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From Poor Buildings to High Performance Buildings: The Spontaneous Green Evolution of Vernacular Architecture

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Abstract: The spontaneous evolution of vernacular architecture mainly relies on the inheritance of architectural traditions and the innovative decisions of occupants, rather than the professional guidance of architects and the promotion of government agencies. This study introduces a new and rapidly developing phenomenon of spontaneous green evolution of vernacular architecture into the professional field, and conducts scientific research on its technical characteristics, system effects, and optimization methods. Based on the phenomenon of roofing of courtyards (CBR) in southern Hebei, we intervene from the professional point of view of architects, make the best use of the situation, and moderately intervene in its scientific development. By re-examining the adaptability of the open and closed attributes of courtyard buildings to specific climatic conditions and living patterns, the performance improvement and potential risks brought by CBR to local vernacular buildings are systematically analyzed, and the improvement strategies and promotion paths of CBR are explored. The research aims to form a relay and interaction between the professional intervention of architects and the spontaneous evolution of folk wisdom, and to explore the sustainable development of vernacular architecture. The findings help to improve the health and comfort of existing vernacular buildings, as well as to contribute to the improvement of rural human settlements.

Keywords: courtyard; climate; evolution; architect; professional intervention

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1. Introduction

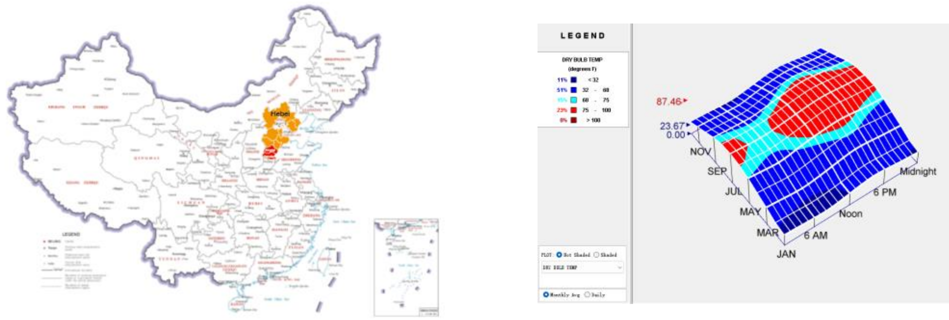
Globally, there is a huge stock of vernacular buildings which represent history, tradition, and local culture, and are also known as living fossils of the evolution of human habitats [1]. Different from formal buildings dominated by professional architects, vernacular buildings have certain characteristics, such as anonymity, rurality, and folkness [2]. Moreover, vernacular buildings will evolve with changes in the external environment and the needs of the occupants, so they are also called progressive buildings [3]. In general, vernacular buildings are more likely to be found in the countryside, with outdated energy systems and weak envelopes [4]. However, with the rapid development of urbanization and the improvements in residents' living standards, vernacular buildings are also changing to cope with modern lifestyles [5,6].

Most architects and researchers focus mainly on apartment or office buildings in urban areas rather than vernacular buildings in rural areas. Furthermore, most of the existing literature on vernacular architecture is more concerned with their cultural attributes and artistic value [7,8]. Considering the huge stock and weak thermal performance of vernacular buildings, the study of their spontaneous evolution is very necessary, which is related to the green development of the building sector and the realization of sustainable development goals [9,10].

This research aims to guide the scientific and sustainable development of vernacular buildings through professional intervention on the basis of understanding the evolution mechanism of vernacular buildings. Specifically, this study selects vernacular buildings in southern Hebei, China as a case study, and identifies the potential technical optimization paths by analyzing their evolution characteristics, potential motivations, and technical performance. Subsequently, a framework for multi-stakeholder engagement is constructed for the further scientific development of vernacular buildings in the region.

