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Socio-Environmental Responsive Strategy and Sustainable Development of Traditional Tianshui Dwellings

Jiayi Shi [1,2], Tao Zhang [3,*], Hiroatsu Fukuda [2,*], Qun Zhang [4] and Lujian Bai [1]

[1] School of Architecture and Civil Engineering, Xi'an University of Science and Technology, Xi'an 710054, China; shijiayi@xust.edu.cn (J.S.); blj4622@126.com (L.B.)
[2] Department of Architecture, Graduate School of Environmental Engineering, The University of Kitakyushu, Kitakyushu 808-0135, Japan
[3] Innovation Institute for Sustainable Maritime Architecture Research and Technology, Qingdao University of Technology, Qingdao 266033, China
[4] School of Architecture, Xi'an University of Architecture and Technology, Xi'an 710055, China; zhangqun@xauat.edu.cn
* Correspondence: zhangtao841120@163.com (T.Z.); t-zhang@kitakyu-u.ac.jp (H.F.)

Abstract: The comprehensive and coordinated sustainable development of residential dwellings requires a response to the multidimensional environment. In this study, typical traditional Tianshui dwellings are selected as research objects, through the methods of field investigation, in-depth conversations, and on-site monitoring, in order to investigate the potential of traditional Tianshui dwellings reacting to natural conditions as well as social environment. The performance of traditional dwellings in the process of regional adaptation expounded and discussed based on seven elements under the conditions of two dimensions: (1) an objective regional response to the natural environment, namely, site selection, courtyard layout, orientation, structure, and envelop enclosure; and (2) a subjective regional response to social environment, namely, spatial order, construction technology, and decorative arts. The results show that traditional Tianshui dwellings are well adapted to local natural conditions and the social background, and that they meet both the physical and psychological needs of residents. In conclusion, this paper summarizes the features of the sustainable development of traditional dwellings learning from the principles obtained from the process of socio-environment responsive strategy analysis. These valuable experiences and design principles can provide references and guidelines for the long-term development of modern architecture not to only reduce energy consumption, but also to increase local social influence.

Keywords: socio-environmental responsive strategy; traditional dwelling; Tianshui; sustainable development

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1. Introduction

With the continuous growth of the population and the rapid development of the economy, humankind's demand for energy is increasing. From a global perspective, 20–40% of energy is consumed by buildings, and this value is as high as 45% in developed countries [1,2]. In China, building energy consumption accounted for the total energy consumption increase from 17.7% in 2014 to 27.6% in 2018 which was approximately quadruple that of 17 years ago [3]. According to the forecast of the China Association of Building Energy Efficiency (CABEE), the growth trend of Chinese building energy demand will continue until 2039 [3]. In this context, sustainable development has become an indispensable and important concept in the field of building construction. Moreover, one of the important purposes of sustainable development is designing and constructing buildings that can provide a comfortable indoor thermal environment, minimizing the use of heating, ventilation, and air conditioning (HVAC) systems as much as possible [4]. To achieve this, buildings should fully be adapted to the natural conditions of the location in the early stages of design.

The unique characteristics of folk craftsmen, local building materials, and cultural circles in different regions lead to unique vernacular buildings and traditional buildings, whose indigenousness, anonymousness, spontaneousness, lack of officialism, traditions, and ruralism can continuously provide precious knowledge to improve the construction of modern buildings [5,6]. The principles from the construction of traditional buildings can be well applied in the construction of modern buildings to produce buildings that consume less energy and the construction of sustainable buildings for the future can be possible if these ideas are reasonably adopted [7–9]. In the process of construction, modern buildings do not pay much attention to the influence of different regions and climates. Thus, it is necessary to carry out filed investigation of vernacular dwellings in order to gain valuable effective measurements to reduce energy consumption, improve indoor thermal comfort, and optimize the quality of the living environment. Tianshui has a cold climate with dry winters and warm summers (Dwb), based on the Köppen–Geiger classification [10]. Other parts of the area, such as Yonsa in North Korea, have similar climatic conditions. A traditional Tianshui dwelling is one of the typical rural adobe building types which are widely found in parts of Northwest China, such as Shaanxi, Sichuan, and Gansu. It is a kind of traditional residence with a high historical value that responds to social and cultural challenges, as well as representative dwellings that have accumulated many useful ecological and climate response requirements. Tianshui is a diverse area with a cold climate, frequent geological disasters, a long history, and multicultural integration located in northwestern China. Traditional Tianshui dwelling is a suitable research sample, which helps to study the formation of traditional houses from different perspectives.

In recent years, research on the regionality and sustainable development of traditional houses has been increasing, mainly focusing on the connection and correlation between natural environments and traditional dwellings. Climate-responsive design strategies, as a tool, are often used in studies on how to use passive design methods to reduce the non-renewable energy required for traditional residential dwellings [11–22]. In addition, scholars also present energy performance evaluations and indoor thermal comfort assessments of residential houses by means of testing [23–26], computer simulations [27–30] and mathematical modeling [31–34] to verify these methods of design. The results prove that climate-responsive design strategies are effective measurements to reduce energy consumption, improve indoor thermal comfort, and optimize the quality of the living environment. In addition, to achieve the comprehensive and coordinated sustainable development of residential dwellings, sustainable designers should not only concentrate on the natural environment, but also attend to assorted kinds of social factors, such as historical backgrounds, culture, religious beliefs, and people 's customs and habits in the places they want to live [35]. Thus, in the study process of socio-environment responsive strategy of traditional dwellings, not only should the focus be on natural aspects like air, water, and climate change, but it should also pay attention to the dimension of social factors [36]. However, nearly all the above studies discussed the effect of natural conditions on traditional buildings from a single dimension, emphasizing the impact of climate or geographic factors on the sustainable development of residential buildings. The authors of these studies ignored the important influence of the social environment on the forming of traditional dwellings, which is also defined as an indispensable aspect in the sustainable development concept.

The influence of socio-cultural factors on designing of traditional villages and dwellings were examined by some experts. Chen et al. [37] proposed the spatial evolutionary process and characteristics of the Chengkan traditional village through cultural-ecological environmental framework. They indicated that the natural, economic, and social environments together were regarded as an ecological environment support system that could be interacted with the traditional village space [37]. Chao et al. [38] analyzed the spatial production of rural culture in Tangwan village in Shanghai. They elicited that the culture was the root of the rural development and the lost culture led to the lost village. Mücahit and Gizem [39] identified a list of underlying factors that contributed to the significance of cultural heritage by conserving heritage values. While conserving heritage values, the re-use of historical patterns can also enhance sustainability. Wang and Chiou [40] summarized the evolution and composition characteristics of Dai residential space. They presented a point of view that architectural form and space composition of Dai dwellings were the crystallization of the collective intelligence of the Dai people in the long process of life and production, which contained the ecological concept, religious beliefs, and national customs of Dai. Regarding traditional Tianshui dwellings, few studies were carried out, mainly focusing on green design methods and heritage protection. Wang [41] simulated the ecological performance of the Tianshui Sihe residential building model from aspects of light environment, wind environment, and thermal environment through Ecotect, Phoenics, and DeST software. Zhou [42] interpreted the specific green experience of Tianshui traditional dwellings adapting to the natural climate and topography at the three levels of settlement level, courtyard level, and single building level. Qu et al. [43] suggested that the residents' awareness of protection should be strengthened, and the government should provide more financial guarantees and improve the support of technical personnel to strengthen the protection of Tianshui cultural heritage. Ma et al. [44] investigated that the protection of traditional residential settlements provides a necessary guarantee for the inheritance of local intangible cultural heritage, and the development of intangible cultural heritage promotes the continuation of the humanistic characteristics of residential settlements. The two promote each other and develop together.

The above literature review illustrates that mostly existing research pay much attention to the historical, environmental, or cultural perspectives of traditional dwellings independently. This paper particularly focuses on the interaction between environmental and social dimesons, and it uses socio-environmental analysis approach as a holistic perspective to insert this concept in the context of the sustainable development of traditional dwellings.

The aim of this work is to analyze the potential of Tianshui traditional dwellings in responding to environmental challenges, as well as social rules, and to explore how the traditional construction principles suit multidimensional conditions. To achieve this goal, the performance of traditional dwellings in the process of regional adaptation is expounded and discussed based on seven elements from both environmental and social dimensions using field investigation, in-depth conversations, and on-site monitoring. Meanwhile, this paper summarizes the features of sustainable development of traditional dwellings learning from the principles obtained from the process of socio-environment responsive strategy analysis. This research can provide new ideas for the design of environment friendly dwellings with the similar climate conditions and social context alongside providing references and guidelines for long-term development of modern architecture not only to save more energy but also to enhance social values.

2. Materials and Methods

2.1. Resarch Area

Tianshui is located in the southeast of Gansu Province. Tianshui is a must-stop station for cities in central China such as Zhengzhou and Xi'an, and cities in northwestern China, such as Lanzhou and Xining; therefore, it plays an important role as a point of agglomeration in the Guanzhong plain (Figure 1). Moreover, Tianshui provides the only access to the Chinese section of the Silk Road, and it is also a gathering place for ethnic minorities with 32 different ethnic groups living in this area. Therefore, due to the uniqueness of the natural and human environment in Tianshui, it is of significant research value to study the socio-environment responsive strategy in Tianshui.

