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Energy Sustainability of Rural Residential Buildings with Bio-Based Building Fabric in Northeast China

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Abstract: Due to the cold winters in northeast China, the energy consumption of the rural residential buildings is much higher in this region than in other regions. In this study, the energy sustainability of bio-based wall construction is examined through applications in rural residential buildings. Comparisons of the energy sustainability of the bio-based wall constructions and the conventional wall constructions are evaluated using IESVE-2019 computational simulation. The results show notable reductions in heating energy requirements and coal use, which is the major heating source for rural residential buildings in China. The results show that reductions of 45.82–204.07 kWh/m^2/year in heating energy requirements and more than 40% in coal use are possible through application of bio-based wall constructions. The application of bio-based wall construction will result in lower seasonal air pollution and coal use through straw burning in northeast China.

Keywords: straw bale construction; rural residential building; energy simulation; heating energy; coal consumption; bio-based building

1. Introduction

China has maintained rapid economic growth over the past decades. The gross domestic product (GDP) growth rate has been around 10% per year from 2000 to 2018 [1]; this rapid economic growth has resulted in high energy consumption [2]. The total energy consumption was approximately 3123 million tons of oil equivalent (Mtoe) from 1991 to 2013, increasing at an annual rate of 8.1% and accounting for 22.97% of the total global energy consumption [3,4]. Coal provided 60.4% of China's total primary energy in 2017, and will continue to play a crucial role in powering China's economy [5]. As such, China produces the highest greenhouse gas emissions in the world [6].

The building industry is the second largest energy consumer in China's national economy, accounting for approximately 20% of the total energy consumption and generating 30% of the CO_2 emissions [7,8]. Residential buildings are specifically responsible for a large portion of this energy use [9] and the resulting CO_2 emissions [10]. Operational energy accounts for over 86% of the life cycle energy, and heating energy is the major contributor to operational energy use in the cold and severely cold regions in China [11]. To address this issue, a series of policies have been issued to achieve energy savings and emission reduction goals in China. These include the design standard for energy efficiency of residential buildings in severe cold and cold zones (JGJ26-2018) [12], standard for the energy consumption of buildings (GB/T 51161–2016) [13], and the design standard for energy efficiency of rural residential buildings (GB/T 50824-2013) [14].

About 600 million people are living in rural regions in China [15]. About 37% of the total energy consumption of the entire building sector can be attributed to rural residential buildings [16]. Of the total energy consumed by rural residential buildings, 56.4% is consumed in northern China and 43.6% in southern China [17]. Energy consumption in rural residential buildings is expected to continue to grow. As a consequence of the recent economic development, rural residents have been building new houses, and the increased energy consumption is an expected consequence of improved thermal comfort [18]. However, despite the high energy consumption, the indoor environment in rural residential buildings generally does not meet the thermal comfort requirements of the occupants [19]. Thus, increasing the energy efficiency of these buildings in northern China would assist in the development of a more sustainable Chinese society.

The insulating properties of the wall structure of these rural residential buildings are highly relevant to their energy consumption in northern China [11]. Solid brick construction is the most common in rural regions. The insulating properties of solid brick are poor and solid brick construction generates a large amount of carbon emissions [19]. In contrast, as a by-product of agricultural activities, bio-based wall construction has better insulation properties and lower carbon emissions [20,21]. Researchers have examined the thermal properties of solid brick construction in rural residential buildings [22–24]. However, research into the energy sustainability of rural residential buildings with bio-based walls is lacking. Due to the good thermal insulation properties of bio-based wall construction, heating energy requirements can be reduced by replacing existing walls with bio-based walls using in-fill straw bales. Similar trends for heating energy requirements can be estimated through modifications required in existing standards of energy efficiency in rural residential buildings [14].

The objective of this research was to analyze the advantages of bio-based fabric construction in reducing the energy consumption of rural residential buildings. The simulation software IESVE was used to simulate the energy consumption of typical rural residential buildings with both conventional and bio-based wall constructions. The energy sustainability of the bio-based wall construction was analyzed for the improvement of building designs according to the different wall constructions. The results of this study provide guidance for planning and design of rural residential buildings in the severe cold and cold regions of China, particularly in northeast China. This research contributes to a better understanding of the energy sustainability of bio-based wall construction in rural regions in both northeast China and other international cold regions.