1.1. Vernacular Buildings in Southern Hebei

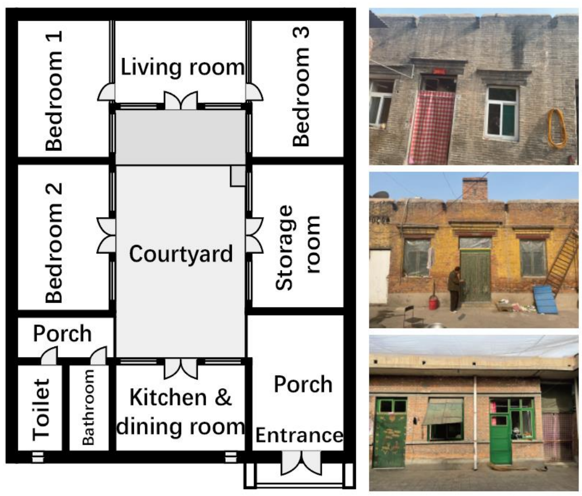
Southern Hebei includes two cities of Xingtai and Handan, with a population of about 16.9 million [11]. Southern Hebei has a humid continental climate and a semi-arid climate, belonging to Dwa/BSk in the Köppen climate classification. The annual average temperature is 13.5 °C. In the coldest month (January), the average temperature is −2.3 °C, and the extreme minimum temperature is −19 °C; in the hottest month (July), the average temperature is 26.9 °C, and the extreme maximum temperature is 42.5 °C (Figure 1). Annual precipitation is about 502 mm, mostly in summer.



(**a**) Geographical location (**b**) Climatic characteristics

Figure 1. Geographical location and climatic characteristics of southern Hebei.

The vernacular buildings in southern Hebei are represented by courtyard buildings with flat roofs [12]. The local vernacular architecture is also known as the "house with two sleeves thrown out" (HTSTO), because parts of the east and west ends of the north house of the building extend southward, like the arms of the main house with outstretched sleeves [13] (Figure 2). The surrounding buildings of HTSTOs are connected end-to-end to form a complete and closed courtyard space inside, which has high defense and privacy [14].



(a) Floorplan of HTSTO (b) Envelope

Figure 2. Vernacular buildings and their enclosure structures in southern Hebei.

The wall materials of the local HTSTO are mainly clay bricks, including three thickness specifications of 240 mm, 360 mm, and 480 mm. Roofs are generally concrete with a thickness between 100 mm and 150 mm. The windows are basically single-layer ordinary glass, and the window frame materials include wood, aluminum alloy, plastic, and steel. Although the winter in southern Hebei is very cold, an HTSTO's enclosure structure is not equipped with any insulation materials, so the overall thermal performance is weak.

1.2. The Spontaneous Green Evolution of HTSTO

For the traditional HTSTO, the courtyard is characterized by being open to the sky. However, local vernacular architecture has seen an evolution represented by the courtyard being roofed (CBR). Specifically, local residents flexibly used materials, such as plastic films and heterogeneous metal plates, to seal the original open courtyard of an HTSTO (Figure 3). In general, CBR technology (CBRT) can be divided into transparent CBRT (T-CBRT) and non-transparent CBRT (NT-CBRT) from the characteristics of roofing materials [15–17].

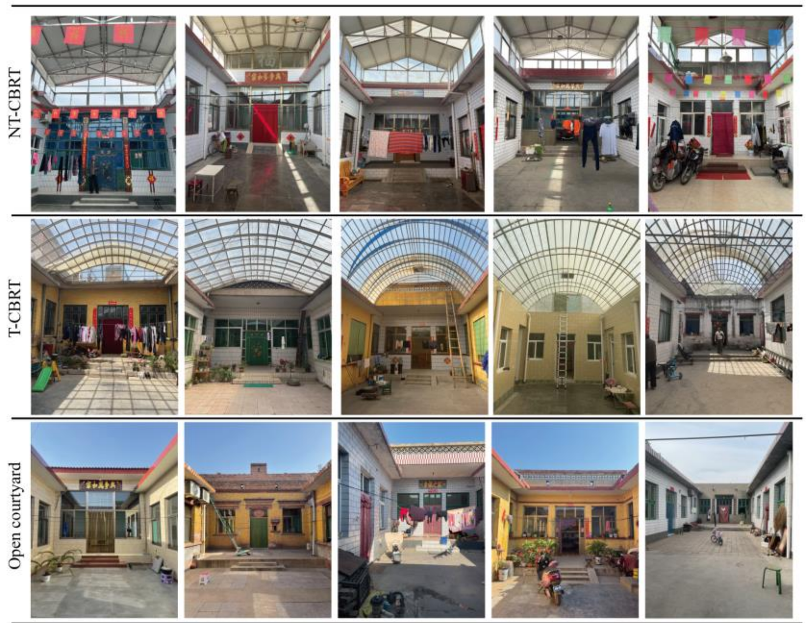


Figure 3. Open courtyards and different forms of CBR.

In addition, the main characteristics of the CBR phenomenon are as follows.

CBR redefines the relationship between architecture, climate, and people. Through CBR, the courtyard is transformed from the original transitional space into an indoor space, and the relationship between architecture, climate, and residents is reshaped. Secondly, the courtyard space with enhanced indoor attributes brings the possibility of functional expansion to adapt to various scenarios for the occupants, and its use efficiency is expected to be improved.