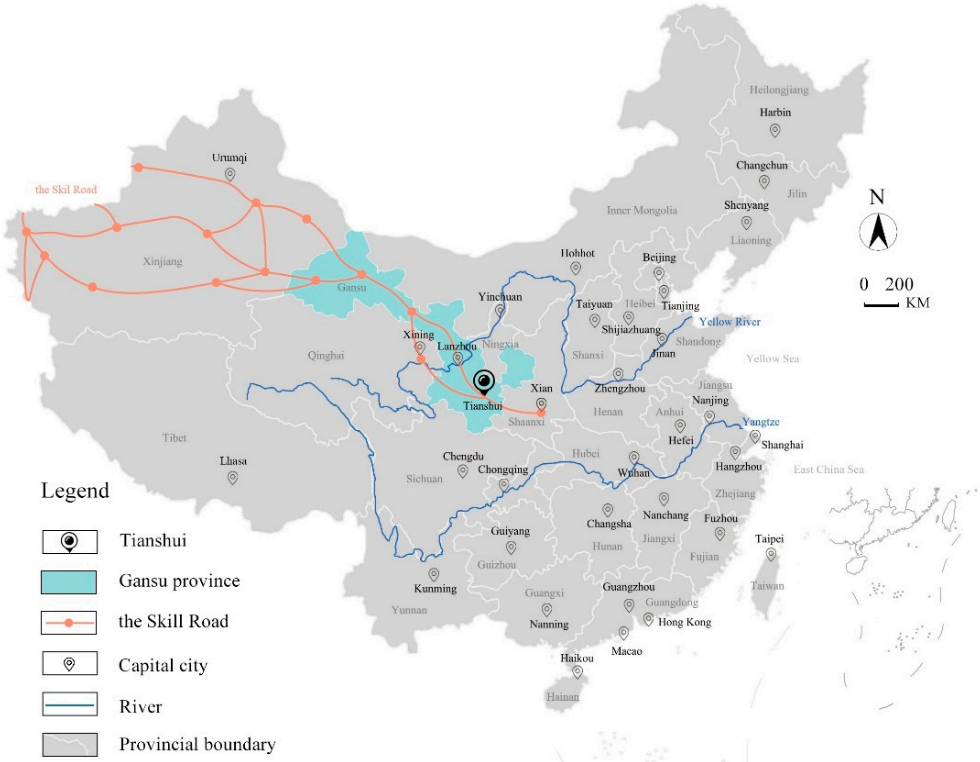
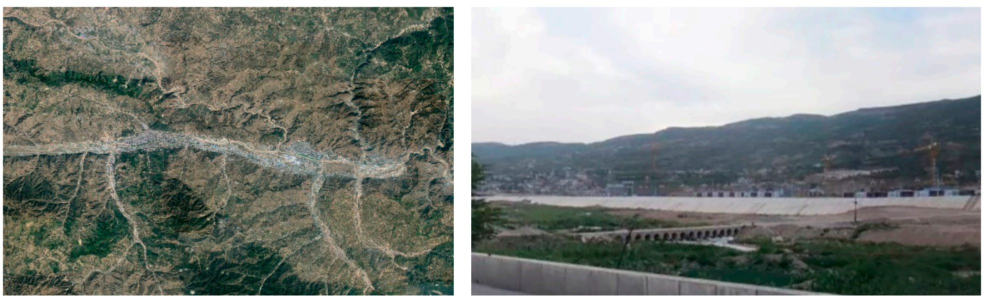


Figure 1. The location of Tianshui in China.

2.1.1. Natural Environment

- Geographical background

Tianshui has an area of 14,325 km^2 where lies between latitudes 34°05′ and 35°10′ N, and longitudes 104°35′ and 106°44′ E. It is divided by the Wei River, which is the largest tributary of the Yellow River into two parts (Figure 2). The northern part of Tianshui is loess hilly landform and the southern part is mountainous landform. The area between these two parts is river valley landform, which has mostly flat topography and mostly dense settlements. The terrain of Tianshui is higher in the northwest than in the southeast with an altitude between 1000 and 2100 m, and an average altitude of 1100 m. Due to the complicated terrain and inconvenient transportation, Tianshui is a place where many people live in poverty.



(**a**) (**b**)

Figure 2. Topography of Tianshui: (**a**) plan; (**b**) image.

- Climate conditions

There are five climate zones (severe cold zone, cold zone, hot-summer and cold-winter zone, hot- summer and warm-winter zone, and temperate zone) according to China's National Standard of Climatic Regionalization for Architecture (GB50176-2016) [45].

Tianshui belongs to the cold climate zone, which is prescribed to meet the requirements of winter cold protection, heat insulation, anti-freezing and does not need to be considered for the summer months.

Table 1 shows the climatic parameters of Tianshui. In this region, the highest monthly mean temperature occurs in July which is 22.8 °C and the lowest monthly means Temperature is −2.2 °C, which occurs in January. The average relative humidity is 69.3% in summer and is 62% in winter. Tianshui has low annual rainfall, but it is concentrated throughout the year; the annual precipitation is 500–600 mm, mostly from June to September. The highest average rainfall is 94.3 mm in July, and only 3 mm of rainfall occurs in December. In addition, the annual sunshine hours are over 2200 h, and the total solar radiation is approximately 5654 MJ/m^2.

Table 1. Climate data of Tianshui.

Season	Spring			Summer			Autumn			Winter		
Month	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**	**January**	**February**
Mean temperature (°C)	6.8	12.7	17.3	21.1	23.2	22.3	16.7	11.0	4.2	−1	−2.2	1.5
Max. temperature (°C)	13.2	20.3	24.4	28	29.5	28.4	22	17	10	5	4.5	7.4
Min. temperature (°C)	1.6	6.5	10.8	14.6	17.9	17.2	13	7	1	−5	−6.2	−3.1
Rainfall amount (mm)	16.4	37.3	57	68.7	94.3	92.5	87.6	44.3	11.6	2.8	3.2	5.2
Rainfall days	7	8	10	11	11	11	11	10	5	3	4	4
Sunshine hours	165.2	197.8	224.3	218.4	234.6	214.4	1851	168.7	147.9	145.7	143.3	135.8
Wind direction	west	south	southeast	southeast/east	southeast/east	east	east	east	north	north	north	northwest
Wind speed (m/s)	1.6	1.8	1.7	1.5	1.6	1.6	1.3	1.2	1.2	1.2	1.3	1.4

2.1.2. Social Environment

- Historical Development

Tianshui is the early birthplace of the development of Chinese civilization. The excavation and research of prehistoric cultural sites have shown that, as early as four thousand years ago, the primitive society of Tianshui in Gansu Province were very active in economic and cultural activities, and there were primitive settlements of considerable scale [46]. During the Yangshao culture period (about 6000 years ago), the plan layouts and building structures formed a certain style. The site area was 60–70 m^2. The walls and doors of the residential buildings were smoothed with grass and mud.

During the Xia, Shang, and Zhou Dynasties (1600 BC), multiple wars broke out between different tribes. The Qiang clan in the northwest region (now in Xinjiang province) constantly invaded eastwards [47]. This led to the continuous flow of exchanges between residents originally living in Tianshui and other ethnic groups, as well as the introduction of culture and commodities into the territory. After the Zhou Dynasty, due to the rich forest resources in the Tianshui area, the timber frame construction underwent new development, and the dwellings were mostly built with logs and wooden boards, which were called "Banwu". This form of construction is the prototype of traditional Tianshui dwellings.

During the Qin and Han Dynasties, with the extension of the Silk Road, commercial trade and the regional economy continued to develop. Tianshui became an important link between eastern and western China. During the Sui and Tang Dynasties, Tianshui was a well-known political, economic, and cultural center in western China, the development of urban planning and architecture was very prosperous. However, due to the Tianshui area suffering from two earthquakes in both the Tang and Yuan Dynasties, almost all cities and buildings were destroyed [48].

The climax of Chinese wood-frame construction, with highly standardized, formalized and institutionalized building forms, occurred during the Ming and Qing Dynasties. At that time, traditional houses in Tianshui formed a mature system with wooden structures for load-bearing and adobe walls for enclosure structures. Today, the form of traditional Tianshui residence is a transformation of the Chinese traditional residence of the Ming and Qing Dynasties but the wooden structure has been simplified.

- Traditional Culture

Patriarchal ethics, feng shui concepts, and national culture influence the internal dynamics of architectural regional differentiation, while population migration, war defense, and business economy are external forces affecting architectural regional differentiation [49]. Tianshui was a strong central force during the Central Dynasty due to the significant accumulation of central power in Chinese history. Its culture is still affected by the mainstream culture of the central plains, and the architectural form is deeply influenced by traditional Chinese Confucian culture. Meanwhile, the history of long-term business contacts and war turmoil has formed the diverse and inclusive characteristics of Tianshui culture. Judging from the current administrative divisions and their corresponding cultural circles, Tianshui is located between several typical cultural circles (Figure 3) [50]. It is this special background that has formed the features of Tianshui culture, which is mainly based on Confucianism and at the same time contains and incorporates other minority cultures.

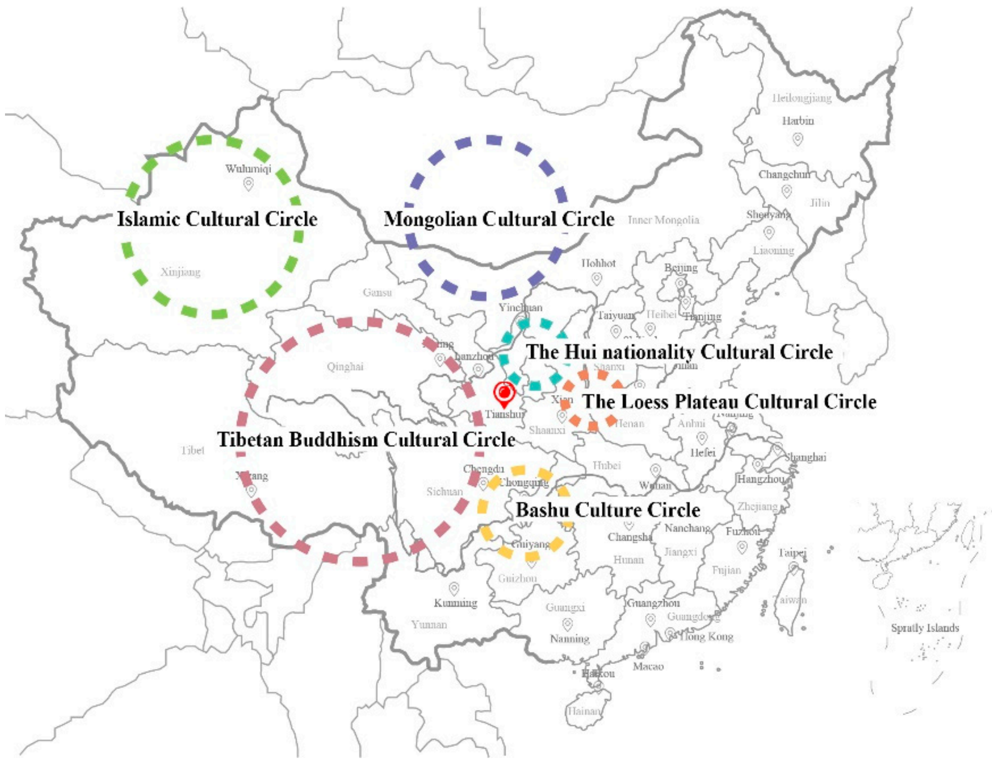


Figure 3. The location of Tianshui between cultural circles.