2. Literature Review

2.1. Rural Residential Buildings in Northeast China

Most of northeast China is in a severe cold region, where temperatures can be as low as −30 °C in winter [25]. To reduce heat losses in this cold climate, the shape coefficients of rural residential buildings in northeast China are minimized [26]. The plans of most rural residential buildings in northeast China are of regular geometry, generally rectangular [27], and most are single-story buildings [28]. There are four typical floor plans of rural residential buildings in northeast China (Figure 1). To meet the resident's requirements, the floor area is typically between 30 and 70 m^2 for basic rural residential buildings. The function of these buildings is simple, consisting of just a bedroom and a kitchen. As the building area increases, the plans focus more on symmetry. To benefit from maximum sunlight, the major living functions are designed to the south, while auxiliary spaces such as storage rooms, are in the north. Since kitchens have both cooking and transport functions, they are often located in the middle. The stoves in kitchens are connected with Chinese "kang" in the bedrooms. According to the family demographic structure and living habits, rural residents adjust the plan designs to a certain extent, but most rural residential buildings in northeast China are still based on the form described above. Due to the lack of independent living rooms and dining rooms in most rural homes, bedrooms are used for sleeping, dining, meeting guests, entertainment, etc.

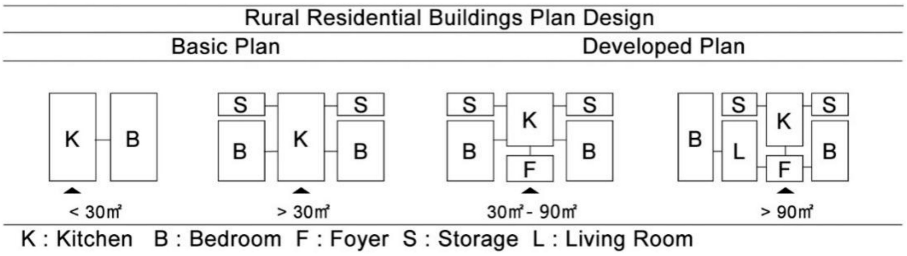


Figure 1. Rural residential building plane design (redrawn from [28]).

In these buildings, the main heating systems include the Chinese kang, rustic heaters, stoves, and heated walls [29,30]. The kang are particularly important because they are used for heating bedrooms [31]. This causes problems with the indoor thermal environment in winter since the temperature distribution is uneven. The temperature in the bedrooms is higher because of the kang, while the temperature in other rooms, such as storage rooms and kitchens, is very low in winter. Overall, the average indoor temperature in winter is too low. Even in the bedrooms, the indoor temperature is approximately between 10 and 16 °C, which is significantly lower than is comfortable for the human body [32]. Furthermore, energy efficiency needs to be improved to reduce energy consumption. The heat efficiency of the traditional kang system is between 36% and 64% [31,33,34]. In comparison with developed countries on the same latitude, the heating energy consumption of rural residential buildings in northeast China is about two to two-and-a-half times higher [32]. With the improvement in the living standards of rural residents, the energy consumption of rural residential buildings in northeast China has been increasing over the past few decades.

2.2. Bio-Based Building Fabric

As an environmentally-friendly constructional material, bio-based building materials such as straw and timber has undergone a revival in popularity during the last few decades. In agricultural production, the harvest of grains such as rice, wheat, and corn is the most important. A large quantity of straw or dried stalks is produced in this process [35]. Straw has been widely used since ancient times for a variety of purposes including fuel, animal bedding, supplement to animal diets, and a building material [36]. As a building material with a long history, straw has been used as a component of roofs and insulation material in almost all continents. In the 1870s, due to the invention of the horse-powered agricultural baler, straw was formed into dense bales that could be used to construct walls. Due to the colonization of North America by Europeans and the lack of traditional building materials in North America, the straw-bale construction technology developed rapidly. Some straw-bale buildings were built over 100 years ago. Since the 1980s, there has been an upsurge in the construction of straw-bale buildings worldwide. In the 1900s, cross-laminated timber (CLT) was manufactured in Europe for the first time [37]. In the 1990s, CLT was not used widely but its use started to grow in Germany and Austria [38]. With the development of CLT structural technology, this material found more applications in architectural engineering [39]. Due to the extensive use of CLT in the construction industry in recent years, the European Cooperation in Science and Technology (COST) published design codes for buildings with CLT structures in 2018 [37].

