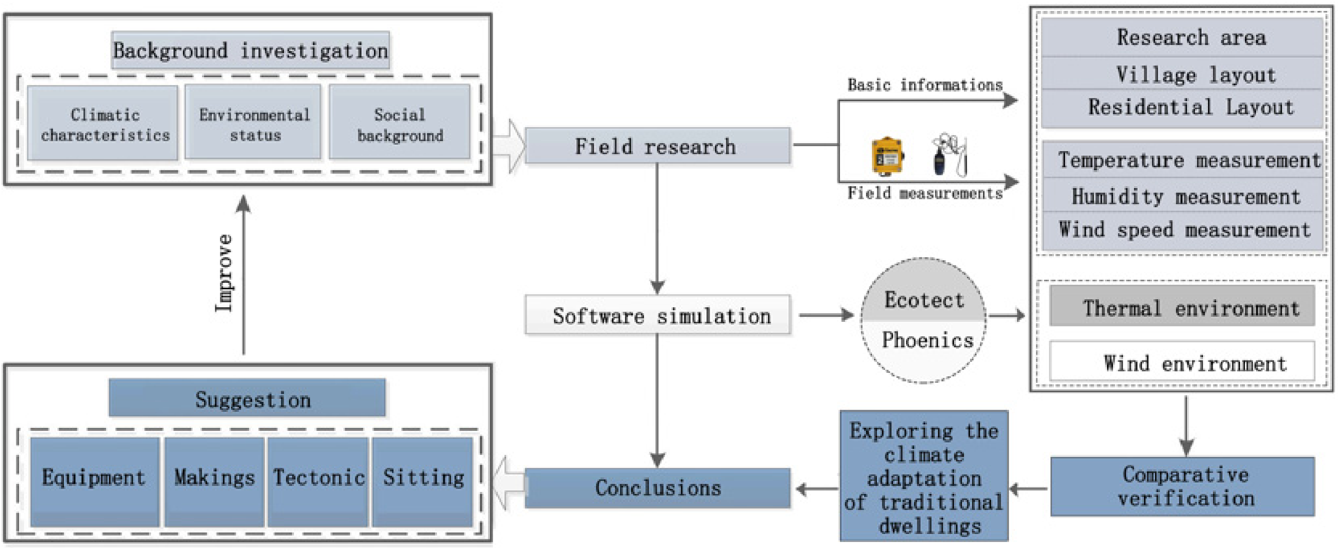

Figure 2. Overall research method framework.

3.1. Research Area

Xuzhou is located in Jiangsu Province, China. The terrain is mainly composed of plains and hills, with an elevation ranging from 30 to 40 m. The annual precipitation ranges from 1000 to 1500 mm, with the main rainy season occurring from June to September. The average daily temperature of the coldest month ranges from 0 to 10 °C, with an average relative humidity of around 70% [38]. In the hot and humid summer, natural ventilation is used to cool and dehumidify residential buildings. In the winter, when humidity is higher and the indoor environment is cold and wet, heating measures are required. Due to the long duration of the summer and winter seasons in northern Jiangsu and the short transitional seasons, ventilation is required in summer and wind protection is required in winter [39]. Therefore, traditional buildings in this region are often oriented parallel to the prevailing wind direction, with taller structures on the north side and lower structures on the south side. Additionally, due to significant fluctuations in river water levels and abundant summer rainfall, drainage is a key consideration in construction in northern Jiangsu. The sites are selected at higher elevations to facilitate the flow of rainwater away from them.

3.2. Village Layout

Located in the center of Xuzhou City, the Hubu Mountain Historical Complex is a typical traditional settlement in northern Jiangsu. The houses are built along the slopes, naturally forming a staggered pattern, so that the whole complex has good ventilation and lighting conditions. Due to the monsoon climate, Xuzhou is cold in winter, and the north wind prevails; therefore, the buildings are positioned facing the mountain on its northern side to block the north winds. In addition, the southeast wind prevails in summer, and the buildings on the slope face the wind from the south; therefore, the indoor ventilation is good, and the effect of the hot and dry climate in summer on the interior of the buildings is reduced. In terms of natural environmental conditions, residential characteristics, unique customs, and many other aspects, the buildings are representative of the typical residential and cultural types in northern Jiangsu. Considering the representative and completeness complete status of the buildings, this paper selected the Yu Family Compound as the object of its empirical research.

3.3. Residential Layout

3.3.1. Form

In Xuzhou's traditional architecture, the courtyard house and three-sided courtyard are the primary building forms. The typical floor plan is a "one bright, two dark" layout with three bays [40]. Wooden partitions are commonly used indoors, with single doors for each partition. The scale of the partitions is relatively small, and their height extends up to the beams, while maintaining the original structure above the beams. This design allows smooth air circulation within the buildings and provides a relatively stable physical environment indoors (Figures 3 and 4).

Figure 3. Courtyard house in the Yu Family Compound.

Figure 4. Jishan Hall in the Yu Family Compound.

The Yu Family Compound faces south with its back to the north, and the plane layout is mostly courtyard houses and three-sided courtyards. It covers a land area of approximately 4000 square meters, with a total building area of around 1400 square meters. The Yu Family Compound is located on a gentle slope of Hubu Mountain, exhibiting variations in elevation and utilizing multiple steps. The central axis is represented by the central courtyard, with the main entrance positioned along this axis. The eastern and western courtyards extend from the central courtyard. In contrast to the flat central courtyard, the eastern and western courtyards have significant terrain differences, resulting in a more flexible and diverse architectural layout. The overall floor plan consists of multiple interconnected three-sided courtyards and quadrangle courtyards, creating a well-balanced and harmonious arrangement.

3.3.2. Structure

1. The wall bases and column bases

The wall bases and column bases of the Yu Family Compound are made of a large number of stones and bricks. Among the commonly used materials in Xuzhou, stone materials are known for their superior compressive strength and waterproofing properties, followed by brick walls. Therefore, in traditional architecture, stone materials are typically employed for the wall base and column bases to prevent the deformation that is typically caused by the long-term contact between wood or adobe bricks within the walls and the damp ground.

2. Walls

The walls of the Yu family Compound are generally thicker, about 500 mm. This is because Xuzhou is located in a cold region with cold winters and hot summers. Thick walls help maintain a relatively stable thermal environment indoors. The walls are primarily constructed using a combination of inner adobe bricks and outer fired bricks, leveraging the physical advantages of each material (Figure 5). Adobe bricks have a high thermal storage coefficient, allowing them to absorb and store heat from the sun during the day and release it at night. The outer brick walls provide excellent rain and moisture resistance, preventing deformation of the inner adobe bricks caused by water exposure.

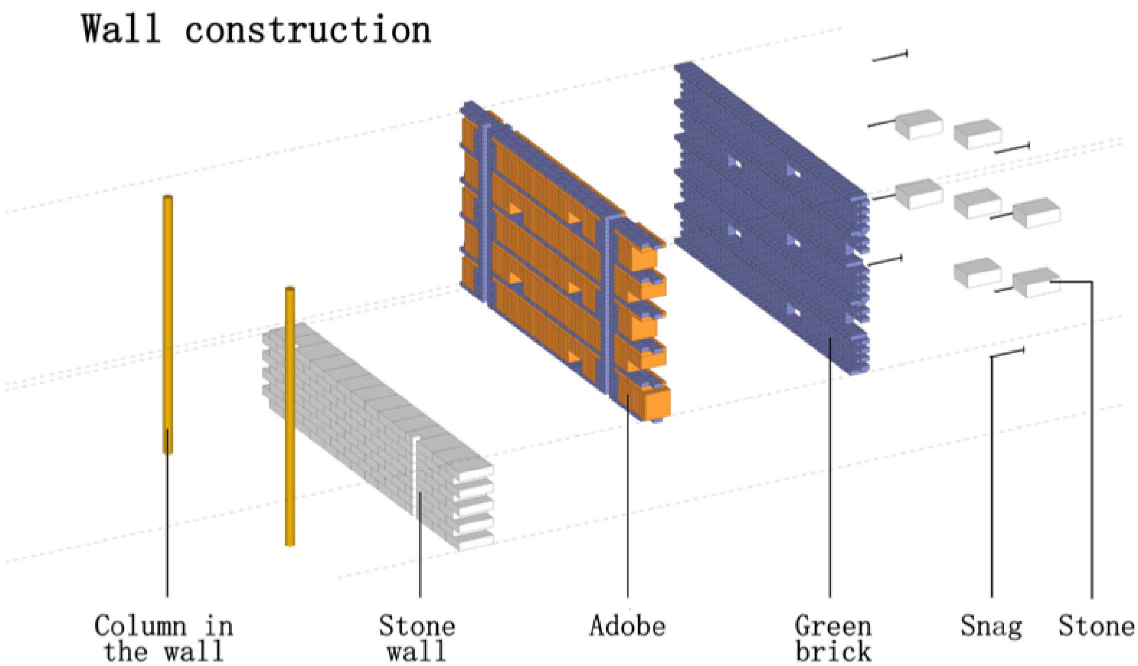

Figure 5. Wall construction of the Yu Family Compound.

3. Door and Window Openings

In the Xuzhou region, summers are characterized by high temperatures and abundant rainfall, leading to high indoor humidity levels. Traditional residential buildings often feature “Moon-gazing windows” on the gable walls, primarily for indoor ventilation purposes. The same goes for the Yu Family Compound. Windows are installed on both gable walls to facilitate air circulation through convection, which enhances the overall airflow within the building. In addition, the Yu Family Compound has ventilation holes installed at the bottom of the walls to promote ground-level air circulation and reduce ground-level humidity.

3.3.3. Materials

The building materials of the Yu Family Compound are typically locally sourced, consisting mainly of raw soil, lumber, bricks, and stones; hence, aiming to conserve manpower and resources. These materials are selected and utilized in different parts of the buildings based on their physical properties (Table 1).

Table 1. Analysis of advantages and disadvantages of building materials.

Typology	Advantage	Disadvantage
Raw soil	Good thermal insulation, recyclable, easy to use local materials	Poor waterproofing, easily deformed in water
Lumber	Low thermal conductivity	Corrodes easily
Brick	Harder, locally sourced	Poor waterproofing
Stone	Harder and more waterproof	Poor ventilation

1. Raw soil

In order to maintain good thermal performance inside a building, the use of materials with excellent insulation properties is a desirable approach. Raw soil is widely used in local residential buildings in Xuzhou because of the simplicity of its extraction, low cost, and recyclability. The walls of the Yu Family Compound use a large number of adobe bricks. The practice is to mix and mold raw earth, air-dry it, and then use it directly for building walls as an insulating layer inside the brick wall. This is known as the inner adobe and outer burnt-brick construction method, which helps to reduce thermal conductivity.

2. Lumber

The main structural components of the Yu Family Compound, such as beams, frames, doors, windows, and partition walls, are mainly made of wood. The main wood used is cedar, with other species such as pine, camphor, and maple. Due to limited timber resources, some of the houses use smaller sized timbers or use different kinds of timber through splicing.

3. Brick

As a whole, a large number of bricks were used in the Yu Family Compound, including for the walls, foundations, and floors. The types of bricks can be categorized into several groups based on their specific uses. Firstly, there are “Green Bricks”, which are primarily used for constructing walls and decorative screens. Secondly, there are thin square bricks, which are commonly used for indoor flooring in higher-grade buildings, such as the main halls. Lastly, there are strip bricks, which have narrower dimensions and are typically used for indoor flooring in lower-grade buildings.

4. Stone

Stone is characterized by hardness, and has a higher compressive strength and hardness compared to brick materials. In addition, stone has the advantages of good water resistance, easy availability, low cost, and low processing requirements. The Yu family Compound is mainly made of limestone, which is gray or white in color. Limestone is used for the foundations, platforms, exterior walls, wall bases, and door and window openings. It not only meets the requirements of indoor waterproofing and moisture resistance but also has load-bearing capacity.

4. Field Measurement

4.1. Measurement Objects

A multitude of buildings with diverse architectural styles can be found within the Yu Family Compound in the Hubu Historical and Cultural Street Area in Xuzhou. In this study, several representative buildings within the Yu Family Compound were selected for an investigation of their indoor physical environment (Figure 6).