CBR is a widely accepted low-tech passive strategy. Compared with the overall improvement in the thermal performance of the envelope structure, the cost of CBR is relatively low, the construction difficulty is small, and the materials are easy to obtain. Due to the simplicity, low cost and good effect of CBR technology, it has been widely accepted by local farmers.

CBR is characterized by spontaneous development and evolution. The emergence and development of CBR was spontaneously formed and popularized by local people, and it has not received in-depth research by professionals, nor has it attracted the attention of local governments.

1.3. Challenges Faced by CBR Development

Since CBR is developed spontaneously, its technical development still faces the following challenges.

Local residents lack scientific understanding and quantitative awareness of CBRT. At present, the development of CBR mainly relies on the transfer of experience among local farmers, rather than the quantitative research and technical research and development of professionals. As the main promoters of CBR development, local farmers have not mastered advanced scientific construction expertise, which leads to uncertainties in material selection, structural design, construction, and use.

The systemic impact of CBR on HTSTO is unclear. The transformation of an HTSTO's courtyard space from the original open to closed brings about a series of changes in indoor environmental parameters. Specifically, CBR can improve the energy efficiency of buildings by improving the overall airtightness of buildings, but the improvement in airtightness also brings risks to indoor air quality (IAQ) [18]. In addition, while CBR may lead to warmer and more comfortable indoor conditions in winter, it may also lead to the risk of overheating in summer [8]. At present, the chain reaction and comprehensive impact brought by the closure of the courtyard are not considered, and the systematic impact of CBRT on the indoor environmental quality of HTSTOs needs to be scientifically analyzed.

In short, CBR is a new type of housing derived from the traditional HTSTO, which has been widely developed in southern Hebei, reflecting the survival wisdom and innovative courage of local farmers. However, there are still many problems and technical bottlenecks in the independent development of CBR, and it is urgent to carry out technical optimization and scientific promotion through scientific research.

2. Literature Review

2.1. Traditional Courtyard Model and Its Energy Efficiency

Previous research has suggested that having an open courtyard can have a positive effect on a building's energy efficiency. Huang, Liu [19] believe that compared with no courtyard occupancy, full use of courtyards can reduce building energy consumption by 7.21% to 33.99% in various situations. Lizana, Lopez-Cabeza [20] found that the microclimate of the courtyard can greatly reduce the impact of urban overheating in the building, eliminating more than 88% of the uncomfortable time indoors. In Iraq, courtyards have been shown to provide occupants up to 38% more comfort throughout the year [21]. In short, the traditional open courtyard is believed to have a positive effect on reducing energy consumption and carbon emissions of the building [22–24].

In addition, there are various factors that affect the energy efficiency of courtyard buildings [25–30]. Shashua-Bar and Hoffman [31] lowered the temperature inside the building by increasing the height of the building and deepening the adjoining courtyard. Muhaisen and Gadi [32] believe that shallow yards are better for buildings that need heating in winter, while deep yards are better for buildings that need shade in summer. Muhaisen and Gadi [33] also suggested that several methods could be used to control solar energy utilization of courtyard buildings, including using light-colored exterior surfaces to reduce solar radiation absorption in summer, and reducing the depth of courtyards so that buildings receive more solar radiation in winter. Yasa and Ok [34] highlighted the important role of the geometric proportions of the courtyard; an optimal geometric proportion is a form that allows minimum radiation in summer and maximum radiation in winter. Taleghani, Tenpierik [35] investigated the impact of courtyard orientation on its energy efficiency and pointed out that configuring swimming pools and green spaces inside courtyards is the most effective heat reduction strategy for Dutch urban blocks.

2.2. Potential Benefits of CBR for Courtyard Buildings

Aldawoud and Clark [36] analyzed the performance of courtyard buildings in four climate conditions: cold, temperate, hot-humid, and hot-dry, and found that open courtyard buildings have better energy performance for shorter buildings, but with the increase in building height, closed atriums exhibit better energy performance. Akbari, Cherati [37] pointed out that most studies investigating the performance of courtyard buildings only consider the performance of a specific season rather than the whole year, which may bias the results. Manzano-Agugliaro, Montoya [38] introduced a model for a Sevillian courtyard with a mobile device, a strategy capable of absorbing solar energy during the day and reducing heat dissipation at night. However, the above studies are mainly based on theoretical assumptions based on software simulation, and there is a lack of empirical research at the application level. In addition, Li and Lei [39] reported that courtyard buildings in Kashgar were closed by glass roofs, and found that the temperature of closed courtyards was 1.8 °C higher than that of open ones. Zhang, Song [40] used multi-layer polycarbonate panels to seal a courtyard building in Qinghai, and the CBR device comprehensively considered technical details, such as ventilation, shading, and anti-condensation.