In China, straw and timber have recently received more attention. As an application of straw, the first straw bale buildings were constructed by the Adventist Development and Relief Agency (ADRA), the central government, and the local government in 1998 [40]. The ADRA also set out standard construction details and construction methods in an unpublished training manual [40]. As an energy-saving material, the development of CLT applications has also increased rapidly. Factories have manufactured CLT building components for application in demonstration projects and several recommendations have been provided by the Ministry of Housing and Urban–Rural Development of China (MOHURD) to accelerate the development of CLT [41]. In 2017, MOHURD published the regulations for timber structure buildings (GB/T 51226-2017), where the restriction that timber buildings over three stories high could not be built was removed. This demonstrates that favorable conditions have been created for the development of timber buildings and that the Chinese government is serious about the development of timber buildings.

There are three significant benefits to the use of bio-based building fabrics in the building industry. Firstly, both straw and timber are environmentally friendly materials. In northeast China, total annual rice production is approximately 203 million metric tons. Most straw is burned in the fields and this results in serious air pollution [42]. If more straw can be used as a building material, these air pollution issues can be significantly mitigated [43]. Secondly, both straw and timber have a powerful carbon sequestration effect. The CO_2 is converted into organic matter and stored in the bio-based building fabric. This increases the quantity of CO_2 sequestered from the environment [44]. These materials have a lower environmental impact on life cycle assessments (LCAs) [45]. Thirdly, straw-bale wall construction has excellent thermal insulation properties. Studies showed that the thermal insulation properties of straw bales and CLT walls are better than conventional wall constructions [46,47], including those of the masonry bricks that are widely used in rural residential buildings in China. Therefore, there is considerable potential to develop a bio-based building fabric with in-fill straw bales and structural timber frames for rural residential buildings in northeast China.

3. Materials and Methods

3.1. Reference Rural Residential Buildings

Four typical floor plans of reference buildings with double pitched roofs were developed from existing rural residential buildings (Figure 2). As there are limited restrictions on the building locations for rural residential buildings, the buildings are designed with an optimized south-facing façade. To meet stricter energy efficiency requirements in northeast China, the window on the north facing façade is designed to be smaller than that on the south facing facade. For the same reason, there is no window on the gable end of these buildings.

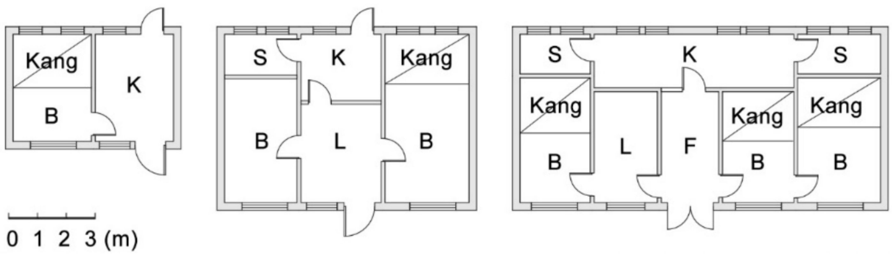


Figure 2. Floor plans of type-A floor plan (**left**), type-B floor plan (**middle**) and type-C floor plan (**right**) in simulation process

The different wall constructions in these buildings were referenced from conventional wall constructions as specified in GB/T50824-2013 and bio-based building fabric (Figure 3). There are no insulation materials in the conventional wall construction, which consists of a solid masonry wall designed to be over 350 mm thick to increase the thermal performance of the residential building. In GB/T50824-2013, the wall construction is designed for improved thermal performance with a designed U-value not exceeding 0.50 and 0.65 W/m^{2}K in severe cold regions and cold regions, respectively [14]. The bio-based wall construction includes in-fill straw bales and timber structural frames. As the thermal transmittance of straw bales is lower than 0.070W/mK [48,49], the thermal performance of the bio-based walls is significantly less than 0.20 W/m^{2}K [50]. This is considerably superior to both the conventional wall construction and the construction standards in GB/T50824-2013.