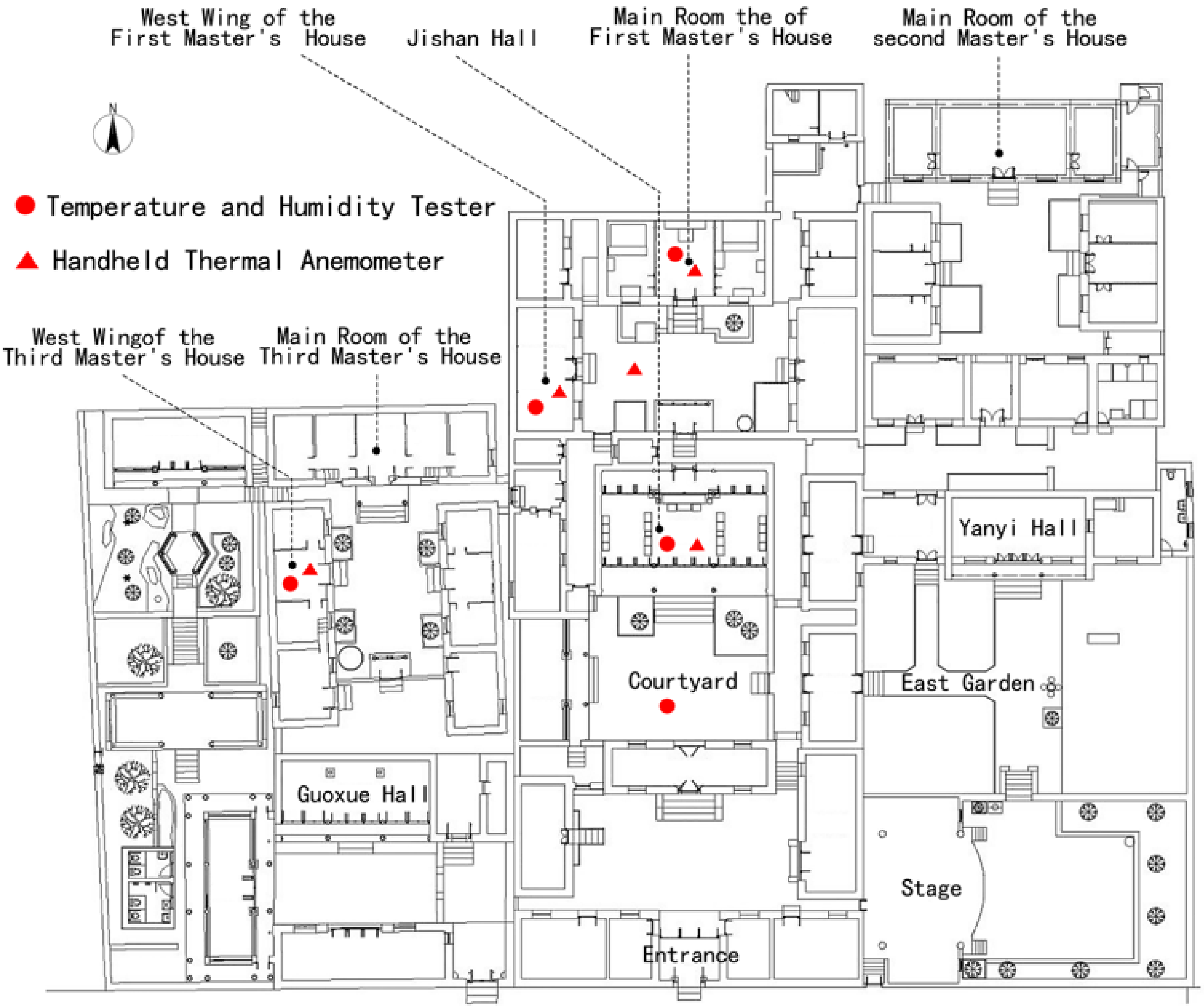

Figure 6. Layout of measuring points in the Yu Family Compound.

4.2. Measurement Setting

In order to comprehensively understand the climatic adaptability of traditional residential buildings in Xuzhou, typical weather conditions during the summer and winter seasons were selected for the evaluation of the indoor and outdoor environments. The measurement locations and corresponding times are depicted in Table 2.

Table 2. Main instruments used in building physical environment testing.

Name of Instrument	Measuring Parameter	Measuring Range and Accuracy	Instrument Picture	Operating Method
Tinytag Internal Temperature Relative Humidity	Temperature and humidity	Temperature measurement range: −25~85; Humidity measurement range: 0~100% RH		Continuous automatic recording every 5 min, day and night.
MODEL 6006 Handheld Thermal Anemometer	Indoor and outdoor wind speed test	Range: 0.01~20.0 m/s (20~3940 PM); Accuracy: ±5% of indicated value or 0.015 m/s (+2 FPM); Resolution: 0.01 m/s		Manual recording, averaged every five minutes.

Instruments were positioned at each measurement point, and data were continuously collected for 72 h. The on-site data collection primarily included the measurement of indoor and outdoor environmental parameters, including indoor temperature, humidity, and wind speed. The testing instruments used are listed in Table 2.

4.3. Measurement Results

4.3.1. Physical Environment Measurements in Summer

In terms of indoor temperature differences, the main room of the First Master's House exhibited the greatest reduction in outdoor peak temperatures during the daytime, while Jishan Hall showed the smallest reduction. The average temperatures of the rooms, from highest to lowest, were as follows: outdoor average temperature (31.89 °C) > Jishan Hall (30.10 °C) > the west wing of the Third Master's House (29.04 °C) > the west wing of the First Master's House (28.76 °C) > the main room of the First Master's House (28.32 °C).

In terms of the fluctuation range in temperature, Jishan Hall exhibited the highest fluctuation, spanning from 27.84 °C to 32.85 °C, with a range of 5.01 °C; followed by the west wing of First Master's House, spanning from 28.12 °C to 32.68 °C, with a range of 4.56 °C; then, the west wing of the Third Master's House, spanning from 28.03 °C to 32.44 °C, with a range of 4.41 °C; and finally, the main room of the First Master's House, spanning from 27.01 °C to 30.22 °C, with a range of 3.21 °C. Furthermore, the range of outdoor temperature fluctuation was 10.32 °C. The highest indoor temperature was found in Jishan Hall at 32.85 °C.

In terms of the delay in outdoor temperature peak values (Table 3), the peak in Jishan Hall occurred 60–240 min later than the outdoor peak, while the main room of the First Master's House experienced a delay of 120–300 min. The west wing of the First Master's House experienced a delay of 30–210 min, and the west wing of the Third Master's House experienced a delay of 90–240 min. The order of peak delays was as follows: the west wing of the First Master's House, Jishan Hall, the west wing of the Third Master's House, and the main room of the First Master's House.

Overall, indoor temperature fluctuations were smaller than outdoor temperature fluctuations. The maximum temperature difference is about 10 °C outdoors and 5 °C indoors (Figure 7).

In terms of air humidity differences, on the whole, the outdoor humidity was still lower than the indoor humidity (Figure 7). The highest relative humidity outdoors occurred on 1 July at 5 am, reaching 72%. The average humidity, ranked from highest to lowest, was as follows: the west wing of the First Master's House (60%) > the main room of the First Master's House (59%) > the west wing of the Third Master's House (57%) > Jishan Hall (52%) > the courtyard (48%).

Table 3. Yu Family Compound summer temperature peak.

Timing	Typology	Courtyard	Jishan Hall	West Wing of the First Master's House	West Wing of the First Master's House	West Wing of the Third Master's House
06.30	Maximum temperature (°C)	35.10	32.15	29.76	29.57	29.80
	Date of occurrence	11:55	15:55	15:55	15:35	15:55
07.01	Maximum temperature (°C)	36.83	31.67	28.69	29.60	29.79
	Date of occurrence	12:55	16:55	16:35	13:35	16:35
07.02	Maximum temperature (°C)	38.49	32.85	29.64	30.91	30.26
	Date of occurrence	14:55	16:35	19:55	16:35	16:35
07.03	Maximum temperature (°C)	34.89	31.89	30.23	32.68	32.44
	Date of occurrence	11:55	12:55	13:55	13:35	13:35

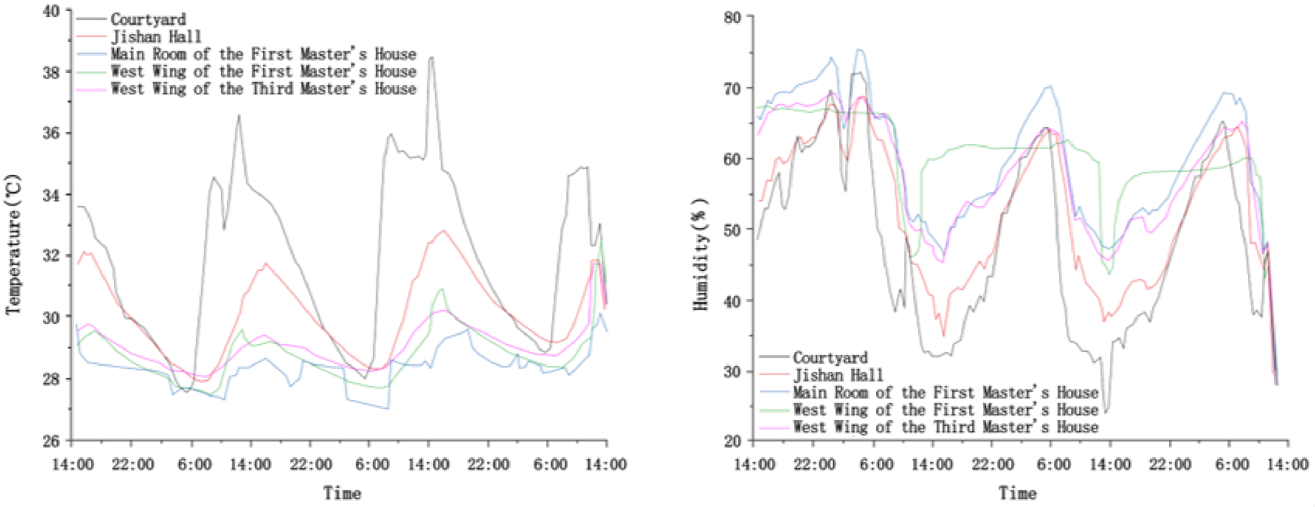

Figure 7. Summer temperature and humidity comparison of the Yu Family Compound.

In terms of the fluctuation range of humidity levels, the courtyard exhibited the highest fluctuation, spanning from 24% to 72%, with a range of 48%; followed by the main room of First Master's House, spanning from 30% to 75%, with a range of 45%; then, the west wing of the Third Master's House, spanning from 28% to 69%, with a range of 41%; then Jishan Hall, spanning from 28% to 69%, with a range of 41%; and finally, the west wing of the First Master's House, spanning from 27% to 67%, with a range of 40%.

In terms of the wind speed, the average wind speed, from highest to lowest, was as follows: the courtyard (0.30 m/s) > Jishan Hall (0.19 m/s) > the west wing of the Third Master's House (0.12 m/s) > the west wing of the First Master's House (0.11 m/s) > the main room of the First Master's House (0.10 m/s).

In terms of the fluctuation range of wind speed, the courtyard exhibited the highest fluctuation, spanning from 0.07 m/s to 1.75 m/s, with a range of 1.68 m/s; followed by Jishan Hall, spanning from 0.04 m/s to 1.08 m/s, with a range of 1.04 m/s; then, the west wing of First Master's House, spanning from 0.03 m/s to 0.64 m/s, with a range of 0.61 m/s; then, the main room of the First Master's House, spanning from 0.04 m/s to 0.51 m/s, with a range of 0.47 m/s; and finally, the west wing of the Third Master's House, spanning from 0.04 m/s to 0.49 m/s, with a range of 0.45 m/s. The maximum indoor wind speed value was 1.08 m/s in Jishan Hall, and the minimum wind speed value was 0.03 m/s in the west wing of the First Master 's House. The indoor wind speed was generally within the range of 0–0.6 m/s, and most of it was less than 0.2 m/s, with a small overall fluctuation (Table 4).

Table 4. Comparison of summer wind speed in the Yu Family Compound.

	Courtyard	Jishan Hall	Main Room of the First Master's House	West Wing of the First Master's House	West Wing of the Third Master's House
Average wind speed (m/s)	0.30	0.19	0.10	0.11	0.12
Maximum wind speed (m/s)	1.75	1.08	0.51	0.61	0.49

4.3.2. Physical Environment Measurements in Winter

In terms of average temperature, the rooms were ranked from highest to lowest as follows: the main room of the First Master's House (6.67 °C) > the west wing of the Third Master's House (5.30 °C) > the west wing of the First Master's House (4.66 °C) > Jishan Hall (4.31 °C) > average outdoor temperature (3.42 °C).

In terms of the fluctuation range of temperature, Jishan Hall exhibited the highest fluctuation, spanning from 1.05 °C to 8.42 °C, with a range of 7.37 °C; followed by the west wing of the First Master's House, spanning from 2.41 °C to 7.51 °C, with a range of 5.1 °C; then, the west wing of the Third Master's House, spanning from 2.82 °C to 7.91 °C, with a range of 5.09 °C; and finally, the main room of the First Master's House, spanning from 4.26 °C to 8.89 °C, with a range of 4.63 °C. Furthermore, the range of outdoor temperature fluctuation is 11.85 °C. The lowest indoor temperature occurred in Jishan Hall at 1.05 °C.