Philokyprou and Michael [8] argued that converting semi-open spaces to closed (especially south-facing) spaces during heating periods can be seen as a positive renovation strategy. At the same time, shade measures should be taken in summer to avoid overheating. Yao, Han [41] added a glass roof to the courtyard to increase its heat storage capacity and turn it into a thermostatic heater for heating the building's interior. Taleghani, Tenpierik [42] found that, in the Netherlands, converting courtyards to atriums reduced heating needs but increased hours of discomfort. The courtyard mode is more dominant from May to October, while the atrium mode is best the rest of the time. Chi, Xu [43] installed a glazed roof installation above the courtyard, creating a greenhouse environment that promotes warmer indoor temperatures in winter (up to 5.5 degrees during the day on a clear winter day). Zhu, Wang [44] discussed the potential benefits of converting courtyards in North China to skylight-covered atriums. The results show that compared with open courtyards, courtyards using CBR have higher energy efficiency, which is very suitable for energy-saving renovation of courtyard buildings in North China.

2.3. Paths Driving the Evolution of Vernacular Architecture

As far as the evolutionary path of vernacular architecture is concerned, its driving forces mainly include occupants, government agencies, and architects. Among them, the occupier-led spontaneous evolution model has a clear problem orientation [45]. The evolution of vernacular architecture is mainly completed by folk craftsmen and residents, and its technical optimization relies on experience accumulation and error correction. However, due to the lack of scientific guidance, the improvement of spontaneous evolution requires a long process, and there is a risk of unreasonable technology breeding and spreading in specific areas. Generally speaking, since the spontaneous evolution is initiated and developed by the occupants, its development conforms to the theory of self-organization and has strong vitality.

For the purpose of energy conservation, emission reduction, and green development, government agencies may also lead the green evolution of some vernacular buildings. This evolution process generally relies on expert decision-making, and relies on some enterprises for technology development and promotion. Although the evolution promoted by the government has the advantages of high promotion efficiency and quick results, some technical measures that have not been fully demonstrated lack the necessary feedback links, resulting in uncertainty in their long-term effects [46].

The evolution of vernacular architecture led by architects generally aims at a clear design concept. Based on a professional design team and engineers, the technology research and development process is highly scientific. However, the architect-led evolution process also has limitations, mainly due to the low participation of occupants and the low efficiency of technology promotion. For example, Wang [47] proposed that architects lack long-term rural life experience, and it is difficult to accurately identify the real and comprehensive needs of farmers in a short period of time. Therefore, Han, Li [45] suggested that architects should constrain the theories and methods cultivated in the urban environment, and lean over to learn from local farmers to understand their real demands.

3. Research Methods

The research process mainly consists of five parts (Figure 4): exploring the motivation of CBR, analyzing the performance of different CBRTs, clarifying the mechanism of CBR's impact on the indoor environment of buildings, proposing technology optimization strategies, and constructing technology promotion paths.

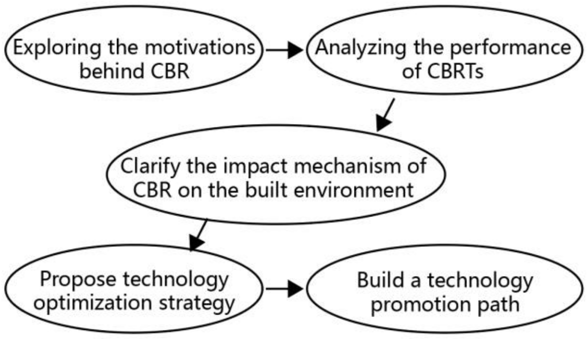


Figure 4. Proposed study procedure.

3.1. Exploring the Motivations behind CBR

Various factors, such as the environmental characteristics, economic development level, and the living needs of local farmers in southern Hebei, constitute the background for the occurrence of CBR. Through field investigations and user interviews, the potential motivations for CBR are identified [48], so as to clarify the incentives for the green evolution of HTSTOs. Fully understanding the formation mechanism of CBR can provide a direction and basis for subsequent technical optimization.