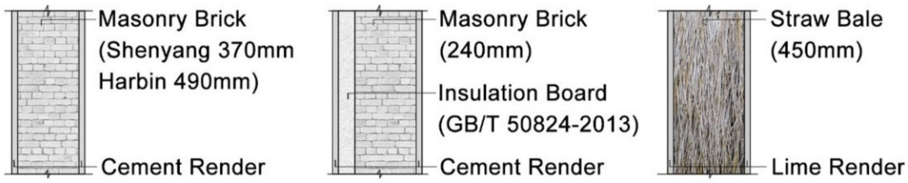


Figure 3. Wall construction of conventional wall (**left**), standard wall in GB/T50824-2013 (**middle**) and straw bale wall (**right**).

3.2. IESVE Simulation Process

According to the standard for climatic regionalization of China (GB50178-93), most regions in northeast China are in the severe cold and cold regions [51]. To represent the main climatic conditions in northeast China, Harbin and Shenyang were selected as the simulation locations (Figure 4).

Figure 4. Regions of Harbin and Shenyang in China.

The designed U-value of the building fabric is listed in Table 1. In conventional rural buildings, the masonry walls perform both structural and thermal functions and the roof is insulated by 100 mm rock wool. As the glazing of conventional rural buildings consists of two layers of single glass windows and a separate layer of plastic sheet applied during the winter [27], the designed U-values are different in summer and winter. A similar modification is also applied to the entrance door with a separate cotton door curtain in winter [27]. Since there are few applications of bio-based building fabric in northeast China, the designed U-value for the building fabric is referenced from the standard constructions in the GB/T 50824-2013.

The indoor environment set-up and the human occupancy factors are provided in Tables 2 and 3, respectively. The heating period of the reference buildings was designed to meet the standard requirements stipulated in JGJ26-2018 for the four regions [12]. Since rural residential buildings have lower designed indoor temperatures (14 °C), the heating period based on heating degree day 18 °C (HDD18) may overestimate the heating energy requirements. The occupancy periods in rural residential buildings are significantly affected by seasonal agricultural activities. As there are limited activities required outdoors during the winter season, rural residents tend to stay at home all day during this season [29].

Table 1. U-value of building fabric of reference buildings in Northeast China (C for conventional construction; S for standard construction in GB/T50824-2013; B for bio-based building fabric).

Building Construction			Harbin (Severe Cold Region)	Shenyang (Cold Region)
U-value of Building Fabric (W/m^{2}K)	Wall	C	490 mm solid masonry wall	370 mm solid masonry wall
		S	0.50	0.65
		B	0.20	0.20
	Roof	C	Plasterboard with 50 mm mineral Fibre slab	Plasterboard with 50 mm mineral Fibre slab
		S	0.40	0.50
		B	0.40	0.50
	Glazing	C	2.8(Winter) 2.8(Summer)	2.8(Winter) 2.8(Summer)
		S	2.2(South) 2.0(North)	2.8(South) 2.5(North)
		B	2.2(South) 2.0(North)	2.8(South) 2.5(North)
	Ground	C	-	-
		S	-	-
		B	-	-
	Entrance Door	C	50 mm wood entrance door (summer) 50 mm wood entrance door with 20 mm cotton door curtain	50 mm wood entrance door (summer) 50 mm wood entrance door with 20 mm cotton door curtain
		S	2.0	2.5
		B	2.0	2.5

Table 2. Design of indoor environment during heating period according to JGJ26-2018 [52] and GB/T 50824-2013 [14].

	Harbin	Shenyang
Heating Degree Day 18 °C (HDD18) [52]	5032	3929
Annual Heating Period	1 October–30 April	10 November–20 March
Lowest indoor temperature [14]	14 °C	

Table 3. Occupancy factors in the IESVE software simulation.

	Bedroom	Kitchen	Foyer	Storage
Occupied Period	0:00–24:00 (winter)	6:00–7:00 & 11:00–12:00 & 16:00–17:00	6:00–7:00 & 11:00–12:00 & 16:00–17:00	Not applicable
	19:00–06:00			
Occupied Density	2 persons	2 persons/bedroom	2 persons/bedroom	Not applicable
Equipment	300 W	2000 W	200 W	50 W

3.3. Analysis of Overheating Risks

Since no air conditioning system is included in rural residential buildings, the overheating risk in the reference buildings was also examined through the simulation process. Since 26 °C is the point at which the overheating calculation in GB/T 50824-2013 is triggered, the window opening mode was used to cool the indoor environment to below 26 °C. Due to safety concerns in rural regions, natural ventilation is not applicable at night; therefore, window opening is limited to the occupied period in rural residential buildings.