In terms of temperature delay (Table 5), the indoor peak temperature of Jishan Hall experienced a delay of 90–155 min compared to the outdoor peak temperature. The indoor temperature of the main room of the First Master's House experienced a delay of 195–340 min. The indoor temperature of the west wing of First Master's House experienced a delay of 140–180 min. The indoor temperature of the west wing of Third Master's House experienced a delay of 140–220 min. The order of indoor temperature delays was as follows: Jishan Hall, the west wing of the First Master's House, the west wing of the Third Master's House, and the main room of the First Master's House.

Table 5. The Yu Family Compound winter temperature peak.

Timing	Typology	Courtyard	Jishan Hall	West Wing of the First Master's House	West Wing of the First Master's House	West Wing of the Third Master's House
12.31	Maximum temperature (°C) Date of occurrence	8.92 13:15	6.55 14:45	8.13 18:55	5.48 15:45	7.21 16:10
01.01	Maximum temperature (°C) Date of occurrence	10.49 13:00	5.34 15:35	6.97 18:20	5.73 15:40	5.14 16:40
01.02	Maximum temperature (°C) Date of occurrence	7.59 14:30	6.24 16:50	7.57 17:45	5.78 16:50	6.02 16:50

Overall, indoor temperature fluctuations were smaller than outdoor temperature fluctuations. The maximum temperature difference is about 12 °C outdoors and 7 °C indoors (Figure 8).

In term of air humidity, the outdoor humidity was still generally lower than the indoor humidity (Figure 8). The average indoor humidity was ranked, from highest to lowest, as follows: the west wing of the First Master's House (53%) > the west wing of the Third Master's House (52%) > the main room of the First Master's House (51%) > the courtyard (50%) > Jishan Hall (49%).

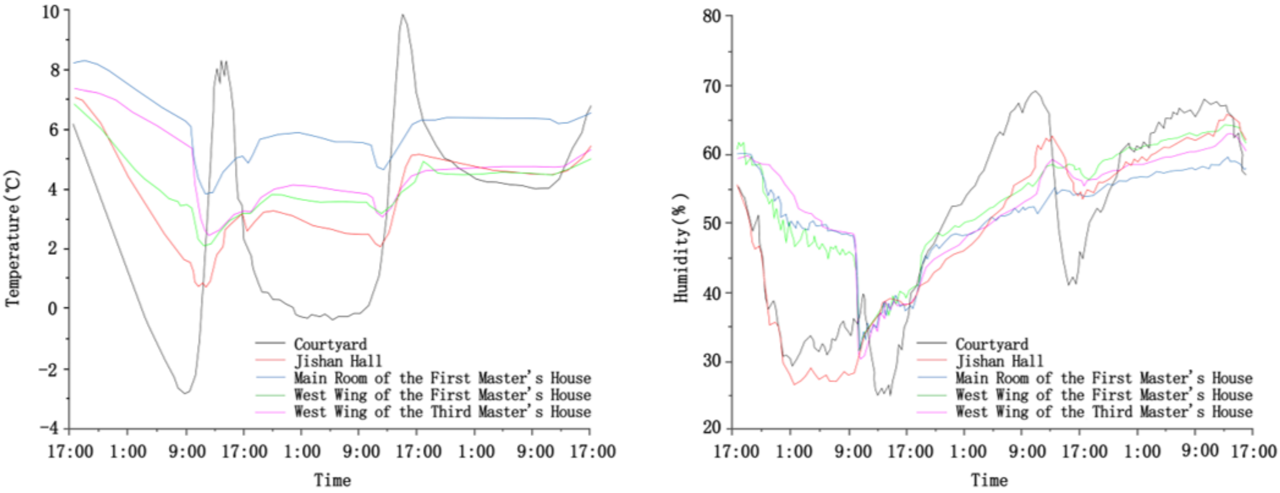

Figure 8. Winter temperature and humidity comparison of the Yu Family Compound.

In terms of the fluctuation range of humidity levels, the courtyard exhibited the highest fluctuation, spanning from 25% to 69%, with a range of 44%; followed by Jishan Hall, ranging from 27% to 65%, with a variation range of 38%; then, the west wing of the Third Master's House, spanning from 30% to 63%, with a range of 33%; then, the west wing of First Master's House, spanning from 32% to 64%, with a range of 32%; and finally, the main room of the First Master's House, spanning from 32% to 60%, with a range of 28%. The maximum recorded indoor humidity was 65% in Jishan Hall, while the minimum was 27%, also in Jishan Hall.

In terms of wind speed, the average wind speed was ranked, from highest to lowest, as follows: the courtyard (0.28 m/s) > Jishan Hall (0.15 m/s) > the west wing of the First Master's House (0.10 m/s) = the west wing of the Third Master's House (0.10 m/s) > the main room of the First Master's House (0.09 m/s).

In terms of the fluctuation range of wind speed, the yard exhibited the highest fluctuation, spanning from 0.07 m/s to 1.06 m/s, with a range of 0.99 m/s; followed by Jishan Hall, spanning from 0.01 to 0.52 m/s, with a range of 0.51 m/s; then the west wing of the First Master's House, spanning from 0 to 0.35 m/s, with a range of 0.35 m/s; then, the West Wing of the Third Master's House, spanning from 0 to 0.34 m/s, with a range of 0.34 m/s; and finally, the main room of First Master's House, spanning from 0.01 m/s to 0.31 m/s, with a range of 0.3 m/s. The maximum indoor wind speed was 0.56 m/s in Jishan Hall, and the minimum indoor wind speed was 0. In terms of indoor wind speed comfort (Table 6), Jishan Hall had the highest value, while the other buildings have similar indoor wind speeds.

Table 6. Comparison of winter wind speed in the Yu Family Compound.

	Courtyard	Jishan Hall	Main Room of the First Master's House	West Wing of the First Master's House	West Wing of the Third Master's House
Average wind speed (m/s)	0.28	0.15	0.09	0.10	0.10
Maximum wind speed (m/s)	1.06	0.52	0.31	0.35	0.34

4.3.3. Measurement Results

The measurement results indicate that the indoor physical environment of the Yu family Compound is more stable in winter and summer than the environment outdoors. The indoor temperature of these rooms remains relatively consistent within the same orientation. However, there exists a significant temperature difference between rooms with different orientations.

In terms of humidity, indoor humidity is generally higher than outdoor humidity in the summer, and indoor and outdoor humidity levels are roughly equal in the winter. The humidity fluctuation amplitude is larger during summer compared to winter, and the average humidity level is also higher during summer compared to winter. In summer, the indoor humidity fluctuation pattern is opposite to that of temperature; meanwhile, in winter, it is similar to that of temperature. The buildings need to be strengthened for summer dehumidification.

In addition, wind speeds inside the building are lower than outside, providing good wind protection. In terms of the fluctuation amplitude of average wind speed, the south-facing rooms have greater fluctuations in summer than in winter; meanwhile, the west-facing rooms have greater fluctuations in winter than in summer.

5. Software Simulation

5.1. Simulation Method

The thermal environment analysis based on Ecotect:

This analysis tool utilizes the Weather Tool climate analysis software, which is included in the Ecotect 2010 ecological building analysis software, to simulate the annual hot and humid environment in the Xuzhou region. The simulation results of Weather Tool are more accurate for residential and office buildings with fewer indoor heat sources. Therefore, it is feasible to analyze passive design strategies for this region. The enthalpy-humidity chart obtained describes the basic parameters of the air, including moisture content, atmospheric pressure, and water vapor pressure, and their relationship with the thermal environment. Weather Tool intuitively analyzes and determines the specific conditions of the indoor and outdoor climate, including factors such as coldness, warmth, dryness, and humidity. It also assesses the deviation between the current situation and the designated comfort zone [41].

The wind environment analysis based on Phoenics:

Through the determination of the basic parameters of the wind environment in the Xuzhou region, the indoor and outdoor wind environments of the buildings are simulated. In outdoor environments, wind speeds below 1 m/s are referred to as calm wind zones, wind speeds between 1–5 m/s are considered ideal, and wind speeds above 5 m/s are perceived as uncomfortable for humans. However, Xuzhou experiences cold winters, and people prefer to be in areas with lower wind speeds. Therefore, in this study, lower wind speeds are evaluated as providing higher comfort in terms of the wind environment during winter, while higher wind speeds are considered more comfortable during summer.

5.2. Simulation Analysis

5.2.1. Specific Climate Analysis for the Xuzhou Area

The meteorological file in CSWD format was imported into Weather Tool, which was derived from Tsinghua University's "China Specialized Meteorological Database for Thermal Environment Analysis of Buildings", and contains the measured data from 270 meteorological stations. In the Chart Overlay menu in the software, we can choose from a variety of passive strategies, options that can expand a person's thermal comfort range. It is important to note that the thermal comfort ranges shown in the charts are for idealized situations. In actual scenarios, there may be errors in the results due to the influence of different materials, practices, and other factors. Furthermore, its operation settings are modular, and it is not possible to set specific information such as boundaries and data models. Nevertheless, these results are still informative for the selection of more effective passive energy efficiency measures in different regions.

Figures 9–14 are psychrometric charts. The blue areas in the charts represent the comfort zone, while the scattered data points represent the combined temperature and humidity data, allowing a more intuitive analysis of the distribution of temperature and humidity and their relationship with the comfort level. From Figure 9, it can be observed that the majority of the year falls outside the comfort zone, with the coexistence of extreme high and low temperatures. Figure 10 reveals that approximately half of the summer is spent in a non-comfort zone, characterized by high temperatures and humidity. In Figure 11, most of the winter is classified as a non-comfort zone, characterized by low temperatures and high humidity.

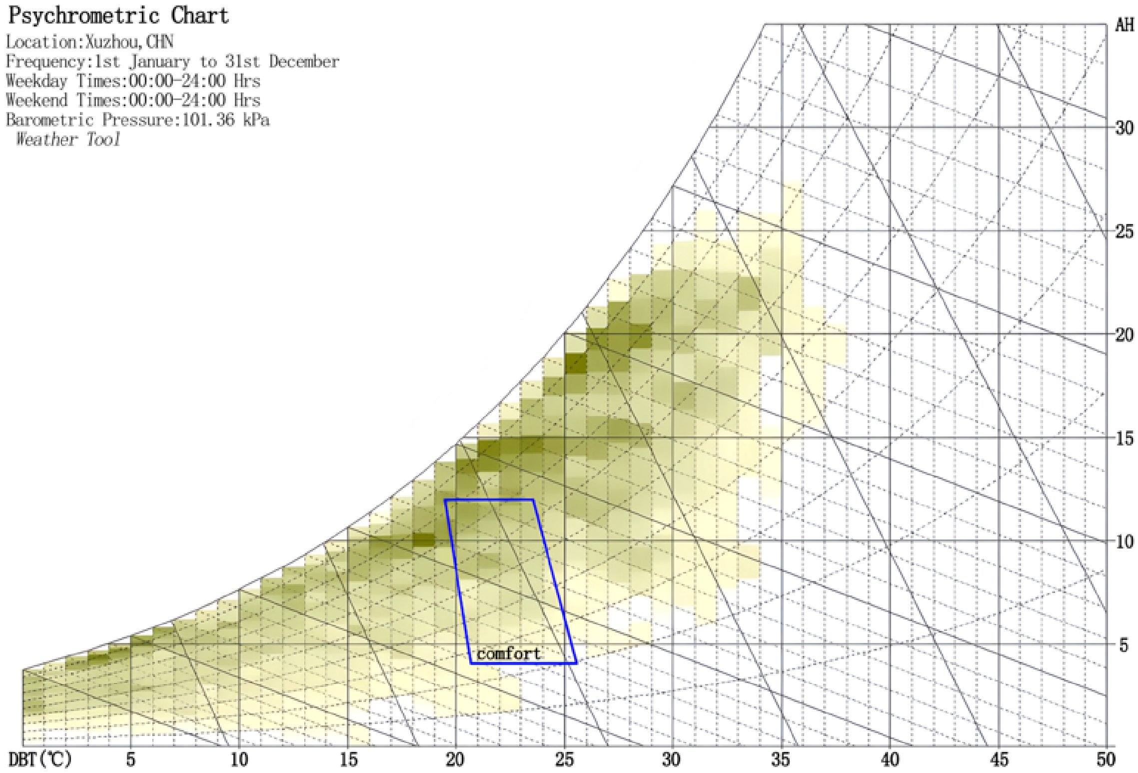

Figure 9. Year-round humidity and heat map and comfort zone of Xuzhou area.