3.2. Analyzing the Performance of Different CBRTs

Based on representative HTSTO cases, including the open courtyard, T-CBRT, and NT-CBRT, the physical environment parameters are monitored by on-site measurement. Specifically, the three selected cases have similar envelopes. The exterior walls are 360 mm brick, the internal partitions are 240 mm brick, the roof is a 150 mm concrete slab, the floor is a 100 mm concrete layer, and the windows are equipped with regular single glazing. The specific physical parameters of the building envelope are shown in Table 1.

Table 1. Physical parameters of building envelope.

Envelope	Constructive Solution	Total Thickness (mm)	U-Value (W/m^{2}K)
Floor	Concrete layer with tiles on the surface.	100	1.077
Exterior walls	Brick wall with plastered sides.	360	1.972
Interior walls	Brick wall with plastered sides.	240	1.328
Roof	Concrete slab with plaster layer.	150	2.043
Windows	Ordinary single glazing.	2.5	5.914

The Renke temperature and humidity recorder was used in this study (Figure 5). The temperature sensor is Renke, the measurement range is −20 °C to 60 °C, the accuracy is ±0.1 °C, and the resolution is 0.1 °C. The humidity sensor is Cos-03, the measuring range is 0–100% RH, the accuracy is ±2%, and the resolution is 0.10%. From June 2021 to June 2022, the cases of open courtyard, T-CBRT and NT-CBRT, were monitored for one year, respectively. In order to ensure the reliability of the monitoring data, the measuring instruments were deployed in the middle of the courtyards of the three HTSTO cases, and they were placed in positions out of direct sunlight. The temperature and humidity data of HTSTO are continuously monitored, and the measuring instrument will automatically record the monitoring data every 10 min. After the end of the year-long monitoring, the recorded data of all measuring instruments were imported into the computer. The recorded data of the three cases of open courtyard, T-CBRT, and NT-CBRT will be merged into one worksheet at a unified time to compare the data.

Sensor	Elements	Measuring range	Accuracy	Resolution
Renke Cos-03	Air temperature	−20°C-60°C	±0.1°C	0.1°C
	Relative humidity	0-100%RH	±2%	0.10%

Figure 5. The equipment used in the study and its parameters.

3.3. *Clarify the Impact Mechanism of CBR on the Built Environment*

Based on on-site measurement, qualitative analysis, and quantitative analysis, and according to the monitoring data of different HTSTO cases, the impact mechanism of CBR on the built environment is analyzed. Furthermore, we compare the similarities and differences in different CBRT's impact on the built environment.

3.4. *Propose Technology Optimization Strategy*

Based on the identified impact mechanism of CBR on the built environment, different optimization strategies for CBRT are proposed. At the same time, combined with the potential motivation of CBR, the best technical optimization path that meets the occupants' residential needs and psychological expectations is screened out.

3.5. *Build a Technology Promotion Path*

We explore the multi-participation mode of "co-evolution" of vernacular architecture. Specifically, the promotion of optimization techniques includes improvement measures of existing CBRTs and newly developed CBRT systems. Based on the determined evolutionary motives and technical optimization strategies, we build an interaction mechanism and cooperation model among architects, occupants, folk craftsmen, and government agencies, and then promote the scientific development of vernacular architecture.

4. Results and Discussion

4.1. *Potential Motivations for the Occurrence of CBR*

Based on questionnaires and user interviews, the motivations for CBR occurrence were identified. The dramatic changes in rural life scenes are an important reason for the development of CBR. The traditional HTSTO is more suitable for agriculture-oriented families. The flat roof is suitable for drying food, while the open courtyard can be used to grow plants and raise animals. However, with the adjustment of the rural economic structure, many farmers choose to work in factories, and families are becoming less and less dependent on agriculture. The popularity and development of television, mobile phones, and mobile Internet have made farmers more willing to stay indoors rather than outdoors.

In addition, the occurrence of CBR is also driven by the following factors. Open courtyards mean high-intensity interaction between indoor and outdoor environments, providing a way for energy exchange, sand intrusion, mosquito nuisance, etc., making it difficult to meet modern farmers' living needs for health, comfort, and hygiene. In recent years, with the rapid development of local industries, changes in climatic conditions, such as severe smog, are challenging traditional vernacular architecture. Existing residential buildings cannot meet farmers' needs for a healthy and comfortable living environment.