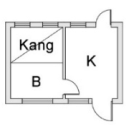
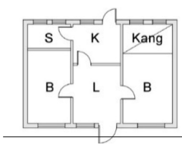
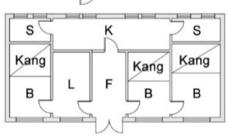
To analyze the overheating period, the simulation results for indoor temperatures were examined using Statistical Product and Service Solutions (SPSS). These results were examined for periods where temperatures exceed 26 °C to evaluate the overheating risks. As typical rural life involves daily work in the fields, days are considered to have an overheating issue when temperatures exceed 26 °C for nine hours or more.

4. Results

To compare the energy saving potential of the bio-based wall construction and the standard wall constructions from GB/T 50824-2013 with traditional wall construction, all three wall construction types were applied in the three reference buildings to conduct the energy simulation process using IESVE-2019. Since the different wall constructions have little or no impact on human occupancy factors, the comparison of the energy saving potential of the different wall constructions did not consider the energy consumption by the residents. As there are no mechanical ventilation and air-conditioning systems in rural residential buildings, cooling energy consumption was excluded from this exercise.

The simulation results for the annual heating energy requirements in rural residential buildings are shown in Table 4. Due to the low winter temperatures and the larger volume–surface ratio, the type A residential building has the highest heating requirement per m^2. The heating energy requirements of the reference buildings were found to be 368.95 and 243.20 kWh/m^2/year for conventional wall construction in Harbin and Shenyang, respectively. As the temperature set point in the simulation for winter heating was 14 °C, the high demand of heating energy is not reflected in the high standard of indoor thermal comfort. Despite the notably larger floor area of the type C residential building, types B and C have similar heating energy requirements. The difference in the heating energy requirements for these two reference buildings was less than 10 kWh/m^2/year in the simulation process with different wall constructions. As a result, the type B floor plan is more suitable for rural residential buildings due to its balance between floor area and energy consumption.

Table 4. Annual heating energy requirement of rural residential buildings with different wall constructions in northeast China.

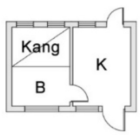
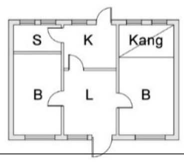
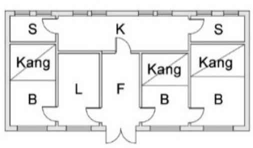
Floor Plan	Floor Area	Wall Construction	Annual Heating Energy in Harbin (kWh/m^2/year)	Annual Heating Energy in Shenyang (kWh/m^2/year)
	31 m^2	Conventional	368.95	243.20
		Standard (GB/T 50824-2013)	213.23	163.06
		Bio-based	164.88	116.92
	72 m^2	Conventional	161.01	114.51
		Standard (GB/T 50824-2013)	110.45	73.35
		Bio-based	85.99	53.33
	124 m^2	Conventional	153.75	106.69
		Standard (GB/T 50824-2013)	109.21	76.21
		Bio-based	89.80	60.87

When examining the heating requirements of the reference buildings with conventional wall construction, significant reductions were found in the heating energy requirements for both the standard wall construction to GB/T 50824-2013 and the bio-based wall construction. For the three different residential building types, reductions of 30.48 to 155.72 kWh/m^2/year can be achieved by replacing the conventional wall construction of the standard wall to GB/T 0824-2013 and reductions of 45.82 to 204.07 kWh/m^2/year by replacing the conventional wall construction by bio-based walls. The largest reductions were achieved in the type A residential buildings with savings of approximately 100 and 150 kWh/m^2/year for replacing the conventional walls by bio-based walls and standard GB/T50824-2013 walls, respectively. In the type B and C residential buildings, the reductions are 45.82 to 75.02 kWh/m^2/year in the heating requirements achieved by the two modified wall constructions. The bio-based walls achieved savings of 15.34 to 24.46 kWh/m^2/year more than the standard wall construction in GB/T50824-2013.

Since the principal heating method for rural residential buildings is the traditional kang in northeast China, the heating energy requirements can be converted to an index of coal use. According to GB/T2589-2008, there are 29,307 kJ of energy in each kg coal equivalent [53]. As rural residents with low income tend to buy low quality coal, the conversion coefficients of coal to coal equivalents are between 0.2857 and 0.4286 kgce/kg [53]. Since the energy efficiency levels of kang are generally poor, the value of heat efficiency applied in this research was between 40% and 50%.