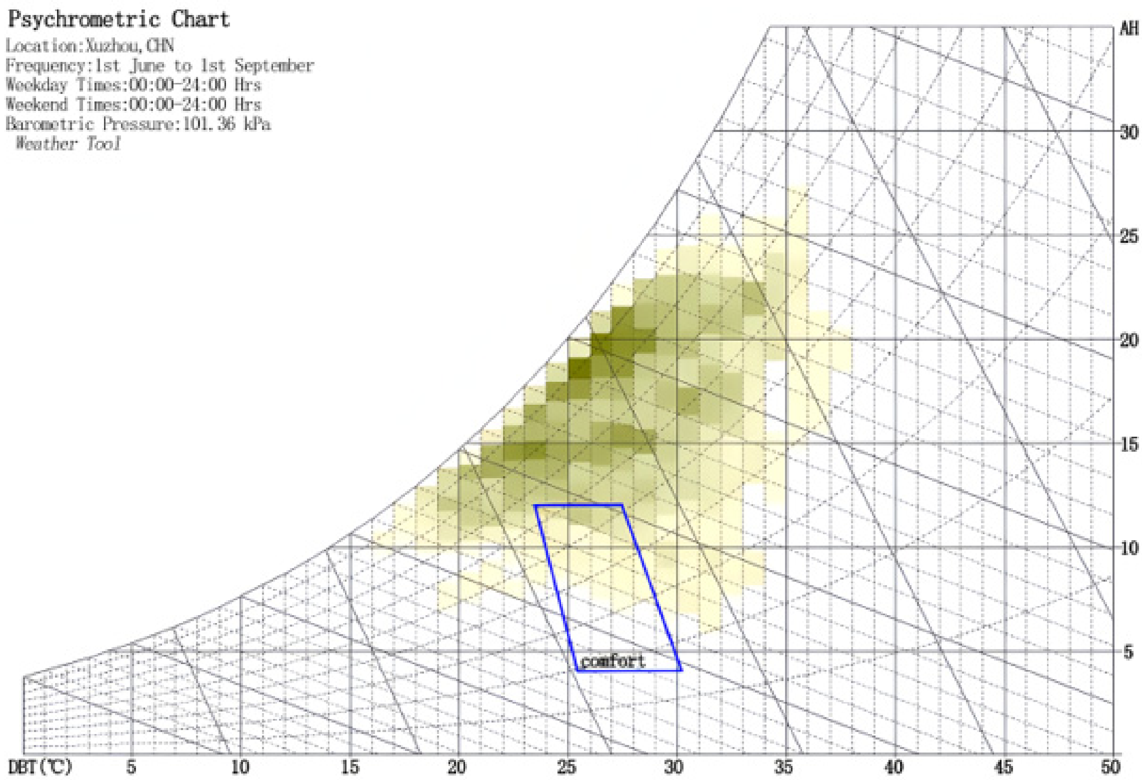

Figure 10. Summer humidity and heat map and comfort zone of Xuzhou area.

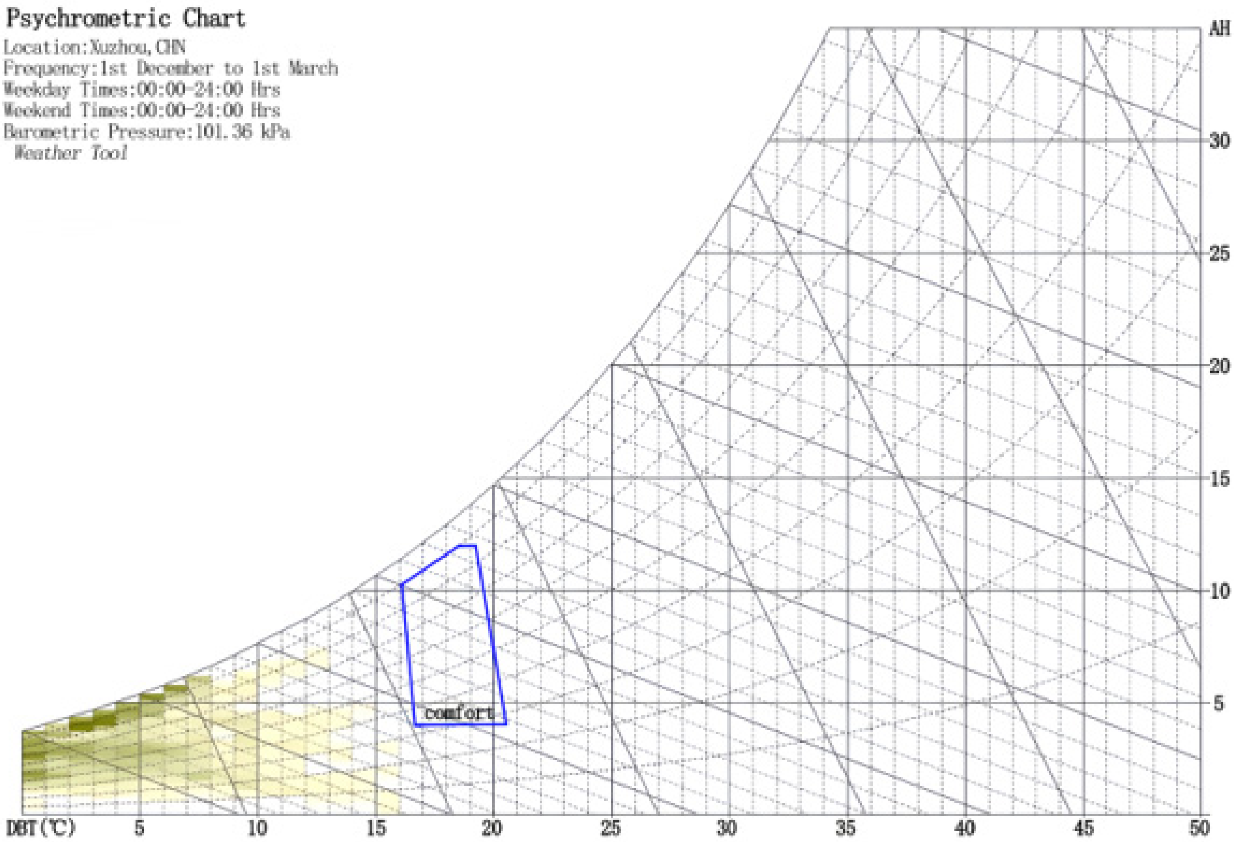

Figure 11. Winter humidity and heat map and comfort zone of Xuzhou area.

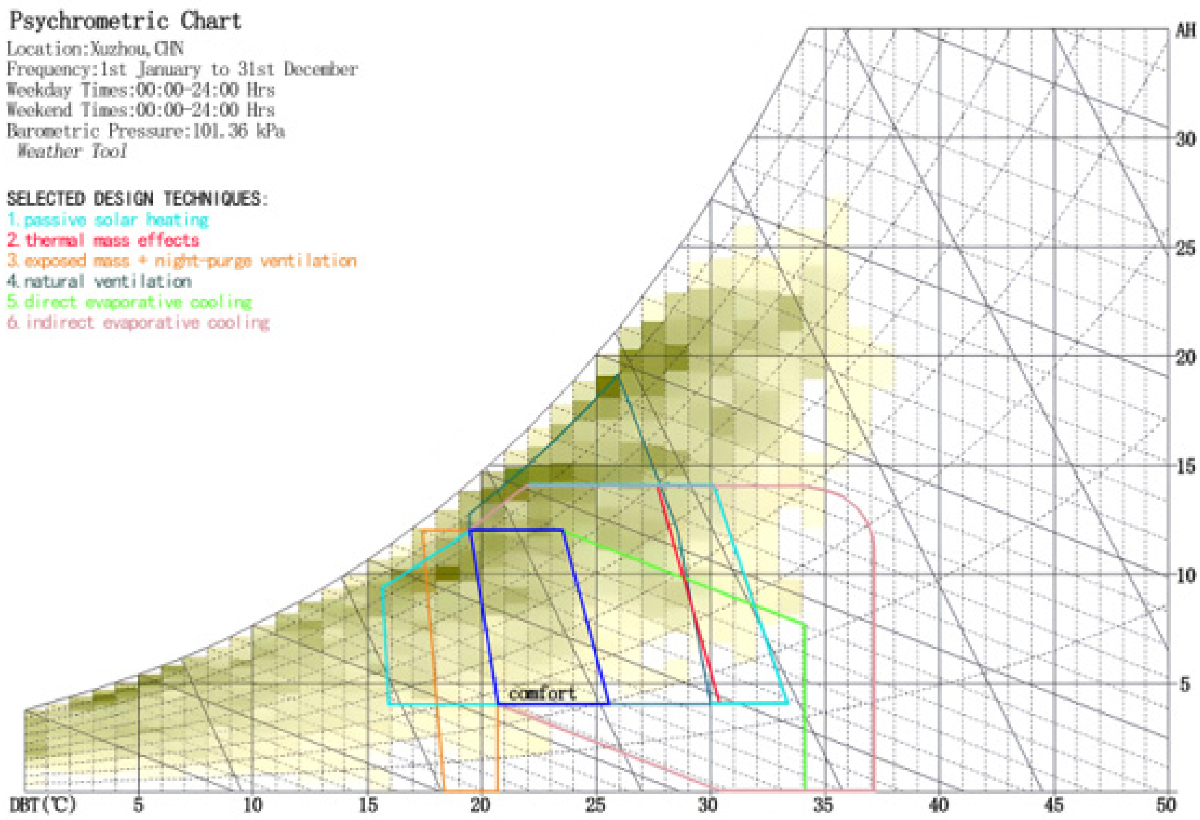

Figure 12. Analysis of comprehensive year-round passive measures in Xuzhou region.

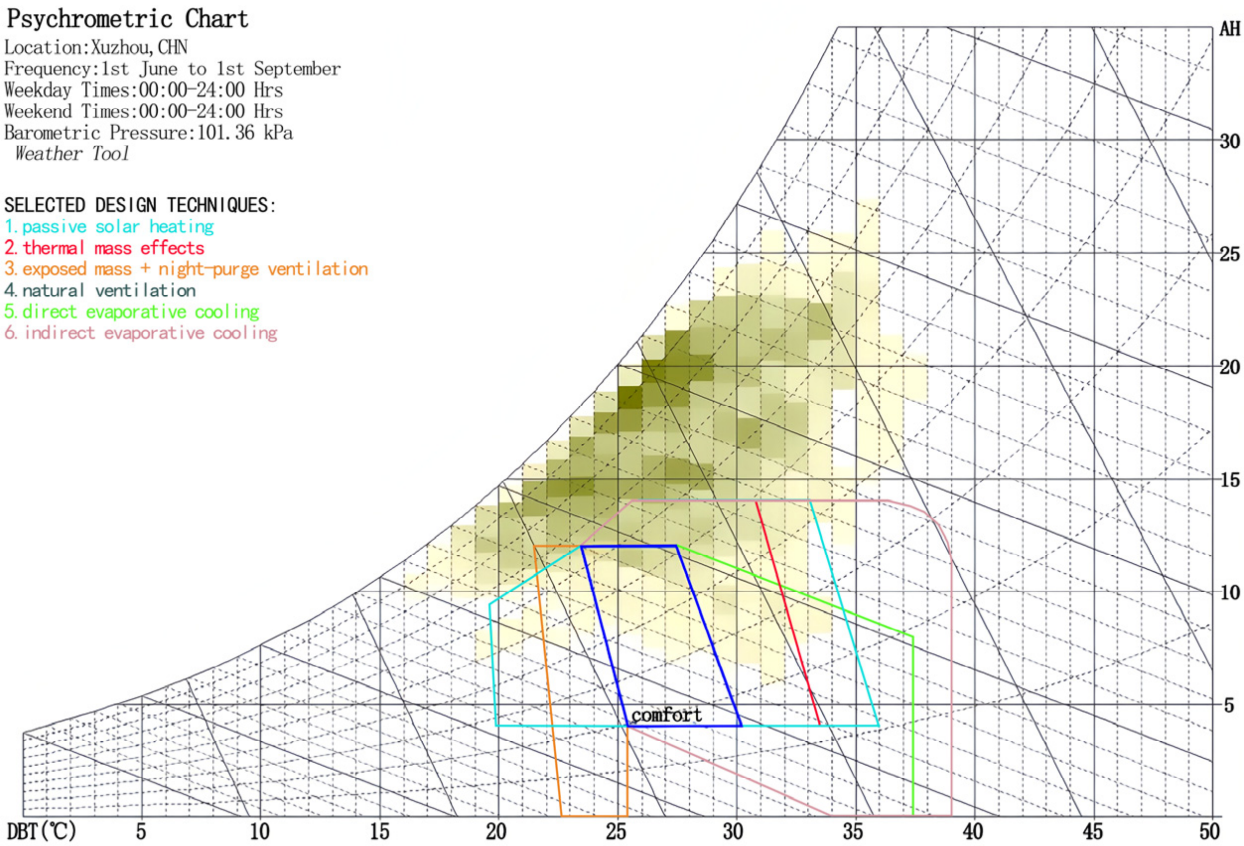

Figure 13. Analysis of comprehensive passive measures in Xuzhou area in summer.