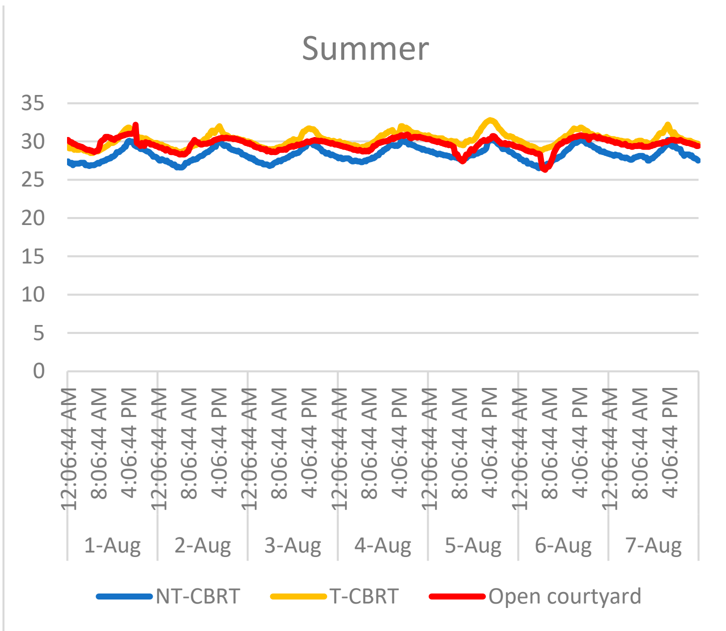
The thermal performance of a brick-concrete HTSTO is weak and cannot match the current energy metering system, which indirectly increases the energy and economic burden on farmers. An HTSTO's existing envelope structure is basically brick walls and concrete roofs without insulation layers, and its thermal performance is very poor. However, a comprehensive upgrade of the HTSTO envelope means a huge economic investment, which many farmers cannot afford. Therefore, CBR can effectively improve the overall thermal performance of the building with less investment, and has become a popular building renovation measure among local people.

CBR expands the original functions of the vernacular buildings. CBR enlarged the interior space of the HTSTO to expand and extend its functionality. The enhanced sealing can prevent the intrusion of external dust and fallen leaves, especially in the windy and sandy spring, and can provide a clean and tidy environment that is easier to maintain. Moreover, CBR also avoids the interference of rain and snow on the use of courtyard space, and can also ensure washing, drying, and other activities in the courtyard in cold weather.

4.2. Performance Analysis and Comparison of Different CBRTs

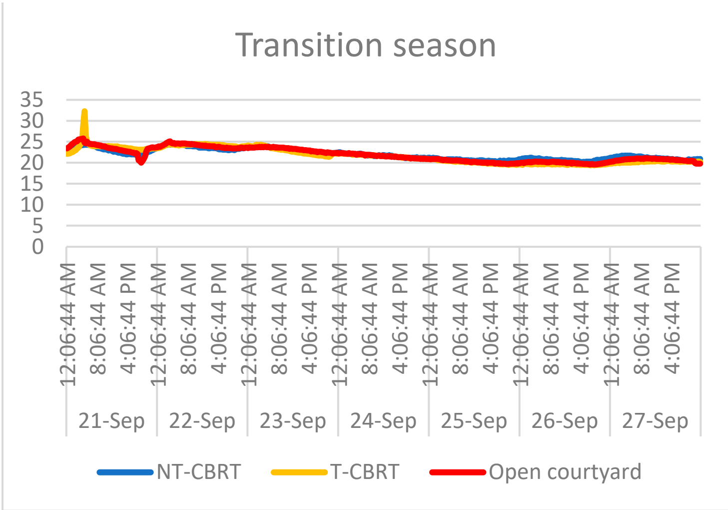
For the courtyards of different vernacular buildings, temperature and humidity monitoring was carried out for one year. The results showed that the temperature of T-CBRT was higher than that of the open courtyard in summer, and the maximum temperature difference could reach 2 °C, suggesting that T-CBRT may cause overheating in summer (Figure 6a). NT-CBRT did not appear to be hotter than the open courtyard in summer, and even had a slightly lower temperature than the latter. This is because there are generally openable windows around the NT-CBRT, and these windows are often open in summer. The risk of summer overheating caused by light-transmitting roofs has been mentioned many times in previous studies, which well validates the monitoring results of this study [49–52].

However, T-CBRT showed a better performance to the NT-CBRT and open courtyard in winter (Figure 6c). In sunny winter days, T-CBRT can increase the courtyard temperature by more than 5 °C, while NT-CBRT can only raise the courtyard temperature by about 4 °C. This is consistent with previous research findings, where Philokyprou and Michael [8] found that converting south-facing open spaces into closed interior spaces can increase temperatures by 6 °C. Chi, Xu [43] also reported that adding a light-permeable roof could raise the temperature of a previously open patio by as much as 5.5 °C. Furthermore, the open courtyard, T-CBRT, and NT-CBRT performed comparably in the transition season, and their courtyard temperatures were almost identical (Figure 6b).