As shown in Table 5, significant reductions in coal use can be achieved through replacing conventional walls by the modified wall constructions. For all three types of reference buildings, the coal use with conventional wall construction was annually approximately 0.7 to 1.2 t more than those with standard wall construction in GB/T50824-2013 and 1.1 to 2.0 t more than those with bio-based wall construction for winter heating. The type B residential buildings have over double the floor area of type A buildings, but the coal use in these buildings is similar to type A for all types of wall construction.

Table 5. Annual coal use for winter heating of rural residential building with different wall constructions in northeast China.

Floor Plan	Floor Area	Wall Construction	Coal Use in Harbin (ton)	Coal Use in Shenyang (ton)
	31 m^2	Conventional	1.54–2.89	1.01–1.90
		Standard (GB/T 50824-2013)	0.89–1.67	0.68–1.28
		Bio-based	0.69–1.29	0.49–0.91
	72 m^2	Conventional	1.59–2.97	1.13–2.11
		Standard (GB/T 50824-2013)	1.09–2.04	0.72–1.35
		Bio-based	0.85–1.59	0.53–0.98
	124 m^2	Conventional	2.61–4.89	1.81–3.39
		Standard (GB/T 50824-2013)	1.85–3.47	1.29–2.42
		Bio-based	1.52–2.86	1.03–1.94

For the reference buildings with the three different wall construction types, the indoor environment in the same simulation location showed limited differences during the simulation process. The reference buildings that have a moderate risk of overheating are in Harbin and Shenyang (Figures 5 and 6). The statistical results for the indoor overheating risk are shown in Table 6. In Harbin, the air temperatures occasionally reach over 26 °C in July and temperatures stay over 26 °C for days at the beginning of August. Even though temperatures exceed 26 °C for 17.61% of the time during the summer months, overheating issues may not be problematic in this region. The periods of overheating are mostly during the day when residents are out of the house; hence, the issue is of moderate concern.

The overheating days (over 9 h with indoor air temperature above 26 °C) occur over less than a week and there is no continuous overheating period in the summer months. The simulation results showed that indoor air temperatures are higher in the rural residential buildings in Shenyang than in Harbin (Figure 6) and that temperatures exceed 26 °C for 28% of the time in the summer months. The air temperatures exceed 26 °C on a diurnal basis after 10 July and are constantly above 26 °C for more than two days at the beginning of August. There were 10 overheating days (over 9 h with indoor air temperature above 26 °C) during the simulation process. The simulation results showed a total of 21 overheating days in July and August; therefore, overheating issues should be considered in future designs of rural residential buildings in Shenyang. Therefore, mechanical air conditioning units may be required in these buildings, which would result in higher energy consumption in these rural residential buildings.

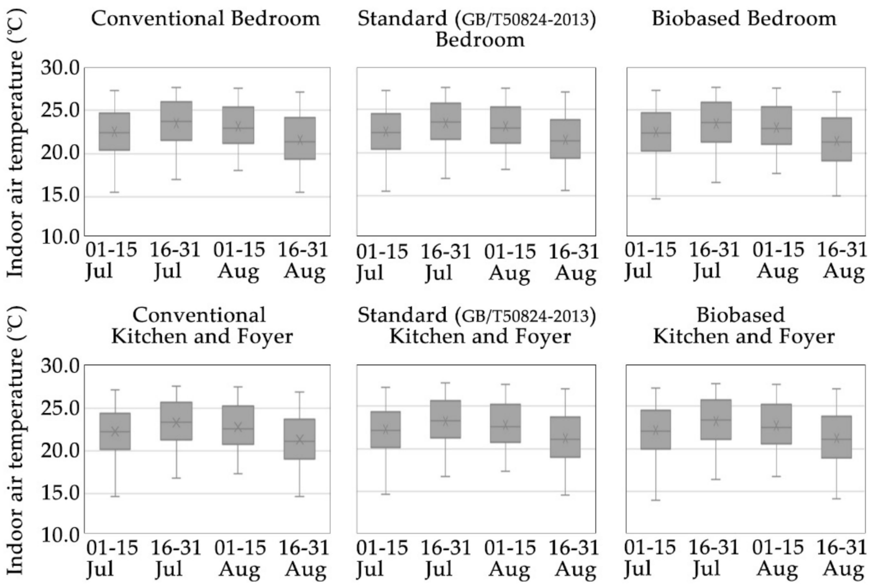


Figure 5. Indoor air temperature of reference buildings in Harbin.