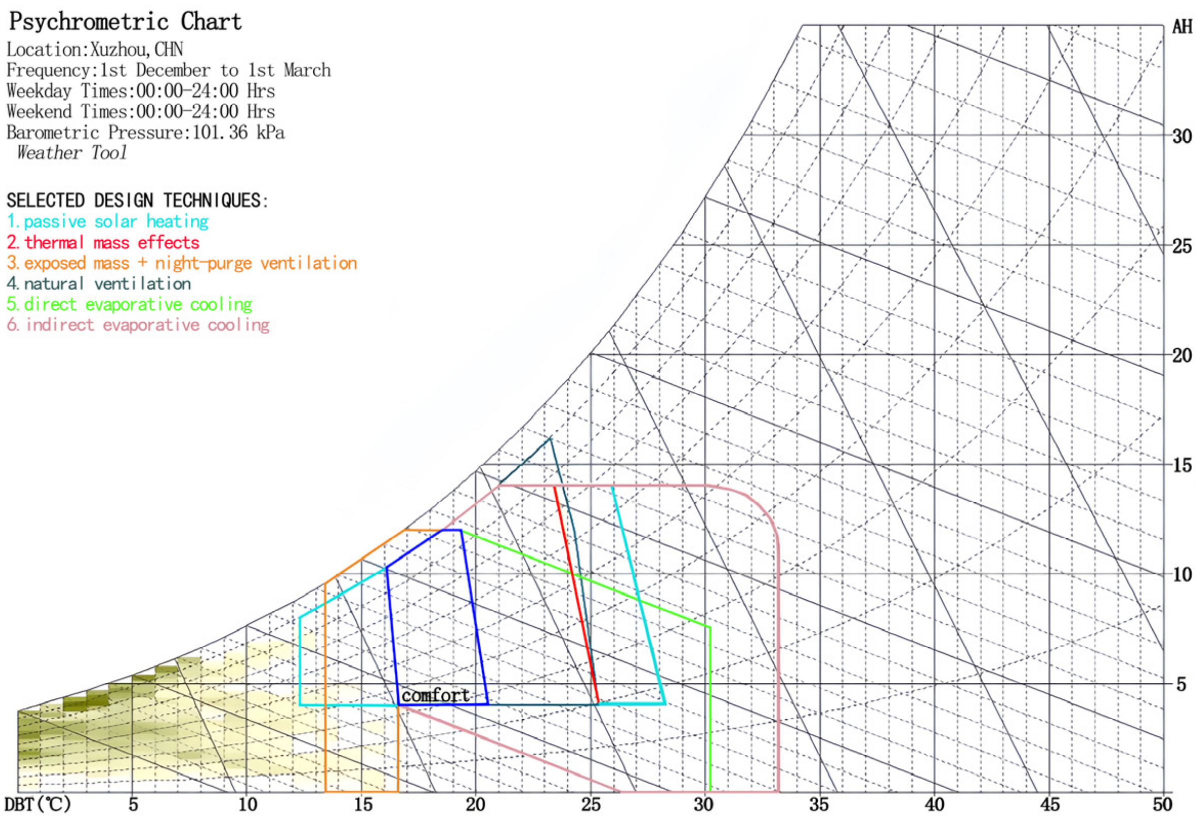

Figure 14. Analysis of comprehensive passive measures in Xuzhou area in winter.

Figures 12–14 show the comfort range after implementing integrated passive measures, as well as the proportion of increased comfortable periods achieved through these passive strategies. The most common passive measures include passive solar heating, high thermal mass envelope, natural ventilation, nighttime ventilation, direct evaporative cooling, and indirect evaporative cooling. With the implementation of integrated passive measures, the proportion of comfortable periods throughout the year then increases by 24%, leading to improvements in indoor comfort. However, the impact of passive measures in winter is relatively limited, and compared to the previous situation, the increase in the proportion of comfortable periods during winter is relatively small with the adoption of integrated passive measures.

From the analysis of Figures 15–20, it can be observed that natural ventilation, nighttime ventilation, and a high-thermal-mass envelope are the three effective passive measures which have significant effects in summer, spring, and autumn. This analysis specifically focuses on natural ventilation, nighttime ventilation, and high thermal mass envelope. Figure 16 shows that through the use of only natural ventilation, the proportion of comfortable time periods throughout the year increases from 7% to 19%. Figure 17 indicates that through the use of only nighttime ventilation, the proportion of comfortable time periods throughout the year increases to 24%. Figure 18 demonstrates that through the use of a high thermal mass envelope, the proportion of comfortable time periods throughout the year increases to 22%. Figure 19 reveals that before and after implementing ventilation measures, the proportion of comfortable time periods throughout the year remains approximately 30%. Figure 20 shows that through the combination of all three methods, the proportion of comfortable time periods throughout the year reaches 30%, which is close to the improvement percentage of 31% achieved with the comprehensive adoption of various passive measures. Among them, when using two ventilation measures, the impact of the high thermal mass envelope on the proportion of comfortable time periods throughout the year is not significant. From the analysis of climate characteristics in the Xuzhou region and modern bioclimatic design, it can be concluded that adopting passive measures can significantly improve the comfort level, and the most effective passive measure is ventilation, which has significant effects in summer, while its effectiveness in winter remains relatively poor.

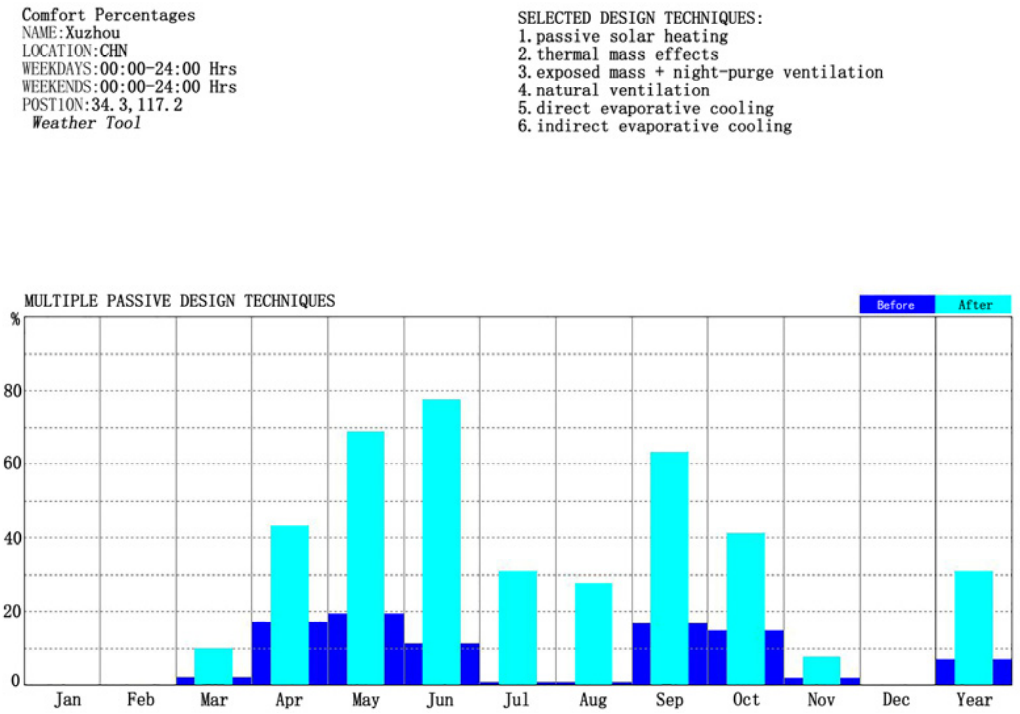

Figure 15. Before and after the adoption of passive measures throughout the year in Xuzhou area comfort rate analysis.

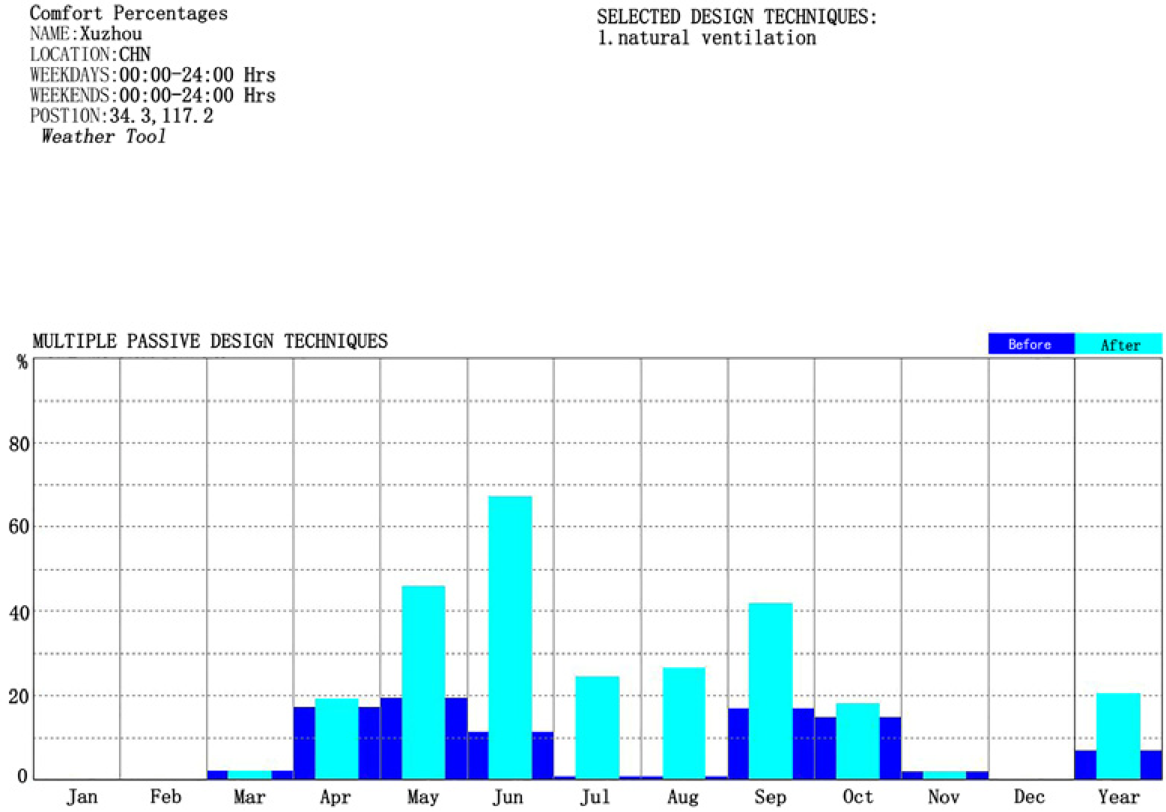

Figure 16. Comfort rate analysis before and after natural ventilation measures in Xuzhou area.

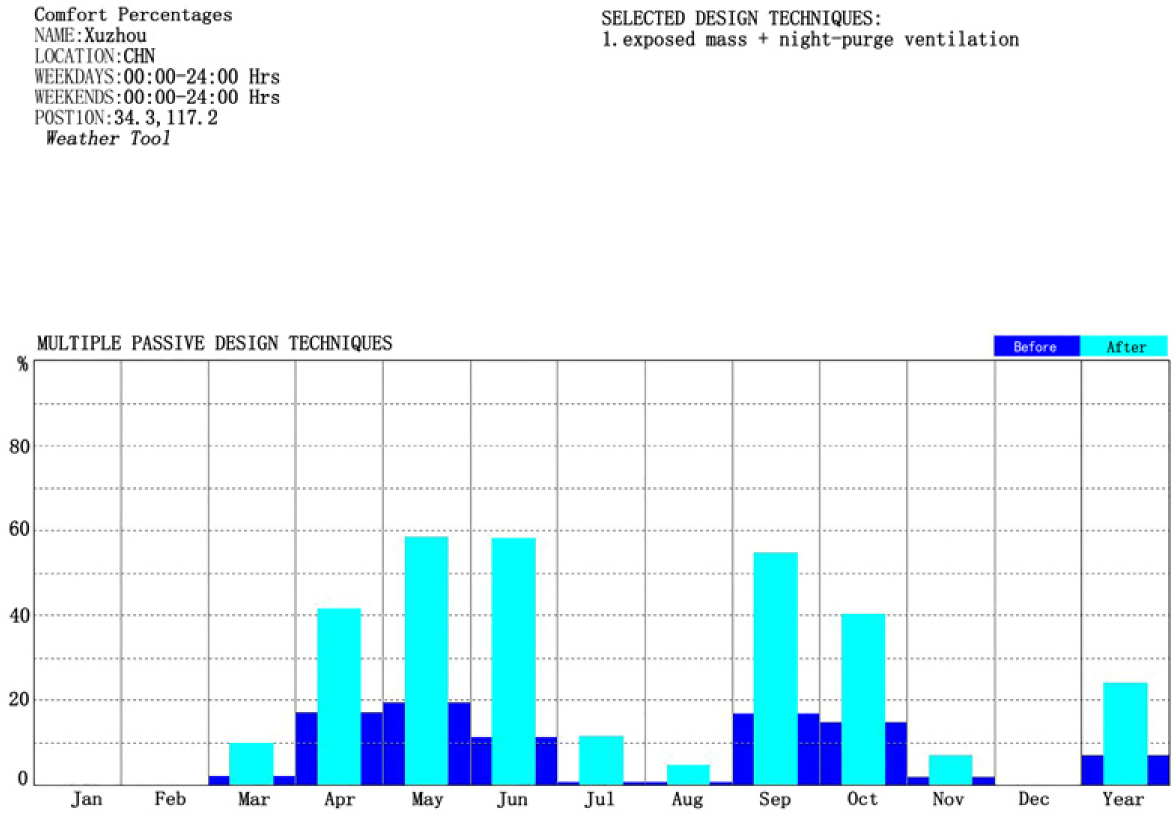

Figure 17. Comfort rate analysis before and after nighttime ventilation in Xuzhou area.