2.2. Methods

In order to gain a deeper understanding of the regional response characteristics of traditional residential buildings in Tianshui and to study the response of residential buildings to natural and social environments, field investigation, in-depth conversations, and on-site monitoring were carried out to explore 5 traditional residential settlements (Jieting, Hujiadazhuang, Luojia, Wahuang, and Juehuangsi) and 200 dwellings from January 2017 to March 2020 (Figure 4). The selection of these five villages was based on the number of traditional dwellings and the integrity of the preservation of dwelling features as the main criteria. This selection method and evaluation standard have been applied and verified in the literature [51,52]. Among the five residential settlements, Jieting and Hujiadazhuang villages were the first batch of villages to be included in the list of Chinese traditional villages. Luojia, Wahuang and Juehuangsi villages are provincial traditional villages containing existing traditional dwellings with well-preserved original features. Due to the inconvenience of transportation, these settlements have been less interfered with modern architectural design methods, and the texture and characteristics of traditional dwellings are well preserved. The local villagers have made traditional houses into houses adapted to the local environment using construction methods that have been developed based on accumulated experience for thousands of years. Specific research information about the settlements and dwellings are shown in Table 2.

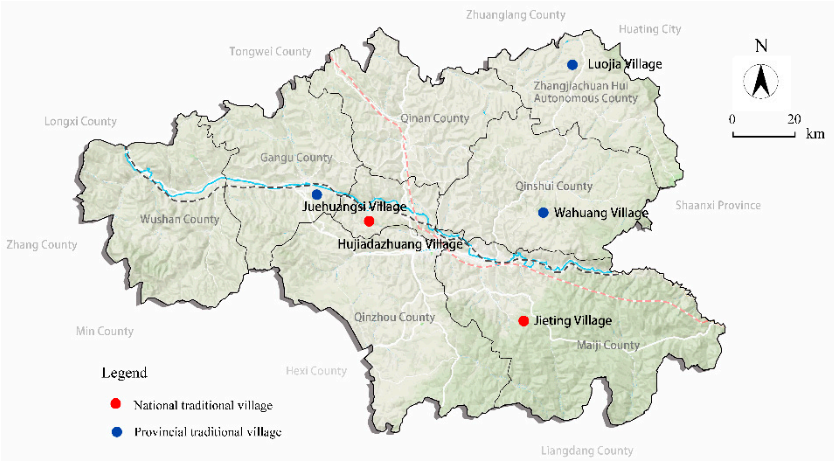


Figure 4. Field investigation sites of Tianshui.

Table 2. Field investigation sites information of Tianshui.

Settlement Name	Proprietary	Population	Area Covered	Total Dwellings	Traditional Buildings	State of Preservation	Surveyed Dwellings
Jieting	collective ownership	3292	3.8 km^2	719	139	Good	69
Hujiadazhuang	collective ownership	3168	3.1 km^2	703	135	Very good	58
Luojia	collective ownership	2800	2.06 km^2	457	73	Good	22
Wahuang	collective ownership	1629	1.5 km^2	112	52	Medium	15
Juehuangsi	collective ownership	3780	3.4 km^2	753	216	Good	36

2.2.1. Field Investigation

In the process of the field investigation, the researchers were focused on two main aspects: (1) collecting, identifying, and organizing the relevant literatures and documents of traditional Tianshui dwellings, and forming a scientific understanding of facts through the study of the documents, and (2) conducting field measurements and using mapping, photo-recording and 3D model technology to record the relevant geographic environment of settlements and the plane, space, structure forms, and specific dimensions of the traditional houses.

We observed and summarized the selected 200 residential buildings, and of these, we chose 36 dwellings with obvious characteristics for a detailed investigation. Specific data, including courtyard layout, orientation, house width and height, structural form, door and window data, house material and wall thickness, roof form and bevel, and decorative patterns, were measured and recorded.

2.2.2. In-Depth Conversations

In-depth conversations and interviews, which are qualitative methods, were mainly used in this research, and they included a combination of structured interviews, non-structured interviews, and participatory observations. Respondents were divided into the following categories: local residents, tourists, government officials, specialists and scholars, and traditional craftsmen and repairers. The respondents comprised 60 local residents, 20 tourists, 12 government officials, 5 specialists and scholars, and 6 traditional craftsmen and repairers. Information was collected during the period from January 2017 to April 2020. The interview questions were compiled based on existing studies [42,53,54], including demographic information, the perception of the residential environment, architecture-related customs and culture, residential evaluations, building construction experience and a clothing checklist.

2.2.3. On-Site Monitoring

A traditional dwelling named Tested dwelling 1 (Tsd1) located in the Hujiadazhaung settlements in order to assess indoor thermal conditions. The plan type of this traditional dwelling comprises regular rectangles with a yard in front. The overall length of the dwelling is 14.2 m, and the width is 4.9 m; the dwelling is divided into three rooms by partition walls without any active heating measures. For comparison, another type of traditional dwelling, named Tested dwelling 2 (Tsd2), was selected in the same village. The plans of the two types of traditional dwellings are almost the same, with only Ts2 using Kangs and stoves (the most common heating combination used by residents of Tianshui) as active heating methods.

The monitoring of the indoor thermal conditions was carried out from 21 January 2017 to 22 January 2017, which is the middle of the winter heating period in Tianshui. The monitoring information included indoor air temperature and relative humidity, outdoor solar radiation, and outdoor air temperature and relative humidity. Figure 5 shows the layout the tested dwellings and the placement of the instruments. All monitoring instruments were set at a height of 1.2 m from the ground, and the data were recorded automatically and continuously for 24 h in ten-minute intervals. The indoor instruments were placed away from heating sources and direct sunlight. The outdoor monitoring points of temperature and humidity were placed in the shade. Table 3 shows the models and technical parameters of the monitoring instruments.

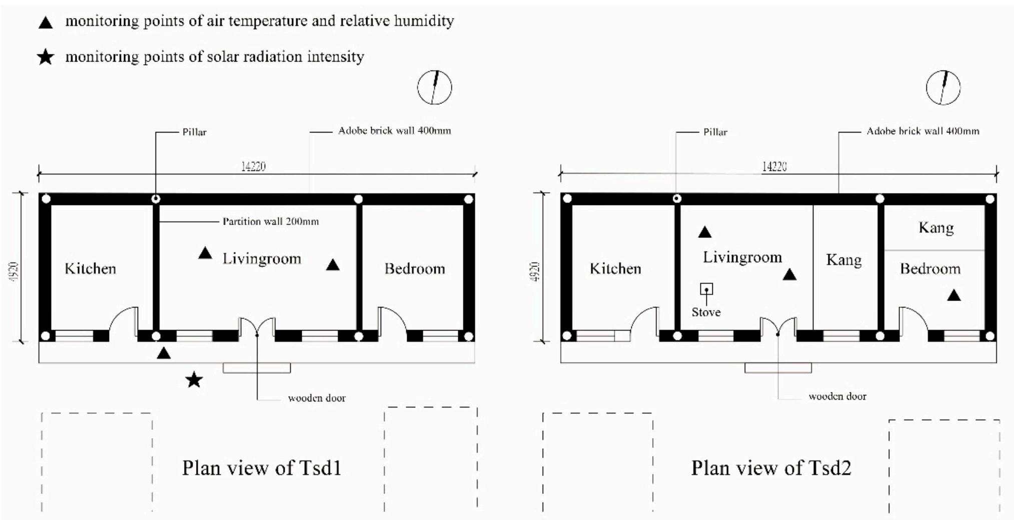


Figure 5. Layout of tested dwellings and the placement of instruments.

Table 3. Models and technical parameters of the monitoring instruments.

Monitored Parameters	Type	Measurement Range	Accuracy	Resolution
Air temperature	175-H1	−20 to 85 °C	±0.5 °C	0.1 °C
Relative humidity	175-H1	0 to 100% RH	±0.5% RH	0.1%
Solar radiation intensity	JTDL-4	0–2000 W/m^2	<4%	0.1 W/m^2

3. Results and Discussion

3.1. Objective Reginal Response of Traditional Dwellings to Natural Environment

3.1.1. Site Selection

The parameters that are essential for the determination of regional architectural differences are terrain and climate [20]. Tianshui has mountainous geographical conditions, a dry climate, and cold winters. The location of Tianshui residential settlements follows the principle of 'back to the mountains and facing the water'. The settlements were always built on the flat ground between the mountains and rivers. The mountains provide a convenient place for residents to cut wood, raise animals, plant fruit trees, and farm. In addition, during war times, the mountains were also a natural protective barrier, protecting the village from invasion by enemies. The river was always near the farmland, providing necessary irrigation and domestic water for the villagers and increasing the humidity of the surrounding air and regulating the microclimate. Jieting village is a typical traditional settlement in Tianshui, located in Maiji District. As shown in Figure 6, Wolong Mountain is located to the north of the village, with the highest altitude of 1227 m and Mao River is located on the south side of the village with a lowest altitude of 1133 m [55]. The buildings in the village are relatively concentrated and connected to each other (Figure 7).

Figure 6. Aerial view of Jieting village.

Figure 7. Space between residences is narrow.

The shape coefficient f, which is defined in Formula (1) as presented by Depecker is an important factor that affects the level of building energy consumption and insulation efficiency [56].

$$f = \frac{F_0}{V_0} \tag{1}$$

where F_0 is the external surface of the buildings and V_0 is the inner volume. Regarding buildings with identical floor heights, as the shape coefficient decreases, the exterior wall area exposed to peripheral environment conditions decreases, and, consequently, the building heating load decreases [56]. As shown in Figure 7, the traditional dwellings in Tianshui were simplified into the rectangular model with sloping roofs so that the shape coefficient could be calculated and compared in different combinations. In the arrangement methods of residential houses in the Tianshui area, one single traditional house (Figure 8a) appears rarely, the combination of two traditional houses (Figure 8b) occurs more frequently, and the combinations of four traditional houses (Figure 8c) appear most often. The shape coefficient of single, two combinations, and four combinations of traditional dwellings can be calculated using Equations (2)–(4), respectively.

$$f(1) = \frac{F_1}{V_1} \tag{2}$$

$$f(2) = \frac{2F_1 - WH}{2V_1} \tag{3}$$

$$f(3) = \frac{4F_1 - 2WH - 2LH}{4V_1} = \frac{2F_1 - WH - LH}{2V_1} \tag{4}$$

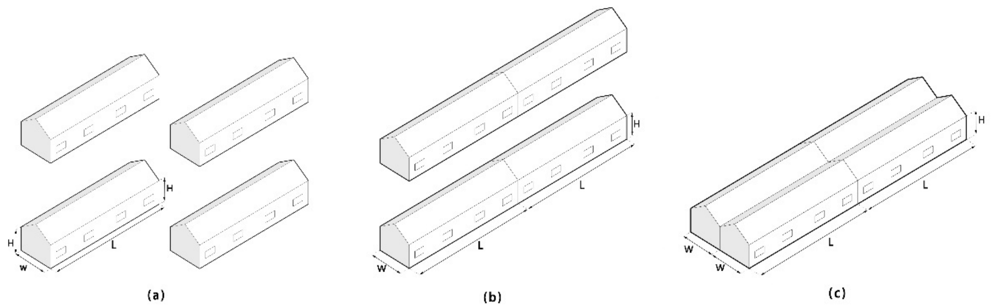


Figure 8. Different arrangement methods of residential groups: (**a**) single; (**b**) combinations of two; (**c**) combinations of four.