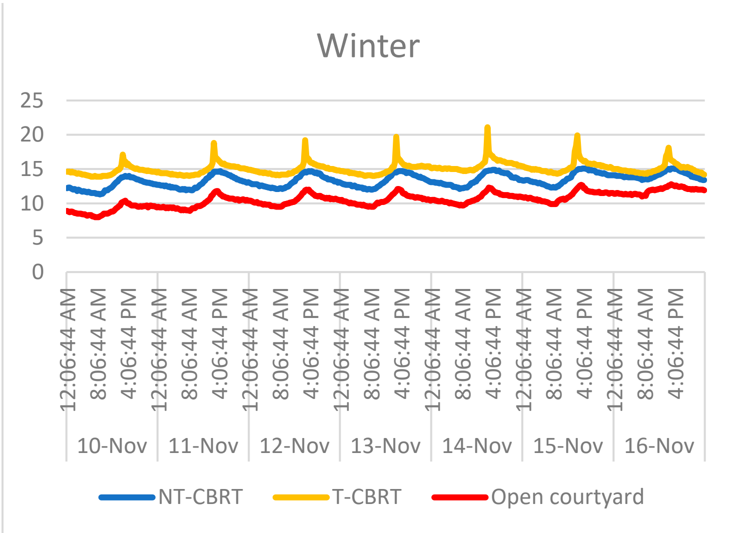


(**a**) Summer monitoring data.

Figure 6. *Cont.*



(**b**) Transition season monitoring data.



(**c**) Winter monitoring data.

Figure 6. Monitoring data for different vernacular buildings.

4.3. Influence Mechanism of CBR on the Performance of Courtyard Buildings

Through actual measurement, it is found that compared with open courtyards, CBR can effectively improve the energy efficiency of buildings and significantly improve indoor thermal comfort in winter. Through different CBRTs, a buffer space is added to the envelope of HTSTO, which was originally directly exposed to the external environment, thereby improving the building's ability to resist external climate fluctuations (Figure 7). During sunny winter days, the courtyard covered by CBRT acts as a conservatory to absorb solar energy and store heat. On winter nights, the enclosed courtyard can transport the heat stored during the day to various functional rooms, and can effectively reduce indoor heat loss at night.

CBRT improves the performance of courtyard buildings mainly by collecting solar energy, storing solar energy, and slowing down indoor heat dissipation. In the cold winter, the temperature of the courtyard covered by CBRT is 3–6 degrees Celsius higher than that of the open courtyard, which reduces the temperature difference between the courtyard and the heated room. The reduction in temperature difference effectively alleviates the heat loss of the heated room leaking to the courtyard through walls, windows, and ventilation. Furthermore, heat leaking from the warm rooms will be collected by the enclosed courtyard, slowing the loss of heat to the exterior of the building, thereby providing a warmer courtyard.

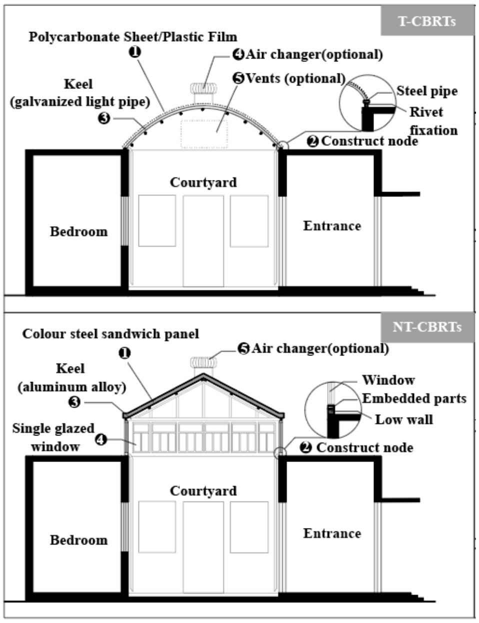


Figure 7. Technical prototype of T-CBRT and NT-CBRT.

Although T-CBRT and NT-CBRT can also effectively improve the thermal comfort of courtyard space in winter, they have slightly different operating mechanisms. Specifically, T-CBRT has better solar energy collection effect due to better light transmittance, while NT-CBRT provides a more stable indoor thermal environment due to the thermal insulation performance of roofing materials. For T-CBRT, the light transmittance of the roof material is the most critical parameter affecting its performance. The use of high light transmitting-materials not only helps to improve the efficiency of CBRT in collecting solar energy, but also helps to improve the indoor light environment [53]. For NT-CBRT, the height of the roof and the volume of the buffer space provided are important factors affecting its performance.