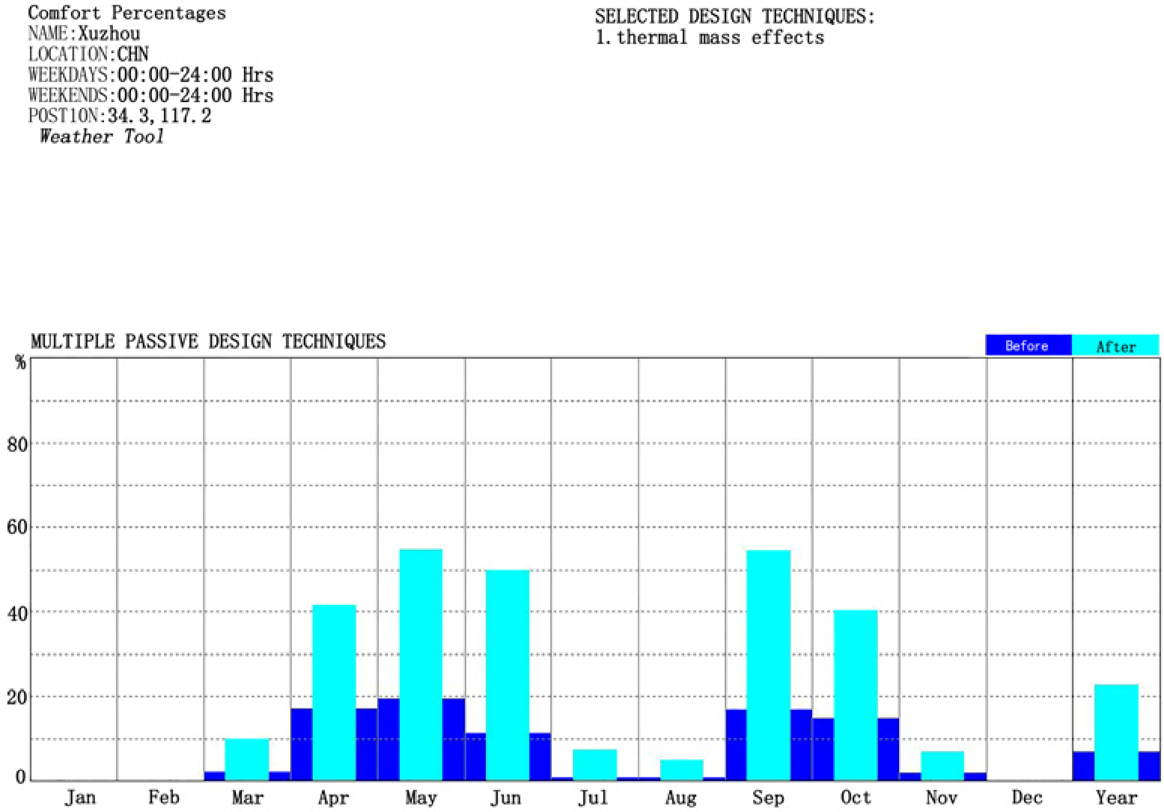

Figure 18. Comfort rate analysis before and after high-heat-capacity mass in Xuzhou area.

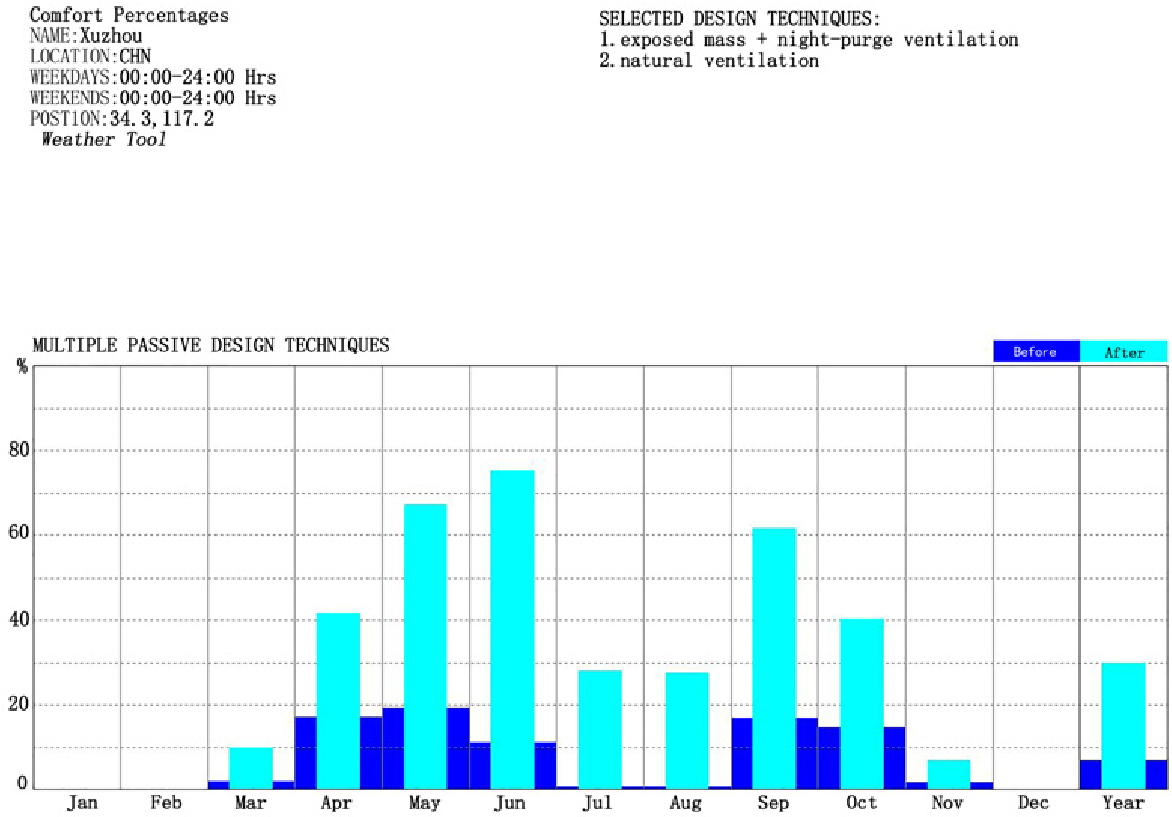

Figure 19. Comfort rate analysis before and after year-round ventilation measures.

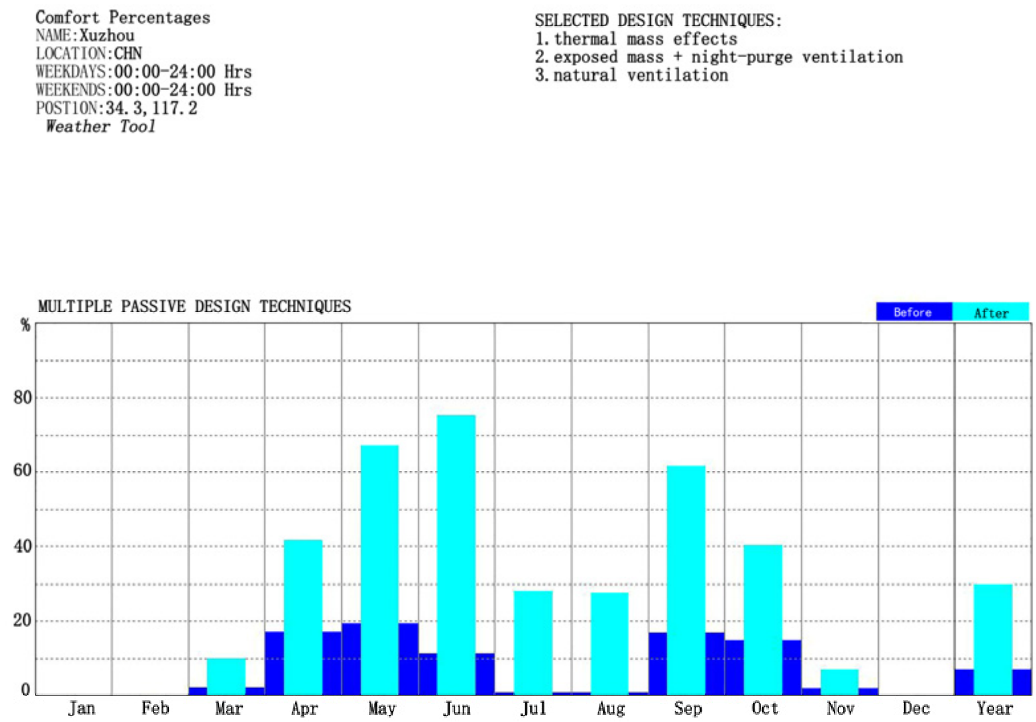

Figure 20. Xuzhou area natural ventilation + night ventilation + high heat comfort rate analysis before and after capacity structure measures.

5.2.2. Building Heat Gain/Loss Analysis

Building heat gain/loss is mainly analyzed from the microscopic aspect of the building's thermal environment, evaluating the factors affecting the thermal environment of the building.

1. Architectural parameter settings

The model is established based on the actual building, and the simulation plan size is simplified and adjusted. The model is appropriately simplified to reduce software runtime, without impacting the final effect. All parameters are set according to the actual situation.

Software parameter settings: Traditional residential buildings primarily rely on natural ventilation, without employing active measures such as air conditioning and exhaust fans. During winter, when it is excessively cold, methods such as coal stoves and hot water bags are used for heating. Therefore, in the area attribute settings, the interiors are considered as areas without a stable heat source. As for the time attribute setting, two people are assigned to each room, primarily engaged in light physical labor. The building construction parameters are set out in Tables 7–10.

Table 7. Architectural parameters of the First Master's main room.

Category	Composition	Thicknesses (mm)	Density (kg/m^3)	Thermal Conductivity (W/(Mk))	Specific Heat (J/(kgK))
Roof	Roof tile	30	2000	0.75	1240
	Plaster 1	40	1400	0.58	1010
	Plaster 2	80	1800	0.62	1010
	White ash	20	1250	0.43	1088
	Brick	25	2000	0.75	1240
Wall	Plastering layer	10	1600	0.81	1050
	Green brick	126	2000	0.75	1240
	Layer of broken bricks	442	2000	0.66	1240
	Green brick	126	2000	0.75	1240

Table 7. *Cont.*

Category	Composition	Thicknesses (mm)	Density (kg/m^3)	Thermal Conductivity (W/(Mk))	Specific Heat (J/(kgK))
Hill wall (above)	Plastering layer	10	1600	0.81	1050
	Green brick	126	2000	0.75	1240
	Layer of broken bricks	442	2000	0.66	1240
	Green brick	126	2000	0.75	1240
Hill wall (lower)	Plastering layer	10	1600	0.81	1050
	Limestone	704	2400	2.04	924
Partitions	Fir	40	500	0.12	2510
Floor	Rectangular tile	40	2000	0.75	1240

Table 8. Architectural parameters of Jishan Hall.

Category	Composition	Thicknesses (mm)	Density (kg/m^3)	Thermal Conductivity (W/(mK))	Specific Heat (J/(kgK))
Roof	Roof tile	30	2000	0.75	1240
	Plaster 1	40	1400	0.58	1010
	Plaster 2	80	1800	0.62	1010
	White ash	20	1250	0.43	1088
	Brick	25	2000	0.75	1240
Wall	Plastering layer	10	1600	0.81	1050
	Green brick	126	2000	0.75	1240
	Middle layer	248	2000	0.66	1240
	Green brick	126	2000	0.75	1240
South wall	Fir floor door	40	500	0.29	2510
Partition	Fir	40	500	0.29	2510
Floor	Rectangular tile	40	2000	0.75	1240

Table 9. Architectural parameters of the First Master's west wing.

Category	Composition	Thicknesses (mm)	Density (kg/m^3)	Thermal Conductivity (W/(mK))	Specific Heat (J/(kgK))
Roof	Roof tile	30	2000	0.75	1240
	Plaster 1	40	1400	0.58	1010
	Plaster 2	80	1800	0.62	1010
	White ash	20	1250	0.43	1088
	Brick	25	2000	0.75	1240
Wall	Plastering layer	10	1600	0.81	1088
	Green brick	126	2000	0.75	1240
	Layer of broken bricks	420	2000	0.66	1240
	Green brick	126	2000	0.75	1240
Hill wall (above)	Plastering layer	10	1600	0.43	1088
	Green brick	126	2000	0.75	1240
	Layer of broken bricks	318	2000	0.66	1240
	Green brick	126	2000	0.75	1240
	Plastering layer	10	1600	0.43	1088
Hill wall (lower)	Limestone	0	2400	2.04	924
Floor	Rectangular tile	40	2000	0.75	1240

Table 10. Architectural parameters of the Third Master's west wing.