Here F_1 is the external surface area of a single traditional dwelling; V_1 is the inner volume covered by a single traditional dwelling surface; L is the dwelling's length; W is the dwelling's width; and H is the dwelling's height without a sloping roof.

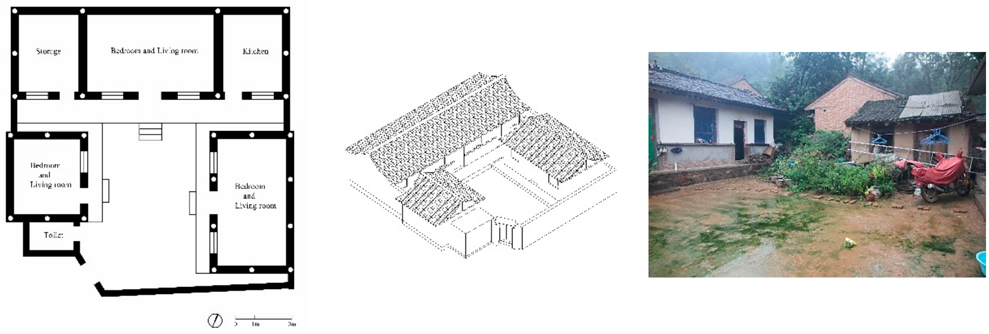
It can be found from Equations (2)–(4) that $f(1) > f(2) > f(3)$; therefore, the arrangement with the combinations of four traditional houses in Tianshui has the best heat preservation and energy saving effect. In summary, the arrangement method of houses with less capacity between the courtyards and small spaces between residential groups in Tianshui can effectively cope with the cold environment.

3.1.2. Courtyard Layout

In the traditional residences, the internal building space is combined with yard space to form a complete living unit. The courtyard form of traditional Tianshui dwellings is mainly composed of the main rooms (living rooms and bedrooms); ancillary rooms (kitchens and toilets); a yard area; and a wall to form an inward courtyard covering an area of about 100–240 m^2, which bears different functional requirements. According to the location, the yard of in the living unit, can be divided into three types: front-yard type, back-yard type, and Sihe-yard type.

- Front-yard type

A yard which in the front of the primary building is the main layout of a front-yard-type residence (Figure 9). The width of the yard is basically equal to the width of the main building usually between 9–15 m and the depth of the courtyard depends on the specific situation of each family.

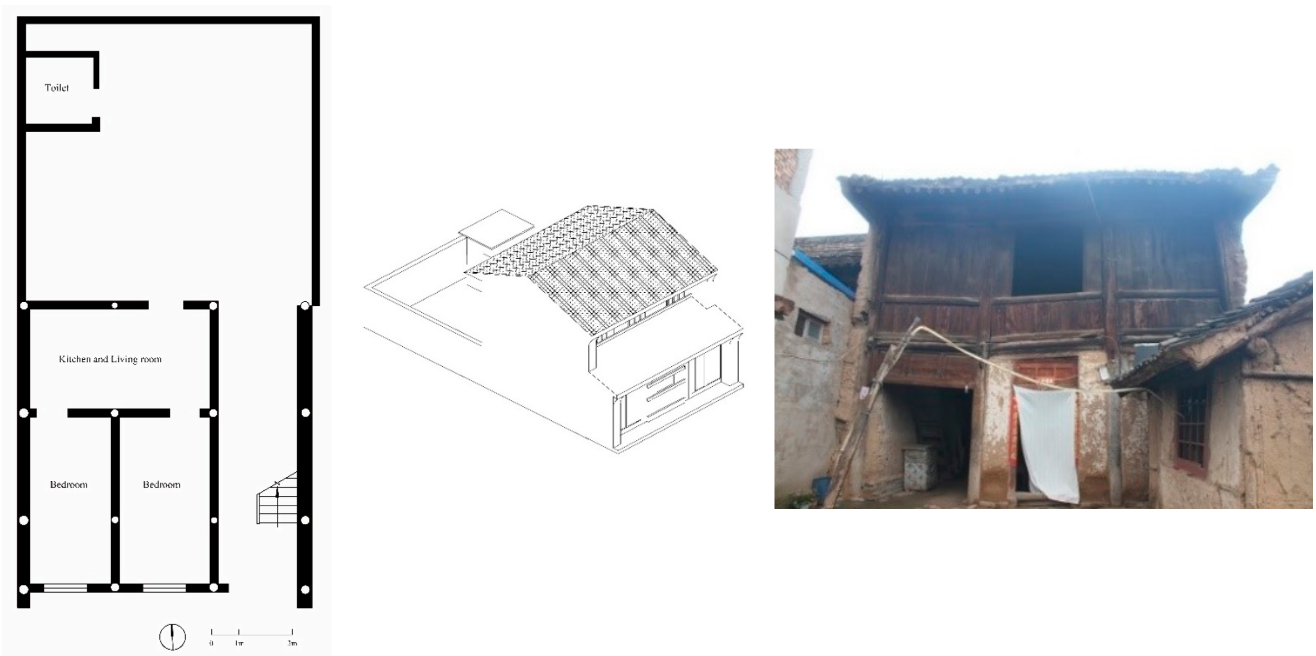


(**a**) (**b**) (**c**)

Figure 9. Front-yard type of traditional Tianshui dwellings: (**a**) plan;(**b**) model; (**c**) image.

- Back-yard type

Back-yard type courtyards mainly appear in street facing dwellings. As the main building is arranged alongside the road, the yard is at the back of the building (Figure 10). The width of the yard is similar to that of the front-yard type and the depth of the yard is no more than 15 m.



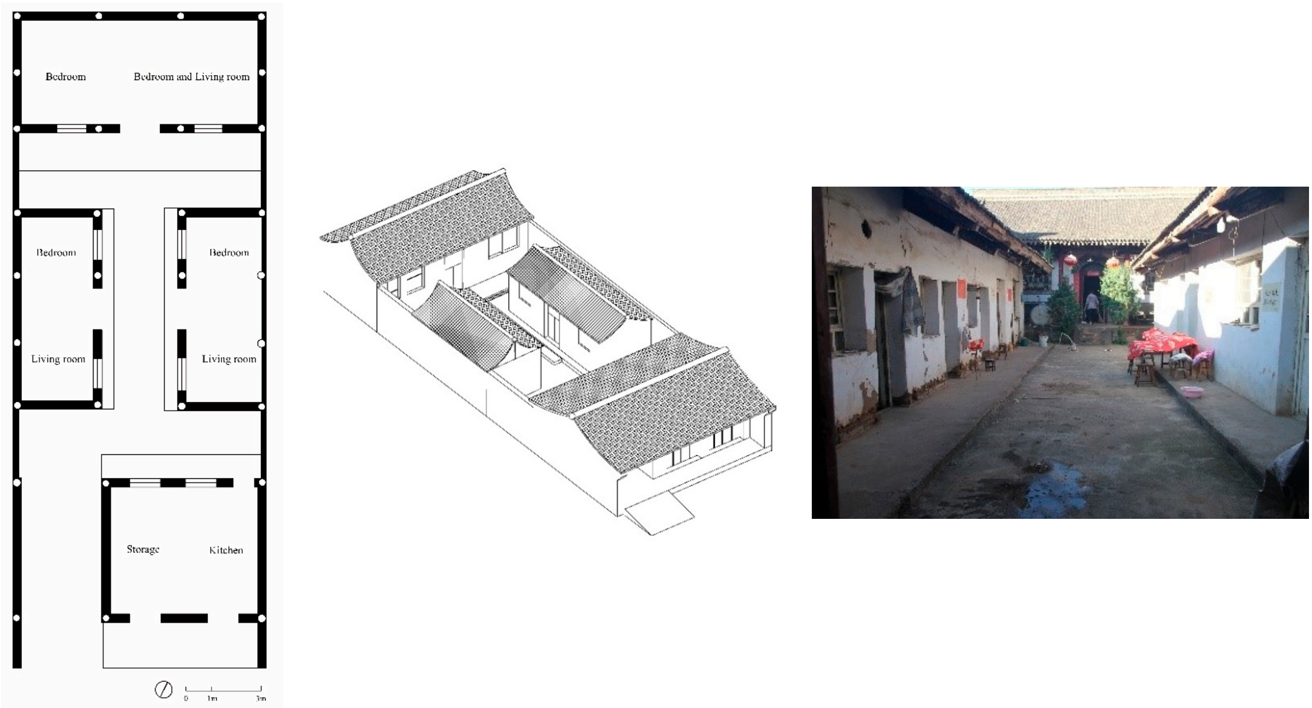
(**a**) (**b**) (**c**)

Figure 10. Back-yard type of traditional Tianshui dwellings: (**a**) plan; (**b**) model; (**c**) image.

- Sihe-yard type

Sihe-yard type courtyards are generally surrounded by buildings on four sides, of which a street-facing front room serves as the entrance to the entire courtyard (Figure 11).

The shape of the courtyard is rectangle-shaped or 'H' shaped, and the width of the courtyard is generally between 9 m and 12 m.



(**a**) (**b**) (**c**)

Figure 11. Sihe-yard type of traditional Tianshui dwellings: (**a**) plan; (**b**) model; (**c**) image.

These three courtyard types were originally developed by residents after a long period of practice considering the demands of lighting, ventilation, farming, daily activities, etc. Residents can receive more sunshine hours when using the front-yard type layout, because there is no shelter in the front of the yard; thus, the front yard is most often used as the place to dry grain and carry out simple farm work (Figure 12a). Compared with the front-yard type, the back-yard type has a more concealed location, often combining toilets and storage areas together (Figure 12b). This type of courtyard leads to a low level of privacy in the main building, and the front is easily disturbed, but it is more convenient to contact with people outside. This type often used for commercial purposes. For the Sihe-yard type, the yard is located in the center of the entire living unit (Figure 12c). It can be used as the core functional space for the organization of each room as well as the place for family members to conduct their daily activities. At the same time, it can also enhance the lighting and ventilation effect of each room. Compared with the previous two types, the Sihe-yard type is more centripetal and has a closer relationship with the architecture.