4.4. Potential Optimization Schemes for CBR

Although the light transmittance of T-CBRT's roofing materials is crucial to its performance, most of its light-transmitting materials are plastic films and polycarbonate sheets that are prone to aging. The light transmittance of these materials will be greatly reduced after aging, which directly affects the solar energy collection efficiency of CBRT. Therefore, light-transmitting materials with aging-resistant properties are suggested as roofing materials for T-CBRT. If the price factor is taken into consideration, the occupants can also replace them regularly on the basis of using ordinary light-transmitting materials to prevent the reduction in their light transmittance. In summer, removing all light-transmitting materials is the best choice for T-CBRT. This converts an enclosed courtyard into an open courtyard and avoids overheating in the summer. If the light-transmitting material is completely fixed, shading measures should be added to it in summer. It is a reasonable choice to completely cover the surface of the light-transmitting material of T-CBRT with a dark shade net, which can reduce the heat discomfort time of the courtyard and protect the light-transmitting material to slow down its aging process.

For NT-CBRT, although the roof height is crucial to its performance, this optimization strategy is difficult to implement in real-world scenarios. An effective alternative is to add thermal insulation measures to the existing NT-CBRT roof, which can effectively reduce the heat dissipation of the courtyard in winter and the risk of overheating in summer. While enhanced ventilation in hot weather is important for both T-CBRTs and NT-CBRTs, the latter can be easily achieved by opening surrounding windows, while the former requires retrofitting to provide more efficient ventilation. In addition, multi-layer hollow anti-aging polycarbonate panels can be used to replace the current NT-CBRT metal roof panels, which can combine the advantages of T-CBRT and NT-CBRT to further improve the performance of CBRT. In this case, the new CBRT can not only collect solar energy to the maximum extent, but also provide a larger heat storage space, which is beneficial to maintain a higher indoor temperature in winter.

4.5. Promotion Path of the Optimized Technology

Wu [46] proposed the concept of "collaborative design", emphasizing the formation of relays and interactions between occupiers, village administrative agencies, and architects. The concept of "collaborative design" also applies to the evolution and development of CBRT. Although the spontaneous evolution of CBR reflects the enthusiasm and creativity of residents, it still requires the intervention of professionals and the promotion of government agencies. Only by combining "bottom-up" folk wisdom with "top-down" scientific guidance can CBR develop more scientifically. Specifically, architects can publicize the technical features and effects of CBRT to local people, and architects can use the media to promote to local residents how to more rationally transform existing CBRT. Moreover, architects can also provide policy recommendations to local government agencies to promote the scientific development of CBRT. In addition, researchers can formulate technical guidelines and provide skills training for folk craftsmen engaged in CBRT, thereby ensuring the high-quality development of CBRT. Researchers can cooperate with relevant companies to produce new CBRTs and reduce the cost of CBRT by increasing production scale. With the participation of multiple parties, the sustainable evolution of CBR will ultimately be promoted.

5. Conclusions

This study conducted scientific research on the technical characteristics, system effects, and optimization methods of different forms of CBRT. We systematically analyzed the performance improvements and potential risks brought by CBR to HTSTOs and explored the improvement strategies and promotion paths of CBR. Specifically, CBR, as a green technology developed spontaneously by the people, can effectively improve the thermal performance of HTSTOs and reduce building energy consumption. Especially in cold winters, CBR can collect and store solar energy, providing a more comfortable indoor thermal environment. T-CBRT and NT-CBRT are two important forms of CBRT, both of which can improve the thermal performance of existing buildings. The sensitive parameter that affects the performance of T-CBRT is the light transmittance of the roof material, while the most sensitive technical parameter of NT-CBRT is its roof height.

This study analyzed the spontaneous green evolution of vernacular architecture from a professional perspective and guided its scientific development. Scientific research on the occurrence and development mechanism of CBR can fill the research gap in the field of spontaneous green evolution of vernacular buildings. The scientific research and performance optimization of CBRT can also effectively improve the health and comfort of existing HTSTO and promote the sustainable development of vernacular buildings.

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Abbreviations

HTSTO	House with two sleeves thrown out
CBR	Courtyard being roofed
CBRT	Courtyard being roofed technology
T-CBRT	Courtyard being roofed technology with transparent materials
NT-CBRT	Courtyard being roofed technology with non- transparent materials
IAQ	Indoor air quality

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