Category	Composition	Thicknesses (mm)	Density (kg/m^3)	Thermal Conductivity (W/(mK))	Specific Heat (J/(kgK))
Roof	Roof tile	30	2000	0.75	1240
	Plaster 1	40	1400	0.58	1010
	Plaster 2	80	1800	0.62	1010
	White ash	20	1250	0.43	1088
	Brick	25	2000	0.75	1240
Wall	Plastering layer	10	1600	0.81	1088
	Green brick	126	2000	0.75	1240
	Adobe brick		1800	0.52	1800
	Green brick	126	2000	0.75	1240
Hill wall (above)	Plastering layer	10	1250	0.43	1088
	Green brick	126	2000	0.75	1240
	Adobe brick	308	1800	0.47	1800
	Green brick	126	2000	0.75	1240
	Plastering layer	10	1250	0.43	1088
Hill wall (lower)	Limestone	0	2400	2.04	924
Floor	Rectangular tile	40	2000	0.75	1240

2. Simulation Result Analysis

From Table 11 below, it can be seen that the heat gain and loss of the building in winter were mainly attributable to the building envelope and cold-air infiltration. Therefore, in building design, the building envelope remains the primary influencing factor for the thermal environment.

Table 11. Analysis of building gains and losses.

Building Type	Timing	Enclosure Heat Transfer (J)	Heat Gain from Solar Radiation (J)	Heat Exchange Due to Air Infiltration (J)	Internal Disturbance Caused by Heat (TCM) (J)	Inter-Area Heat Transfer (J)
Jishan Hall	Coldest day	−15,634	1873	−101,245	3360	12,600
	Hottest day	9844	972	17,657	3360	−10,832
The main room of the First Master's House	Coldest day	−79,913	4779	−34,500	11,907	7998
	Hottest day	36,573	2959	7697	11,907	−8176
The west wing of the First Master's House	Coldest day	29,669	1152	4867	9165	−39,007
	Hottest day	−837,736	1374	−21,814	9165	35,494
The West Wing of the Third Master's House	Coldest day	−84,670	1093	−22,742	9119	5396
	Hottest day	28,832	1366	5074	9119	−5535

5.2.3. Wind Environment Simulation

Before performing the wind environment analysis calculation, we need to set the parameters relating to the wind environment:

Boundary setting: the length and width of the experimental scene are five times the length and width of the building, and the height is three times the height of the building.

Wind speed: based on the statistics of wind speed in the Xuzhou area in the relevant literature, this paper determines the simulated wind direction in winter as northwest (NNW), with an average wind speed of 2.3 m/s, and sets the wind direction in summer as southeast (EES), with an average wind speed of 2.7 m/s [42].

Ambient temperature and air pressure: In 2023, the average daytime temperature in the Xuzhou area was 9.1 °C in winter, with an average barometric pressure of 1024 hPa. In summer, the average daytime temperature was 30.8 °C, with an average barometric pressure of 1006 hPa.

Profile type: select the built-in equation. Generally, exponential equations are chosen for plain areas, and logarithmic equations are chosen for hilly or mountainous areas. Since the present site is a hilly area, the logarithmic equation is chosen here.

The courtyard is the main activity space of traditional houses, and the ventilation of the courtyard directly affects the comfort of the residents. The center of gravity of a person is usually considered to be at 1.5 m; therefore, the outdoor wind environment at 1.5 m is used as the basis for evaluating the wind environment of the courtyard.

Figures 21 and 22 show the wind environment simulation of the Yu's compound.

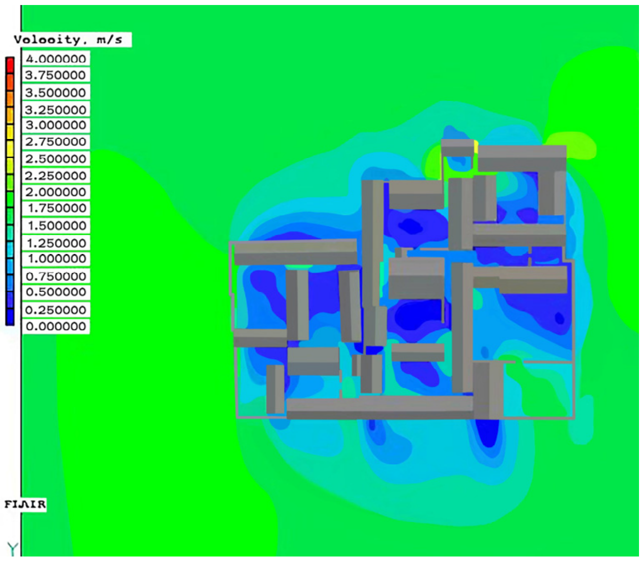

Figure 21. Summer wind environment simulation.

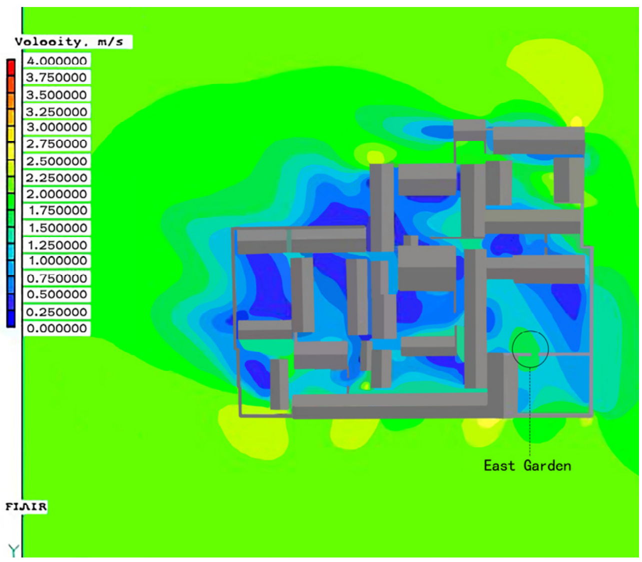

Figure 22. Winter wind environment simulation.

The architectural composition of the Yu Family Compound is relatively complex. In the summer, courtyards connected by alleys have higher wind speeds than ordinary courtyards (Figure 21). The wind speed in the three-sided courtyards is higher than that in the quadrangle courtyards. The maximum wind speed in a courtyard is 2.25 m/s, and the minimum is 0. Courtyards with more openings have a higher wind speed than those with fewer openings, generally decreasing from the entrance inward. In the winter, the maximum wind speed in the courtyard is 2.25 m/s, and the minimum is 0. The maximum courtyard wind speed occurs in the East Garden (Figure 22), which has only one building, a theater, and three surrounding walls.

5.3. Energy Model Calibration

Building energy consumption, as the core research output reflecting the thermal and energy performance of the case study building, was selected for calibration to match real data of the building to measure the accuracy of the model in the software simulation process [43]. The test standard applies the statistical value error NMBE (normalized mean bias error) and instantaneous value error CV(RMSE) (coefficient of variation of the root mean square error) of ASHRAE 14. Typically, models are declared to be calibrated if they produce NMBEs within ±5% and CV(RMSE)s less than 15%, when using monthly data [44].

Among the four buildings, we used the architectural model of Jishan Hall (Figure 23) as the calibration object. As the main building of the Yu Family Compound, it has a floor area of 109 square meters. The actual energy consumption comes from the management of the Yu family compound. The main parameters affecting the accuracy of the simulation results were fine-tuned, including meteorological data, building envelope dimensions, thermo-physical parameters, and other operational settings. The model calibration process, as illustrated in Figure 24, was used to obtain a calibrated energy model that would meet the ASHRAE 14 acceptable criteria.

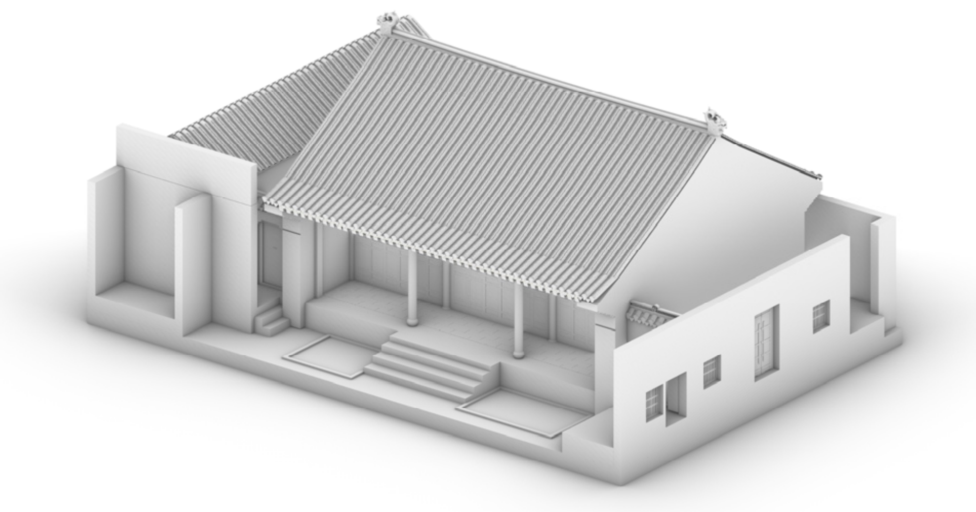

Figure 23. 3D view of the model of Jishan Hall.

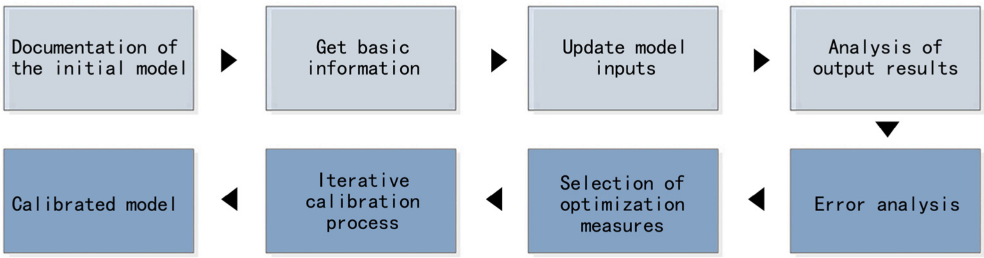

Figure 24. Process of model calibration method [45].

The comparison of the simulated energy consumption and the actual energy consumption for each month of the year is shown in Figure 25. Table 12 lists the percentage deviation between both energy results, all of which are in accordance with ASHRAE 14 standards [44]. Thus, the model was deemed calibrated.

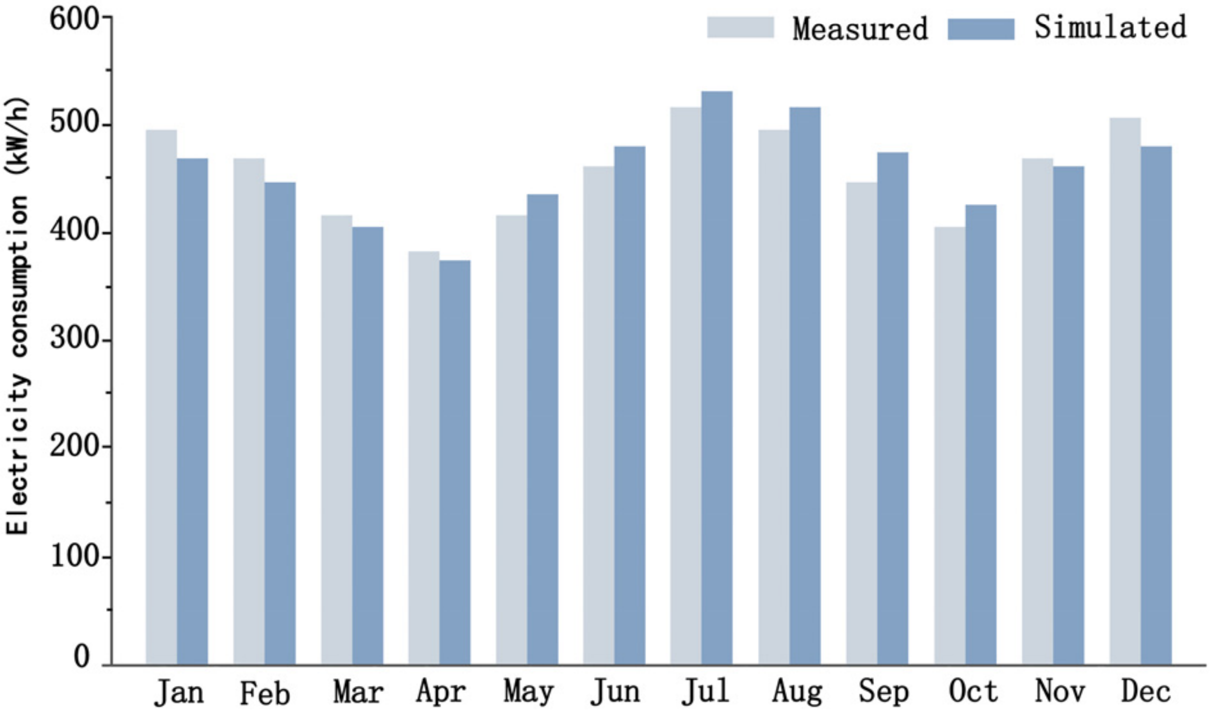

Figure 25. Monthly simulated energy consumption versus measured energy consumption.