(**a**) (**b**) (**c**)

Figure 12. Characteristics of different courtyards: (**a**) front-yard type; (**b**) back-yard type; and (**c**) Sihe-yard type.

3.1.3. Orientation

Although there are differences in the types of yards, the orientation of the main room is always south–north in Tianshui dwellings [57]. Tianshui is in the northern hemisphere, and the north–south direction can maximize the sunshine hours of the dwellings. Additionally, Tianshui has lower air temperatures in winter, and the layouts with southern exposure can provide enough sunshine in winter. Moreover, the orientation of the main building is rotated 15 to 30 degrees to the west since the dominant wind direction of Tianshui is east and southeast in summer. Buildings can use draughts to cool down when facing the windward side during summertime. As shown in Figure 13a,b, the residences facing directly north–south are parallel or have a small angle to the main wind direction in summer, resulting in lower ventilation efficiency. After rotating 15 to 30 degrees to the west, the residence forms an angle or becomes perpendicular to the main wind direction, which increases ventilation efficiency (Figure 13c,d). This is one of the passive cooling methods commonly used in residential houses.

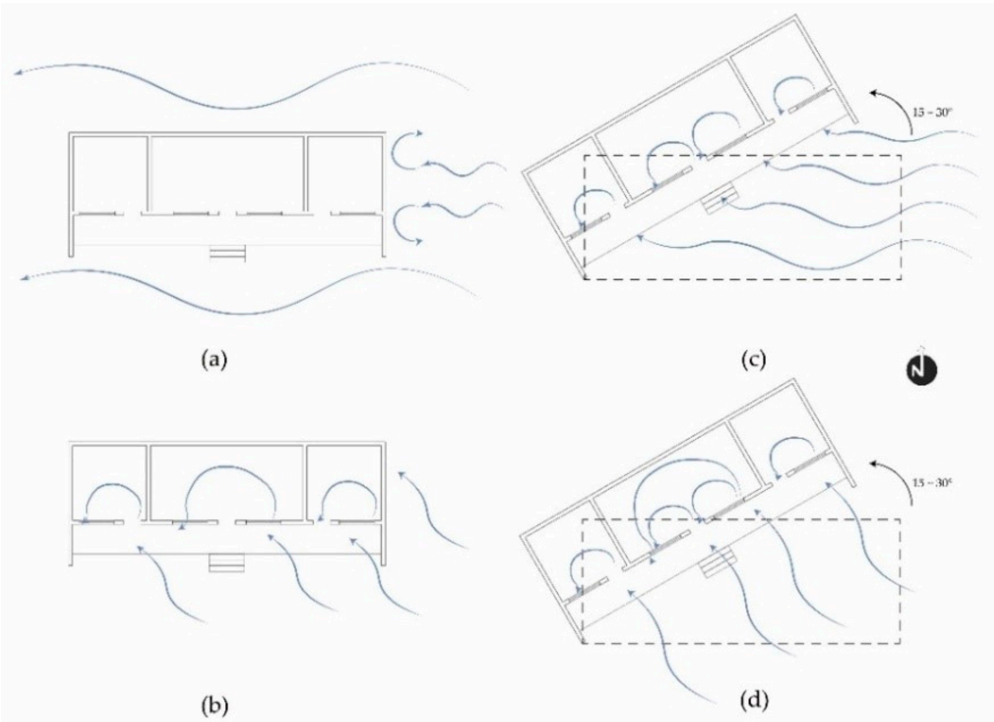


Figure 13. The effect of main room orientation on summer ventilation efficiency: (**a**) before; (**b**) before; (**c**) after; and (**d**) after.

3.1.4. Structure and Envelop Enclosure

- Structure

Post-and-lintel construction was used to build the structure of traditional Tianshui dwellings. This kind of construction mainly uses wooden frames, and it is found in ancient buildings, especially in the northern area of China, there are few or no columns in the interior space. Due to the frequently occurring earthquakes in Tianshui's history, the following adjustment was made to traditional post-and-lintel construction in order to further reinforce the structure: the middle pillar was built directly from the ground to the roof to support the ridge purlin. Figure 14a shows the configuration of the structure, which is composed of beams and columns. This weighing structure transfers the weight of the house from the roof to the pillars, then to the beams, and, finally, to the foundation; tenons and mortises are used to intersect various elements, so that the wall only serves as an enclosure structure. Not only does the weight-bearing frame offer a good anti-seismic effect, but it also creates many flexible conditions for the arrangement of the positions of windows and doors.

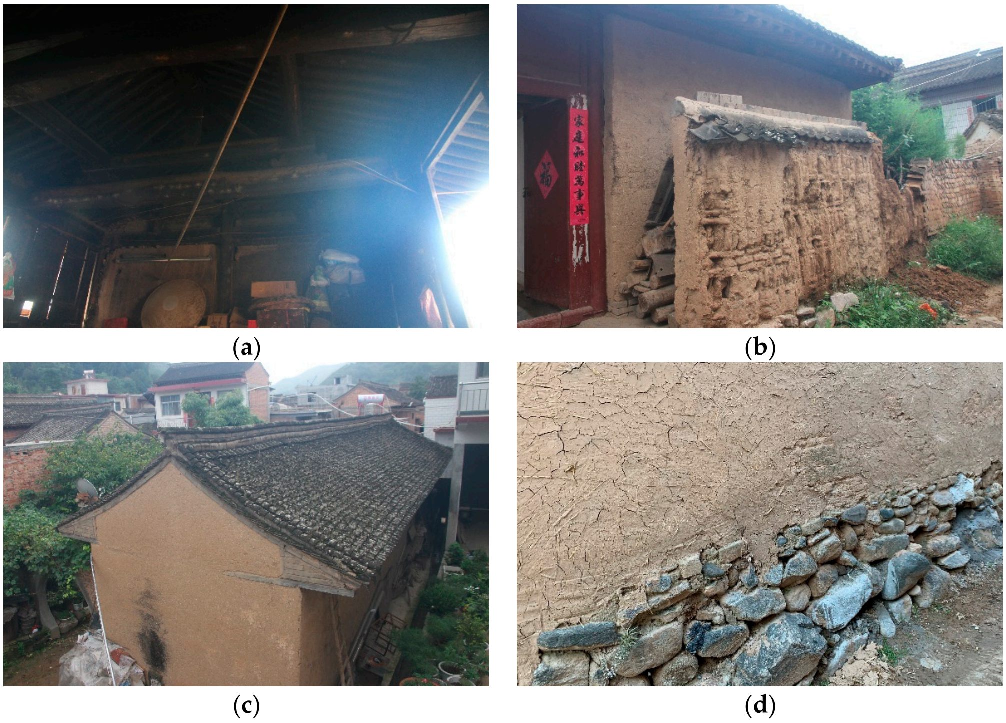


Figure 14. Structure and envelope enclosure of traditional Tianshui dwellings: (**a**) structure; (**b**) wall; (**c**) roof; and (**d**) foundation.

- Walls

The enclosure of traditional Tianshui dwellings adopts the principle of using natural and local materials to reduce the economic cost of transportation. The materials of the wall mainly include raw soil, wooden slats, and tiles (Figure 14b). Raw soil is the main material of the external walls while wooden slats and tiles are used to increase moisture resistance of the walls. The efficiency of the building of traditional Chinese houses highly relies on the thermal mass from the roof, walls, and floors [58]. In traditional Tianshui dwellings, no other type of wall insulation was added that could impact the building fabric. Only the thickness and the material properties of the raw soil itself were used to improve the U-value of the building walls. The thickness of the exterior walls ranges from 400 mm to 600 mm. In order to reduce heat loss, the transparent opening area of the maintenance structure is reduced as much as possible, so only windows on the south-facing wall are opened.

- Roof

Hard mountain-style roofs are the most commonly used roof form for traditional houses in Tianshui and even in northern China (Figure 14c). The roof consists of purlins, beams, and tiles, and the purlins and beams bear the weight of the tiles. Meanwhile, grass, mud, and straw are spread on the purlins as a thermal insulation layer, and tiles are paved to form a waterproof layer. Since most of the precipitation in Tianshui occurs during the summer, short-term heavy rainfall is likely to occur, so the roof area where the eave meets the gable wall, is built with bricks in order to prevent rainwater from flowing down from the slope of the roof and dampening the adobe wall.

- Foundation

The foundation of the traditional dwellings in Tianshui is paved with local stones, generally 250–400 mm high (Figure 13d). These stones can effectively prevent the capillary action of groundwater, which makes the wall damp, so that the durability and the thermal performance of the house are not affected by moisture.

3.2. Analysis of Indoor Thermal Conditions in Winter

3.2.1. Adaptive Thermal Comfort

Various types of thermal adaptive comfort models have been developed by relevant researchers in different countries and regions. Based on extensive investigations, Yang and Liu et al. [59,60] used linear regression to establish the following model of human thermal comfort adaptability in cold climate areas where Tianshui is located:

$$T_n = 16.862 + 0.271 t_0 \quad R = 0.89458 \tag{5}$$

where T_n is the neutral temperature, and t_0 is the outdoor mean dry-bulb temperature. The annual adaptive thermal comfort temperature for 80% of occupants ranges from 15.8 to 29.1 °C.

3.2.2. Air Temperature and Solar Radiation

Figure 15 shows the changes in the indoor temperature of the two main rooms in Tsd 1, the outside air temperature and solar radiation in winter. During the monitoring period, the peak solar radiation is 640 W/m^2, which was recorded at 13:00 on 21 January, and the cumulative value of solar radiation is 11.9 MJ/m^2. The outdoor air temperature has a diurnal variation of 8.1 °C. The lowest outdoor temperature occurs from 08:00 to 08:10 am, which is −4.3 °C; the highest outdoor temperature is 3.8 °C, which occurs at 16:10 pm; and the average outdoor temperature is −1.6 °C. The indoor temperature fluctuates slightly in both the living room and bedroom, which have variations of 2.0 °C and 1.7 °C, respectively. The average air temperature of living room and bedroom is 1.2 °C and 1.1 °C, respectively. When comparing the average solar radiation and outdoor air temperature with the air temperature of the bedroom in Tsd1, the solar radiation drops sharply after 16:10 in the afternoon, and the outdoor air temperature drops significantly (from 3.8 °C to −1.9 °C). The indoor temperature of the living room and bedroom in the traditional dwelling remain constant, and only drop by 1.3 °C (from 2.1 °C to 0.8 °C) and 1.2 °C (from 1.9 °C to 0.7 °C) in 7.5 h, respectively. It can be seen that the envelope structure (soil wall) of traditional houses has good thermal stability. Although the heat transfer coefficient of raw soil (1.4 W/m^2 K) is lower than that of the brick (7.92 W/m^2 K) and concrete block (8.78 W/m^2 K) materials (commonly used in newly built houses in Tianshui), the raw soil materials of the walls of traditional houses have better heat storage performance and a higher thermal inertia index. The earth wall can fully absorb the heat of solar radiation during the day when sunlight is abundant, and releases it slowly at night, which helps maintain indoor thermal comfort.