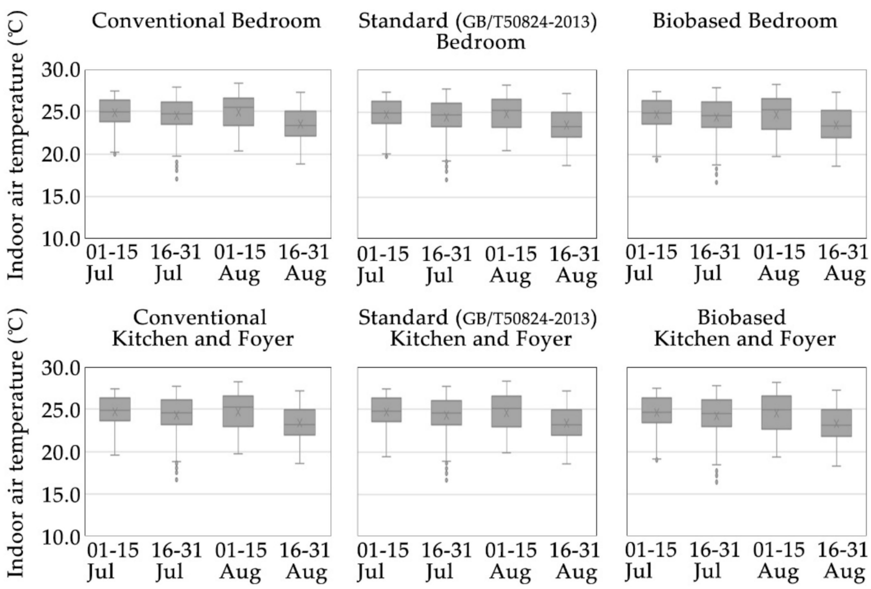


Figure 6. Indoor air temperature of reference buildings in Shenyang.

Table 6. Analysis of overheating period of rural residential buildings in Shenyang and Harbin during summer.

	Harbin	**Shenyang**
Percent of hours over 26 °C	17.61%	28.63%
Days with over 9 h over 26 °C (1st July–15th July)	1	4
Days with over 9 h over 26 °C (16th July–31st July)	4	5
Days with over 9 h over 26 °C (1st August–15th August)	2	10
Days with over 9 h over 26 °C (16th August–31st August)	0	2

5. Discussion

5.1. Improvements of Energy Efficiency Standards

The simulation results demonstrate the notable potential to increase the energy efficiency levels of existing rural residential buildings that have a conventional construction. Even though the target indoor temperature for winter heating is referenced from the existing standard (GB/T50824-2013), it is notably lower than widely acknowledged comfortable temperatures. The bio-based wall construction features superior insulation properties compared to the standard wall in GB/T50824-2013, whereas the heating energy requirements in the reference buildings are comparable for the two wall constructions. As a result, improvement in the insulation properties of all the components of the building envelope will result in both increased comfort of the indoor thermal environment and improved energy efficiency levels for rural residential buildings during the winter season. The energy efficiency levels can be further examined using machine learning techniques [54].

As coal is the major heating energy source for rural residential buildings, reductions in energy consumption can help to reduce the air pollution produced by coal burning. Existing research has identified a clear connection between coal-fired domestic heating and seasonal air pollution in North China [55,56]. The simulation results showed that a notable reduction in coal consumption can be achieved by replacing the conventional wall construction. For each reference building type, the reductions range from 29% to 42% and 42% to 56% for standard wall constructions in GB/T50824-2013 and bio-based walls, respectively (Figure 7). The reductions achieved by bio-based walls are more significant for the type A and B rural residential buildings. As a result, replacing conventional walls by bio-based walls will result in greater air quality improvements than if standard walls in GB/T50824-2013 are used.