Table 12. Error values for the simulated and measured data.

Indices	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
NMBE	3%	2%	4%	3%	−1%	−3%	−4%	−3%	−5%	−2%	1%	2%
CV(RMSE)	8%	6%	10%	9%	2%	7%	11%	9%	13%	5%	3%	4%

5.4. Simulation Results

Thermal Environment: Buildings within the Yu Family Compound are mainly constructed using materials such as bricks, stones, and earth. The roofs are primarily composed of tiles. There are various types of walls, among which the buildings with the inner adobe and outer fired-brick walls exhibit better thermal insulation performance compared to those built fully with stone. The main reason is that the internal filler materials increase the thermal resistance of the walls. Similarly, the buildings with thicker walls exhibit better thermal insulation performance.

Wind Environment: The layout of buildings within the Yu Family Compound is characterized by external enclosure and internal openness. These buildings are primarily single-story structures, and the courtyard walls are relatively high, often reaching a height of 2.5 m, serving as a protective barrier. After being obstructed by surrounding buildings and courtyard walls, the outdoor wind experiences a reduction in wind speed upon reaching the inner courtyard. Additionally, due to the small size of windows in traditional buildings, the airflow is impeded, resulting in lower indoor wind speeds. Some buildings incorporate partition windows to increase the ventilation area and the presence of opposing doors in the central hall promotes air convection, slightly improving natural ventilation within the building. Overall, traditional residential buildings exhibit poor performance in terms of natural ventilation.

6. Exploring the Climate Adaptation of Traditional Dwellings

6.1. Village Siting Adaptability

Feng Shui, an environmental science that originated in ancient China, considers the natural environment, the man-made environment, and landscape vision in a unified way. It is a reflection of the traditional Chinese concept of the universe, nature, and aesthetics [46], and has been a very important factor in site selection since ancient times.

Site selection in Feng Shui theory follows the principle of facing toward the sunny side and away from the shadowy side, facing away from the mountain and toward water, with an orientation towards the south or southeast. There are many considerations in Feng Shui theory, but the main focus is on choosing a suitable geography and climate to create a favorable environment. The buildings are built along the slope, naturally forming a staggered pattern, providing the entire settlement with good ventilation and lighting conditions. Because of the monsoon climate, Xuzhou experiences cold winters with a prevailing north wind and mountains to the north that can block the wind. In addition, when the southeast wind prevails in the summer, the buildings located on the slope are oriented to face those southward winds, which brings good indoor ventilation and helps reduce the impact of hot and dry summer weather on the interior of buildings.

In Xuzhou, due to the flooding caused by the Yellow River, the higher terrain in the region has become the preferred location for site selection [47]. For example, the current Xuzhou Folk Museum is located on the Hubu Mountain, where the Ministry of Revenue was situated in ancient times. The building was constructed along the mountain terrain due to multiple relocations of the government office caused by Yellow River flooding. Finally, it was situated on the Hubu Mountain, attracting wealthy families to reside in the area. Furthermore, areas near canals and lakes, or those with robust flood control and discharge capabilities, have also been common settlement sites near the Xuzhou region. For example, Yaowan Town in Xinyi City is located near the canal, with minimal impact on residents' daily lives due to limited fluctuations in the water levels. If the terrain is relatively flat, it often features flat land with embankments dug around houses and homesteads, connected to ponds, and thus achieving a comprehensive effect of water storage and flood control. For example, Tushan Town in Pizhou City is located near the canal, with Tushan hills and ponds connected via ditches within the area, providing a good flood control effect. These are all methods for settlements to adapt to the environment and resist floods in the long term.

6.2. Residential Adaptability

6.2.1. Individual Buildings

The traditional building construction method in Xuzhou is gradually developed on the basis of long-term integration with the natural environment. Building materials are often locally sourced and used according to material properties; materials with good waterproofing properties are commonly used in areas where nodes are susceptible to moisture; walls are thicker and heavier, making it easier to cope with changes in the outdoor environment and maintain a better level of indoor comfort; and in order to minimize the exchange of heat between the indoor and outdoor environments, the building windows are smaller in size, resulting in limited ventilation. To ensure indoor ventilation, high windows are often installed, or vents are set up at the base of the wall.

6.2.2. The Courtyard Situation

1. Climate regulation

The courtyard space is an open space enclosed by the surrounding buildings, which has a stronger sense of openness than gray space and provides the main outdoor activity space for residents. Compared with the outdoor space, the degree of enclosure in the courtyard space reduces the impact of changes in outdoor temperature and renders it a buffer space for indoor and outdoor activities (Figure 26). Furthermore, the geometrical parameters of the courtyards have opposite effects on shaded and sunlit performance in summer and winter [48]. Xuzhou is situated in the transition zone between the cold regions and the region with hot summers and cold winters. Compared to Xuzhou quadrangle courtyards, quadrangle courtyards in Beijing are wider and longer due to the specific lighting requirements. On the other hand, Jiangsu and Zhejiang quadrangle courtyards are relatively narrower due to the shading requirements. The proportions of Xuzhou quadrangle courtyards are average and fall somewhere between the two aforementioned categories. The courtyards share some similarities but also exhibit some differences when compared between the categories mentioned.

Figure 26. Courtyard in the Yu Family Compound.

In terms of an individual courtyard, its opening is upward, and the surrounding enclosing interface constrains the horizontal direction of the air flow; therefore, the air flow in the courtyard is slower than the outdoor air flow, which is more conducive to people's daily comfort. When the heat storage material around the building demonstrates good performance, the material slowly releases heat at night, which creates a small temperature difference in the courtyard. Then, the courtyard space becomes a climatic buffer layer for the whole building, enriching the overall climatic gradient of the building and thus creating a more comfortable space under adverse conditions.

2. Courtyard microenvironment

In traditional residential courtyards, there are many green plants, and tall trees are planted on both sides of the entrance to the building. These trees have lush branches and leaves in summer, which block sunlight and lower the temperature in the courtyards and indoor areas. They have a large number of leaves on them that wither in winter, providing no shade from the sun, and then the buildings directly receive a large amount of sunlight, thereby causing an increase in the indoor temperature. There are usually many shrubs growing beneath the trees, which help to lower the temperature and regulate the microclimate primarily through the process of photosynthesis, thereby enhancing the thermal comfort of the courtyards. Furthermore, water tanks are often situated in the corners of courtyards, and some courtyards feature a central water pool, which serves a dual purpose as both an ornamental feature for fish farming and lotus planting, as well as a firefighting resource in case of fire. Additionally, during the hot summer months, the evaporation of water also helps lower the temperature of the courtyard, making it a win–win situation.

7. Conclusions and Suggestions

7.1. Conclusions

The construction of traditional dwellings is a process that allows local residents to comprehend the natural and human environment in which they reside. The local residents of Xuzhou instinctively prioritize low-technology solutions in their building construction, which are specifically manifested in the integration of buildings with the local natural environment, the utilization of locally sourced natural materials, excellent adaptability to local climate conditions, and minimal construction costs and energy consumption, showing the characteristics of harnessing local resources, utilizing stone materials, and embracing low-technology solutions. These measures maximize the integration of construction and life into nature, effectively utilizing nature and achieving a harmonious coexistence with nature without relying on high-tech means. Traditional dwellings evolve in a continuous struggle with the local climate and environment, ultimately achieving a balanced and scientific construction method.

In addition, there is a special type of courtyard space inside the courtyards of traditional buildings in Xuzhou—cold alleys. These are the narrow alleys between courtyards that are usually arranged along the longitudinal direction of the buildings and for which the width is relatively constrained, such that their height-to-width ratio is relatively high. There are such cold alleys in both flat and hilly building compounds, of which the Hubu Mountain Yu Family Compound is a typical example (Figure 27). As mentioned above, these alleys are not only narrow but also have a large height-to-width ratio; therefore, the alleys are only insignificantly affected by the sun's rays and receive less heat. Meanwhile, the ventilation is better; therefore, the alleys can stay cool.

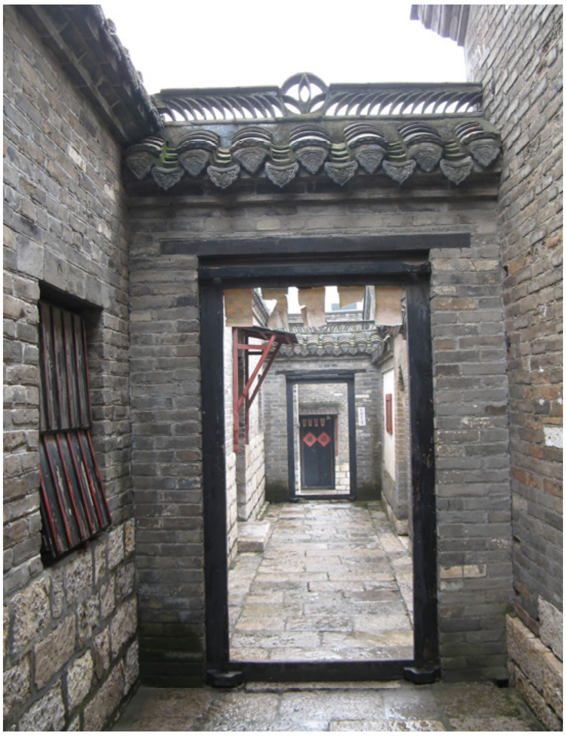

Figure 27. Cold alley in the Yu Family Compound.

This study combines qualitative and quantitative analyses to investigate the climate-responsive solutions used in traditional residential buildings in the Xuzhou region, and the characteristics of traditional dwellings as well, including village layout, dwelling forms, dwelling structures and dwelling materials. The simulation software programs Ecotect and Phoenics were chosen to compare and analyze the indoor environmental measurements of typical dwellings in northern Jiangsu.

In the measured data, the maximum temperature fluctuation of each room of the Yu Family Compound in winter was 7.37 °C, the maximum humidity fluctuation was 38%, and the maximum wind speed fluctuation was 0.51 m/s. In summer, the maximum temperature fluctuation was 5.01 °C, the maximum humidity fluctuation was 45%, and the maximum wind speed fluctuation was 1.04 m/s. The maximum fluctuation of outdoor temperature in summer was 10.32 °C, the maximum fluctuation of humidity was 48%, and the maximum fluctuation of wind speed was 1.68 m/s; in winter, the maximum fluctuation of temperature was 11.85 °C, the maximum fluctuation of humidity was 44%, and the maximum fluctuation of wind speed was 0.99 m/s.

In the simulated data, the use of passive measures significantly improved the comfort of the built environment, with the most effective passive measure being ventilation, which was effective in summer, spring, and autumn and relatively ineffective in winter. In addition, heat gain and loss in buildings in winter were mainly attributable to the building envelope and cold-air infiltration.

The results show that the traditional brick- and wooden-structure residential buildings in Xuzhou adopt passive design strategies and are well adapted to the local climate in terms of form, material, and structure. There is also a need to optimize the buildings' moisture resistance and ventilation for better comfort. Improvements in these areas will help provide a healthy indoor environment for other dwellings in the area.

7.2. Suggestions

The following measures are suggested:

The optimization of the overall architectural landscape of the village. The density of buildings should be considered in an integrated manner in order to achieve a more stable internal environment. Buildings that are too densely packed will reduce ventilation and heat dissipation and can easily interfere with the residents' daily lives. Too much spacing between buildings is not conducive to heat preservation and wind protection in winter. The rational planning of building clusters can reduce the surface area of buildings in direct contact with unfavorable external environments, give full play to the climate-regulating advantages of thick walls and patios of traditional residential buildings, and overcome their inherent shortcomings.

The design of site selection, orientation, indoor space layout, and building openings to conform to the topography and make full use of the local wind direction to achieve a good natural ventilation effect.

Attaching importance to shading and sun protection, relying on "climate buffer space" and "transition space" to form a good heat insulation and self-shading effect, combining with greening and water bodies to create a good indoor and outdoor thermal environment.

Adopting the double-layer enclosure structure of inner adobe and outer fired-brick walls plus wood-paneled interior walls to increase the heat storage capacity of the walls and improve the thermal inertia.

Adopting an overhead ventilation floor structure to increase the moisture-proof and heat-preserving effects of the building as a whole.

Improving the airtightness of windows and doors to reduce cold-air infiltration in winter. Selecting windows and doors of appropriate proportions to balance summer ventilation efficiency with winter heat loss.

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