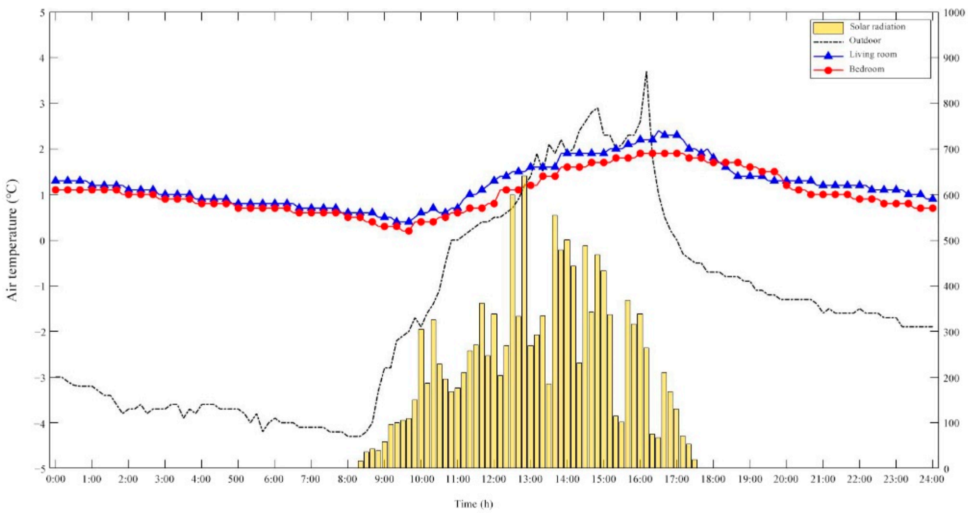


Figure 15. Air temperature of main rooms in Tsd1 and solar radiation.

Since the weather is cold in winter, auxiliary heating is necessary to meet the residents' demands for indoor thermal comfort. Figure 16 shows the changes in the indoor temperatures of the two main rooms in Tsd2, which use kangs and stoves for auxiliary heating. The common thermal energy resources used for kangs and stoves are bioenergy products, such as biogas, straw, and branches. During the monitoring period, the air temperatures of the living room and bedroom stay relatively stable. The average temperatures are 17.2 °C in the living room and 17.5 °C in the bedroom. It must be noted that, compared with the bedroom, the temperature in the living room will be slightly higher during the day and lower at night. The temperature is altered by residents' daily activities, which take place in the living room during the day and in the bedroom at night. In addition, cooking activities in the kitchen, which is the adjacent room, also provides a certain amount of external heating transfer to the living room. According to the monitoring results, even though the outdoor temperature is below 0 °C for 76% of the time during the monitoring period, the indoor air temperature of the traditional dwelling is always maintained within the annual adaptive thermal comfort temperature range (15.8 to 29.1 °C). In conclusion, traditional residential houses can meet the physical need of residents with the use of conventional heating methods.

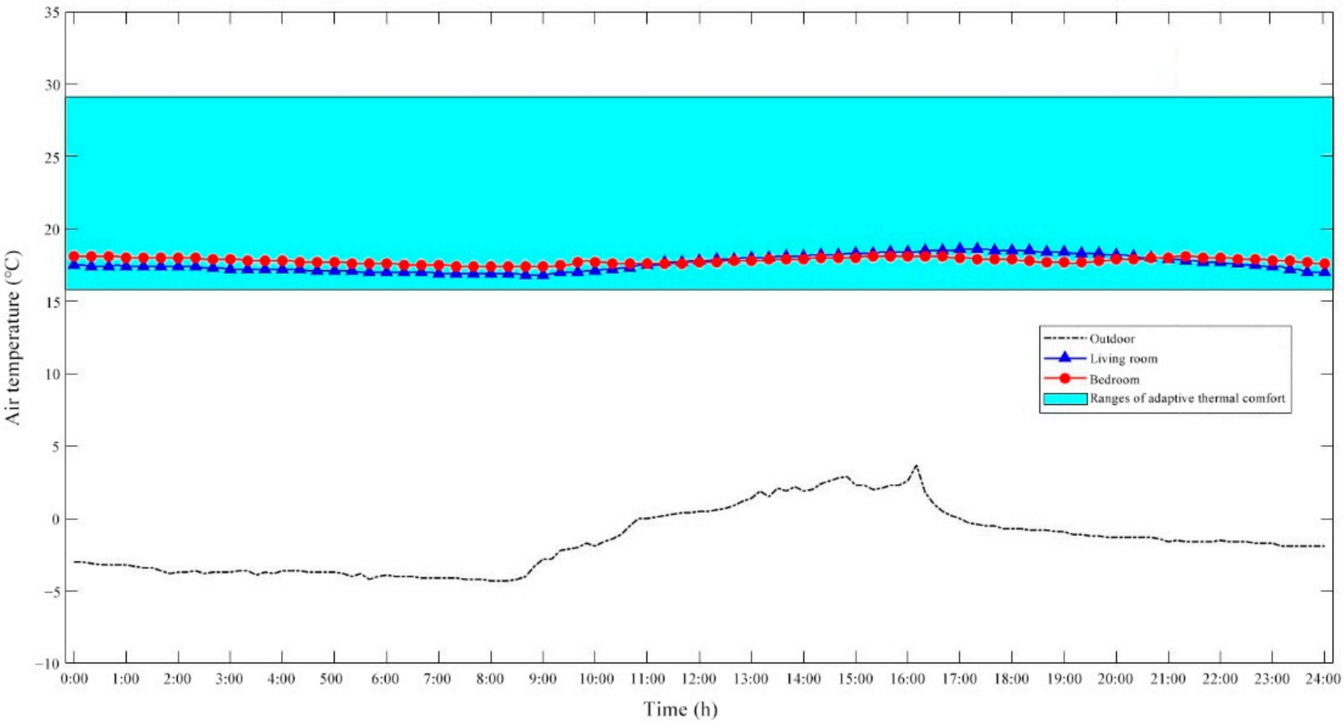


Figure 16. Air temperature of main rooms in Tsd2.

3.2.3. Relative Humidity

As shown in Figure 17, during the 24-h measurement, the outdoor relative humidity ranges from 24.7% to 75.1%, with a large fluctuation of 50.4%. The relative humidity of the living room is relatively stable, and it ranges from 49.5% to 60.3%, while the relative humidity of the bedroom ranges from 48% to 60.2% in the traditional dwelling Tsd1. The raw soil material has a certain capability that allows it to regulate and maintain humidity. Figure 18 shows the relative humidity variations of the monitored rooms in Tsd2. The indoor relative humidity stays stable and does not fluctuate with the outdoor relative humidity. The bedroom and living room have fluctuations of 5.1% and 7.7%. Due to the auxiliary heat source, the rooms in Tsd2 are, overall, less humid than the rooms in Tsd1. Most time, both of the traditional dwellings are in the relative humidity comfort zone (30% to 60%).

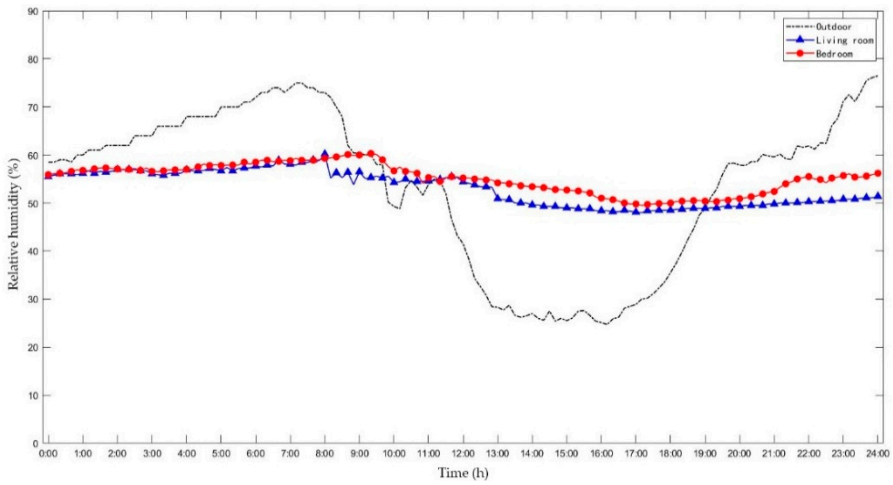


Figure 17. Relative humidity of main rooms in Tsd1.

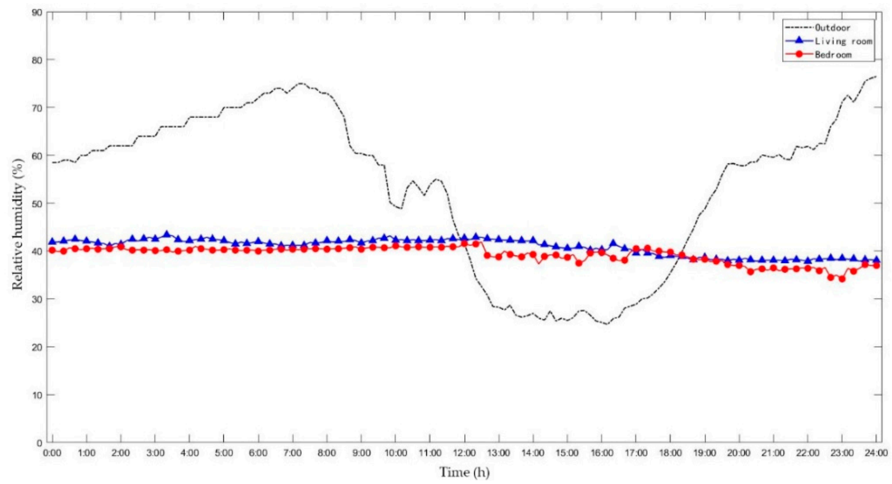


Figure 18. Relative humidity of main rooms in Tsd2.