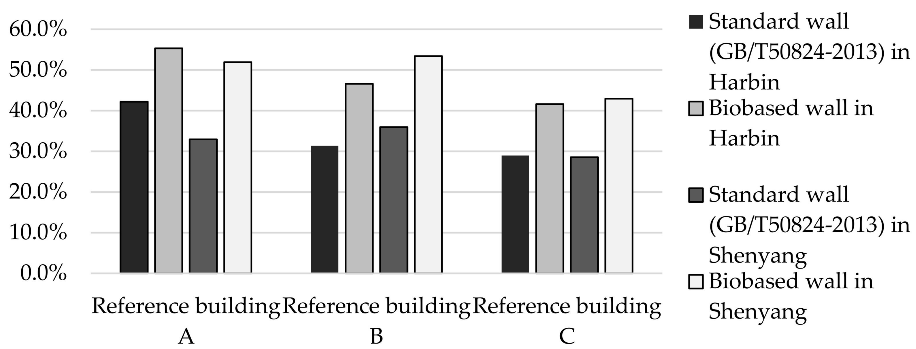


Figure 7. Reduction ratio of coal use of reference buildings with modified wall constructions in comparison with conventional residential buildings.

5.2. Indoor Environment and Summer Overheating Concerns

According to GB/T50824-2013, the lowest acceptable indoor temperature is 14 °C for rural residential buildings. The targeted heating temperature is notably lower than the comfort air temperature, as widely acknowledged. However, due to the choice of the kang as the preferred heating method, the indoor thermal comfort levels are acceptable to the residents. The kang performs as a radiator and heat emitter for human occupation during winter, and the surface temperatures are maintained above 30 °C during the heating period [55]. As a result, residents can remain in a comfortable thermal environment in rural residential buildings during the heating period.

The simulation process identified periods of potential overheating in the reference buildings in both the severe cold regions and cold regions. In the severe cold regions, the overheating period mainly occurs during the day when the rural residents are likely to be out in the fields rather than at home. As a result, the overheating concerns may not be important. However, overheating concerns may be problematic for the rural residential buildings in cold regions in northeast China. The simulation results showed that a long period of overheating occurs during the first week of August. Further consideration of solar shading systems and mechanical air-cooling systems should be included in the design of rural residential buildings in these regions. The increased cooling load will result in higher energy consumptions of rural residential buildings, which can be mitigated through smart building techniques and technologies [57].

5.3. Materialisations and Environmental Impacts

In comparison with conventional building materials, the low environmental impact is the major advantage of bio-based building materials [58,59]. As northeast China is one of the major agricultural regions, straw is widely available in the region as a by-product of agricultural activities. The local availability of building materials ensures abundant raw materials for construction and minimal requirements for long-distance transport. This decreases the dependence of the raw building materials on fossil fuels and hence decreases the environmental impact.

Due to the extensive agricultural activity in northeast China, the environmental treatment of straw has been an issue with local farmers and local governments for some time. Approximately 15% of the total rice production is cultivated in northeast China [60], with production and cultivated area continually increasing in this region [61]. As there are limited applications for the straw, this material is often burned in the fields, which causes annual seasonal air pollutions issues [62]. The use of rice straw in the building industry could significantly help to mitigate this issue in northeast China.

6. Conclusions

In this research, the potential energy sustainability advantages are analyzed through arising from the application of bio-based wall construction to rural residential buildings in northeast China. Overall, this research furthers the understanding of the energy efficiency levels of rural residential buildings in northeast China through assessing the benefits of modifying these buildings to incorporate bio-based wall systems. When compared with monitoring data, systematic errors were identified in the simulation process, which could be corrected through both in-field monitoring research and more accurate simulation models.

The research results indicated that bio-based walls can significantly increase the energy efficiency levels of rural residential buildings, with a corresponding decrease in coal demand for winter heating. The improved thermal insulation properties of bio-based wall construction can reduce heating energy in comparison to the standard wall construction in GB/T 50824-2013. By replacing conventional walls with bio-based walls, the annual heating energy requirements are reduced by 45.82 to 204.07 kWh/m^2 for different types of rural residential buildings in different regions in northeast China. This corresponds to a reduction of over 40% in coal consumption in rural residential buildings with bio-based walls compared with conventional construction. In relation to overheating issues, further designs of rural residential buildings should consider air-cooling methods in the cold regions, whereas there are no requirements for summer cooling in the severely cold regions. The uses of bio-based walls in rural residential buildings can reduce both the environmental impact of building construction and the seasonal air pollution issues in northeast China, thus contributing to local and global reductions in CO_2 emissions.

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