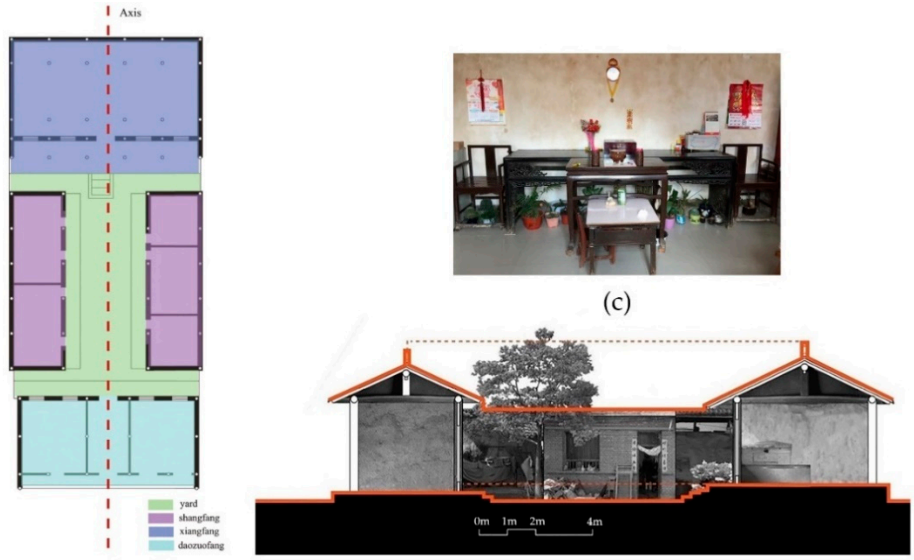
3.3. Subjective Reginal Response of Traditional Dwellings to Social Environment

3.3.1. Spatial Order

- Ritual system

In ancient Chinese society, the Confucian ritual system can be regarded as being composed of laws, regulations, and moral standards. The concept of hierarchy was indispensable to the social environment at that time. This kind of concept is manifested in the functional layout, building volume, and space arrangement of the residential buildings as an internal sense of order. In terms of the functional layout, the patterns of Tianshui residential houses are distributed in a symmetrical shape with a central axis (Figure 19a). The residential concepts of middle parents and respect for seniority (the beginning of the axis is the most noble position, which is called 'shangfang', and this is where the elders of the family usually live). Along the central axis, the spatial sequence descends in sequence. Rooms on both sides of the axis are where the juniors live, or they are used as auxiliary rooms called 'xiangfang'. In addition, western 'xiangfang' is higher in rank than eastern 'xiangfang', so it is often an accommodation place for older brothers. The room opposite 'shangfang' is called 'daozuofang', which is the end of the axis 'Daozuofang' is the lowest grade house, generally used as an auxiliary space, such as a kitchen, bathroom, or storage. In terms of building volume, the depth and width of 'shangfang' are the largest among the group of family buildings (Figure 19b). In particular, the ridge is significantly higher than that in other rooms, and the steps at the entrance are also higher than those of 'xiangfang'.

In terms of space arrangement, ancestral memorial tablets or incense burners are arranged in the middle of 'shangfang', and tables and chairs are placed below, which are also the largest in size and shape, thus showing respect for the clan (Figure 19c).



(a) (b) (c)

Figure 19. Ritual system embodied in traditional dwellings: (**a**) functional layout; (**b**) building volume; (**c**) space arrangement in 'shangfang'.

- Moderation system

The moderation system provides the core ethics of Confucianism and the most valued principle of traditional Chinese thought [61]. The deep meaning of the moderation system emphasizes the harmony between man and nature, which is reflected in the development of Chinese architecture, which does not pursue excessively large houses. The scale of traditional Tianshui dwellings also follows this principle. The width of traditional Tianshui dwellings is generally about 12 m and the depth depends on the function of the house. There is a certain modulus of the construction and the depth of 'shangfang' is usually 4.5 m, 5.4 m, or 5.7 m, while that of 'xiangfang' is 3.6 m, 3.9 m, or 4.2 m. The distance between the eaves and steps ranges from 2.7 to 3.2 m, and the height between the roof and the ground is from 4.2 to 4.8 m. Not only does the scale of traditional dwellings meet the needs of production and life, but it also provides an approachable space experience.

Furthermore, although Tianshui houses are very closed to the outside world, they also have a modest architectural idea in defining the space in the courtyard. In the architectural design, it can be seen that the eaves of the building are very long, so there are plenty of gray spaces defined by the eaves and steps. These gray spaces are the bridges between the indoor and outdoor spaces, and they reflect the hierarchical relationship between public space, semi-public/private space, and private space (Figure 20). This organic blend of indoor and outdoor spaces demonstrates a modest and harmonious view of building construction.

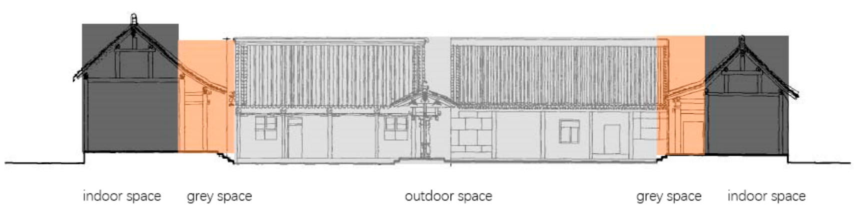


Figure 20. Indoor and outdoor space transition.

3.3.2. Construction Technology

Throughout history, Tianshui has often been attacked by foreign national forces and affected by religion and multi-ethnic integration, resulting in Tianshui houses widely incorporating the construction technology of ethnic minorities and different regions. The locality of Tianshui construction technology is embodied in the construction method of the walls, which can be divided into the production of making adobe bricks and building methods. The construction technology of making adobe bricks of traditional dwellings gradually developed from the 'Huji' construction technology used in Xinjiang and Inner Mongolia (Figure 21).

Figure 21. Adobe bricks.

As shown in Figure 22, there are six kinds of building skills used for traditional dwellings. The use of building skills is determined by the residents themselves. Among them, the third type is the most commonly one. Regardless of the building skills, branches and rattan are used among adobe bricks as stiffened plates every half a meter to enhance the tensile and compressive properties of the wall.

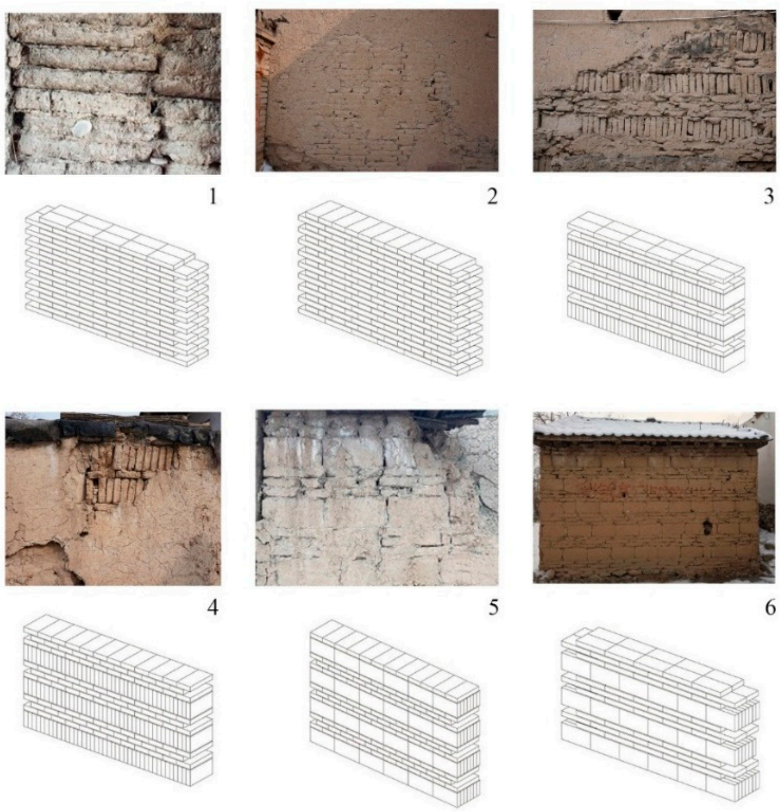


Figure 22. Six kinds of building skills: 1. Pingding; 2. Pingding and Pingshun; 3. Ceding and Pingshun; 4. Ceding and Pingding; 5. Pingding and Ceshun; 6. Ceshun and Pingshun.

3.3.3. Decorative Arts

Wood and stone carvings are mainly used in the decoration of traditional Tianshui residences. Residents' strong desires for good lives and their strong pursuits of good health are often expressed in architectural decoration with the use of metaphors. For example, the turtle symbolizes longevity in traditional Chinese culture. Windows are decorated with lines of turtle shells (Figure 23a). The dragon symbolizes auspiciousness, so it is often used on the front of the entrance door. Meanwhile, the decoration art of traditional folk houses in Tianshui also embodies the integration of ethnic and religious cultures that influenced the area via the Silk Road. In addition to the strong influence of orthodox Confucianism on the overall spatial layout of the building, the extended Baxian symbols that symbolize Taoist culture (Figure 23b), the Ruyi patterns and the Swastika symbols that symbolize Buddhist culture (Figure 23c,d), and the flower patterns that symbolizes Islamic culture (Figure 23e) often appear in Tianshui dwellings' decorative patterns.

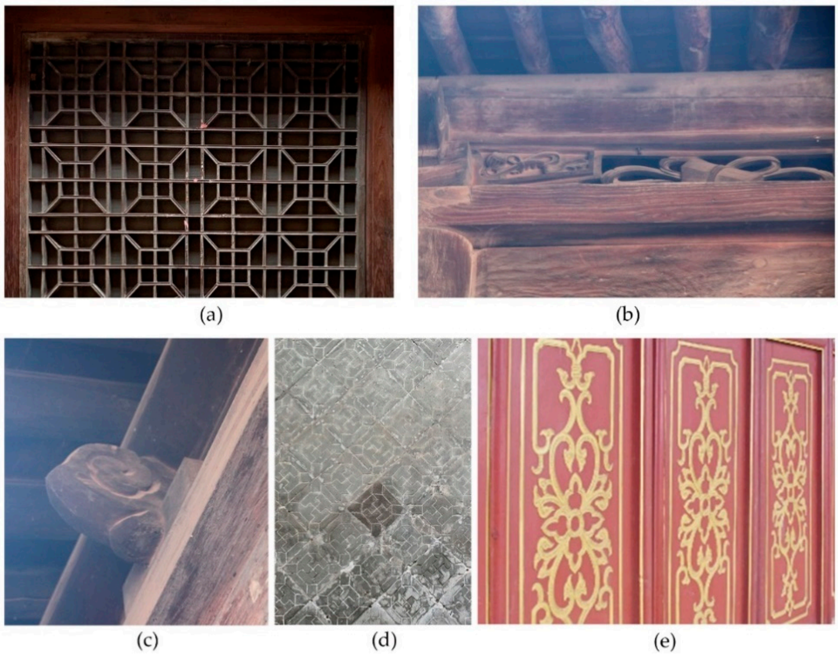


Figure 23. Decorative patterns: (**a**) turtle shell pattern; (**b**) flower pattern; (**c**) Ruyi symbols; and (**d**) Bagua symbols; (**e**) flower pattern.

In brief, the overall decoration style of traditional Tianshui houses is simple. This is because Tianshui has been in a state of social instability for a long time. In order to conceal their wealth from being plundered by intruders, the residents chose a plain and light way to decorate their houses.

4. Sustainable Development of Traditional Dwellings in Tianshui

The enlightenment and principles obtained from the process of regional adaptation and the way in which the sustainability concept was embedded into the traditional dwellings can provide references and guidelines for the long-term development of modern architecture. This research analyzes the response of traditional Tianshui dwellings to natural and social conditions and determines the features of sustainable development of traditional residential houses as follows.

4.1. Characteristic 1: Showing Strong Respect to Nature

A proper architectural ecological attitude is a prerequisite for a harmonious coexistence between humans and nature, as well as the foundation for sustainable development [62]. The construction process of modern buildings does not pay enough attention to this point, as it tends to provide a unified physical environment rather than setting up a center in the dwelling and people's agency space in response which requires a large amount of non-renewable energy. Today, humans continue to explore the relationship between the coordinated application of modern materials and the protection of the natural environment for example, the replacement of fossil fuel energies with renewable energies [63]. The traditional dwellings in Tianshui emphasize the importance of respecting nature in the process of site selection, construction, and development. This intrinsic performance of adapting to nature is reflected in several aspects, such as a reasonable location selection, climate response, and energy conservation.

In this study, the principles and the design characteristics that show strong respect to the nature in traditional Tianshui dwellings are summarized in Table 4.

Table 4. Characteristic 1: Showing strong respect to nature.

Principles	Design Characteristics
Reasonable Site selection	• In order to easily obtain natural resources, such as wood and stone, traditional settlements are located near the mountains; • Adjacent rivers are used for irrigation and to obtain domestic water, while regulating the microclimate; • The distance between residence groups is minimized to cope with the cold environment.
Respond to geography and climate	• The orientation of the main functional space is north-south so that maximum solar radiation can be gained; • The dominant wind direction is faced in summer in order to use draught for passive cooling; • A system where the structure is separated from the envelope enclosure is used in order to adapt to high-frequency earthquakes; • Waterproof layers and bricks are used in roofs to prevent rainstorms from wetting the wall which can affect the quality and life of the building.
Energy conservation	• The full use of local materials such as raw soil, wood, and stones is made to reduce the waste of resources during transportation; • The southern wall of the residential buildings acts as a thermal mass, absorbing solar radiation during the daytime and transforming it into thermal energy during the nighttime in winter; • The area of the transparent enclosure is reduced to minimize the heat lost through the external windows and doors.

4.2. Characteristic 2: Inheriting Traditional Culture

The development of traditional architectural culture is the carrier of inheriting local characteristics, a representative that inherited regional cultures and history, and it is also an effective means used to avoid the phenomenon of 'thousands of same imagines of the city' [64,65]. Traditional dwellings are representative of the inherited the regional cultures and history. The negative and positive influences of culture on architecture cannot be ignored in the pursuit of standardized modern housing. In order to achieve comprehensive and sustainable development, it is necessary to use traditional dwellings as a carrier to promote the self-sustaining of local consciousness under the symbiosis of culture, human and nature [66]. In this study, the principles and design characteristics of inheriting traditional culture in traditional Tianshui dwellings are summarized in Table 5.

Table 5. Characteristics 2: Inheriting traditional culture.

Principles	Design Characteristics
Inheritance of mainstream culture	• According to Confucian culture, elders live in rooms with the highest scale and highest grade; • The positions of rooms with different functions are arranged according to the axis symmetry; • The residential courtyard is at the center of the building, symbolizing the unity of the family; • Based on Chinese history and legends, animals and myths are adapted as archetypes to decorate doors and windows.
Integration of foreign cultures	• Houses are decorated with ethnic cultural patterns; • "The 'Huji'" technique from ethnic minorities is incorporated and transformed into construction technology with local features.

4.3. Characteristic 3: Regarding the Feelings of Users of the Space

Providing users with comfortable experiences (both physiologically and psychologically) is the main function of residential buildings. At the physiological level, every step of the building's full life cycle involves influencing factors related to the user's physical health and safety. Among them, the effects of the production (including the selection and construction of materials) and operation (indoor physiological sensation and adjustment capabilities) are more obvious [67]. At the psychological level, the spatial scale, height, and color can make users have different degrees of feelings while also affecting their mental health and wealth.

In this study, the principles and design characteristics that consider the feelings of the users of the space in traditional Tianshui dwellings are summarized in Table 6.

Table 6. Characteristic 3: Regarding the feelings of users of the space.

Principles	Design Characteristics
Pay attention to physical health	• Raw soil material has good indoor thermal and humidity environment adjustment abilities, and the indoor temperature and humidity can be maintained in a relatively stable state; • Natural and environmentally friendly materials, such as wood, stone, and mud, are selected as construction materials to reduce the waste, pollutants, and harmful gases generated during the synthetic process; • The dwelling layout, namely, front-yard type, back-yard type, and Sihe-yard, is selected according to the consideration of lighting, ventilation, family structure, production mode, daily activities, and economic situation.

Table 6. *Cont.*

Principles	Design Characteristics
Focus on psychological feelings	• An appropriate architectural scale is used to create a comfortable living experience; • Semi-private space (gray space) is increased to create a soft transition between private space (room) and outdoor space (yard) based on the harmony between humans and nature; • Activity and gathering spaces are considered between dwellings for communication between residents and provide opportunities for socializing.

5. Conclusions and Suggestion

5.1. Conclusion

In this study, the socio-environment responsive strategy of Tianshui residential buildings and the possibility of sustainable development were analyzed. The results show that that design principles of traditional Tianshui dwellings, which were constructed by paying the careful attention to the climate conditions and social contexts in order to meet the requirements of residents' lives from both physical and psychological aspects, can be seen as successful sustainable strategy. The major findings are as follows:

(1) The design principles are applied in response to natural environment. The settlements are close to mountains and rivers in order for the residents to obtain rich natural resources, as well as for the regulation of the microclimate, the optimization of climate orientations, the compaction of building patterns and layouts, the maximization of the use of solar energy and nature ventilation for passive heating and cooling, the selection of raw soil with excellent local thermal performance as the outer wall material, the improvement of post-and-lintel construction structure in order to resist earthquakes, and the addition of moisture-proof layer to prevent the effects of summer rainfall;

(2) The measurement results show that without any active heating measures, the average indoor temperature of the traditional dwellings is approximately 2.8 °C higher than the average outdoor temperature. Moreover, the fluctuations in the daily air temperature in the living room and bedroom of the same dwelling are 6.1 and 6.4 °C lower than those in the outdoor temperature. The fluctuations in the outdoor relative humidity are 39.6% and 38.2% higher than those in the living room and bedroom. Traditional Tianshui dwellings have good indoor heating and humidity regulation ability;

(3) With heating methods that use bioenergy resources, the average temperature is 17.2 °C in the living room and 17.5 °C in the bedroom. The indoor air temperature of the traditional dwelling always maintains within the annual adaptive thermal comfort temperature range (15.8 to 29.1 °C). The relative humidity of the indoor rooms is always with in the comfort zone (30% to 60%). Traditional residential dwellings can meet the physical need of residents by using conventional heating methods;

(4) This study also explained how social environment factors affect the spatial organization of traditional residential buildings in terms of the formation of the architectural system, which emphasizes hierarchy based on Confucianism, space arrangement in the direction of a north to south axis according to family status, construction technology incorporating multi-ethnic wisdom, and the usage of decorative patterns according to customs and culture.

5.2. Suggestion

With the consistent economic development, improvement in the standards of construction, and the transformation of modern lifestyles and methods of production, the traditional Tianshui dwellings have been greatly influenced by foreign cultures and customs, resulting in various western-style buildings, and brick-concrete houses making an appearance [40]. This indicates the contradictions in this process of transformation from traditional dwellings to newer concrete structures and the trend of new materials and technologies replacing traditional handicrafts is appealing. The analysis shows that in the design process of modern buildings, the rational use of the design criteria of traditional buildings can effectively reduce energy consumption and protect cultural heritage, which can also help the government and scholars to propose reasonable, efficient, and complete solutions for area planning and architectural design [68]. Based on the above research content, the following design suggestions are presented:

(1) Reasonable settlement selection and landscape pattern are the premises for adapting design methods to the natural environment and social background [20]. The location of Tianshui residential settlements is based on the principle of 'back to the mountains and facing the water'. This method of arranging dwellings not only permits the south-facing buildings to receive more sunlight, but also considers the role of the river in regulating the microclimate. In addition, it conforms to the axis design method of Chinese Confucianism and enhances familial cohesion. We should incorporate and improve these measures in the modern architectural design process;
(2) The main material used for the exterior walls in current newly-built Tianshui residential buildings is fired clay brick, which is expensive to transport and generates construction waste during the entire life cycle of the building [69]. Instead, stabilized earth with straw as the thermal insulating material displays a better thermal performance during winter and can be sourced and processed locally [70]. It would be advantageous to employ and promote this technique in poor rural areas;
(3) Considering the economic conditions and regional characteristics of rural Tianshui, the wood grain pattern can be used as a decorative component and does not assume the role of thermal insulation. Double-layer insulating glass with a wooden frame could be selected as an exterior window [15]. Meanwhile, to achieve better lighting, the wooden decorative window sash should be flexible enough to be dismantled when needed;
(4) From the perspective of safeguarding the traditional architectural style and the convenience of better drainage, the sloping roof of the building has to be preserved. Since only a single layer of grass, mud, and tiles is laid on the purlins, the heat transfer coefficient is extremely large. A plastic benzoic board of a certain thickness could be used as the insulation layer to improve the thermal performance of the sloping roof [67].

This research can provide guiding policy advice for Tianshui area or even regions with the same natural environment and similar cultural background to achieve long-term development and green sustainability of residential buildings. Furthermore, in future, we will conduct comparative research to qualitatively study the effectiveness of these sustainable development strategies on residential buildings by testing and simulating indoor the thermal environment of traditional dwellings.

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