

Article

Analysis Based on Ecotect Software of the Energy Consumption and Economic Viability of Solar Collector Pig Houses with Different Roof Forms and Translucent Materials

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Abstract: This study investigated improvements in solar energy efficiency in pig houses with different roof types and translucent materials using Ecotect simulation software v2011. An experimental pig house in Qian Guo County, Songyuan City, was selected as the research object. First, the optimal building orientation for pig houses was explored by analysing the solar irradiance received as a primary indicator. Next, the energy consumption of pig houses was simulated using various translucent materials in the roof. Various roof types were designed based on the optimal translucent material. The energy consumption of these designs was compared with that of the experimental pig house. Finally, the economic viability of the different pig houses was analysed. The results showed that the optimal building orientation for a pig house was south by west 25°. Among the pig houses with equal-slope roofs using FRP daylighting boards, double-layer polycarbonate (PC) sheets, flat glass, and organic glass as translucent materials, the pig house using double-layer PC sheets required the least amount of additional heat during the heating season (62,109 kWh). For pig houses with double-layer PC sheets, four roof designs were assessed (equal-slope roof, front and rear roofs with unequal slopes, upper and lower staggered unequal-slope roof, and four-equal-slope roof), and it was found that the pig house with a four-equal-slope roof required the least amount of additional heat during the heating season (48,138 kWh). The economic analysis indicates that the combination of a four-equal-slope roof and double-layer PC sheets is the most cost-effective option, with the lowest total life cycle cost. This design saves 9521 USD compared with the experimental pig housing, effectively improving solar energy utilisation efficiency. These analyses provide a reference for exploring the thermal performance of pig houses.

Keywords: solar energy; Ecotect; pig house; translucent material; energy consumption



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1. Introduction

With the development of large-scale pig farming, the thermal environment of pig houses has been widely recognised as an important matter [1–3]. In the northern regions of China, where winters are cold and prolonged, pig houses are typically heated through the combustion of coal, oil, and natural gas using hot-air stoves, radiators, and underfloor heating to provide heat compensation [4]. However, this practice not only increases the cost of pig farming but also leads to environmental pollution [5]. As a clean and renewable energy source, solar energy has emerged as an important research direction for regulating the thermal environments of pig houses. Studies have been conducted to enhance the utilisation efficiency of solar energy, reduce winter heating costs, and minimise environmental pollution [6–10].

However, studies on improving the utilisation efficiency of solar energy in pig houses have mainly focused on sidewalls and roofs [6,8,10,11]. The results showed that the heating performance of solar collectors installed on roofs was better than that of collectors installed

on sidewalls [7,12]. The use of translucent roofing material and the roof form directly influence light transmission and thermal insulation performance, ultimately affecting heat compensation during the heating period in pig houses. Wang et al. [13] conducted energy-saving renovations on the roofs of pig houses and implemented preheating and fresh air ventilation to effectively reduce pig house total energy consumption. Liao [14] used large-area translucent materials on the south side of sunlit pig houses, increasing the temperature in sunlit pig houses by 8.2 °C compared with conventional pig houses during the cold season. Liu et al. [15] compared the winter housing temperature between traditional open-air and double-layer plastic film translucent material pig houses. Their results showed that throughout the winter season, temperature in the double-layer plastic film pig houses increased by 18.5–21 °C compared with the open-air houses. Yu et al. [16] designed a hexagonal roof of a piglet house, effectively saving energy and increasing annual solar radiation received. Pan et al. [17] conducted research on solar energy-insulated pig houses using plastic films as translucent materials, focusing on monoslope, gable, and single-arch roof forms. Their results showed that the gable-roof solar-energy-insulated pig houses effectively increased heat retention. For translucent materials, double-layer plastic films or double-layer glass can be used. Feng et al. [18] suggested that double-slope roofs exhibit good insulation effects. Using colored steel composite and sun panels for the roof not only increases the lighting in the house but also achieves winter insulation. These studies focused on the combination of roof forms and translucent materials to analyse how to improve the utilisation efficiency of solar energy.

Currently, research on pig house energy consumption is primarily conducted through field measurements and software simulations, which can effectively address the drawbacks of large workloads, slow measurement speeds, and inconvenient operations associated with field measurements [19,20]. Ecotect software can effectively assist in designing energy-saving buildings and is mainly used for the simulation and analysis of a building's thermal, lighting, and sound environments, as well as economic aspects [21–23]. Although it is mostly used for civilian buildings, its application in the agricultural field has broad prospects [24–26].

This study was based on a modified experimental pig house in Qian Guo County, Songyuan City, Jilin Province, China. The Ecotect software was used to conduct a 1:1 modelling analysis. The main objective was to investigate the energy consumption and economic feasibility of solar collector pig houses with different translucent materials and roof forms, with the ultimate goal of identifying an optimal solution for enhancing the solar utilisation efficiency of such pig houses in the northern region. Table 1 presents a summary of key findings from the relevant literature.

Table 1. Summarizes the key findings from the relevant literature.

Title	Authors	Main Findings	Citation Numbers
Research Progress of Heating Process and Heating Equipment for Closed Livestock and Poultry Houses in China.	Shi Z.F.; Ji Z.Z.; Xi L.	Using solar energy to heat livestock and poultry houses saved energy and reduced pollution.	[6]
Combined active solar and geothermal heating: A renewable and environmentally friendly energy source in pig houses.	Islam M.M.; Mun H.; Bostami R.M.B.A.; et al.	Compared with the traditional heating system, the solar and geothermal combined heating system significantly reduced electricity consumption, CO ₂ emissions and costs.	[7]
Analysis of light environment and thermal performance of piggery with different wall materials based on Ecotect.	Yuan Y.M.; Song Y.; Xie C.H.; et al.	Measured values were compared with simulated values using Ecotect software, with a relative error range of 0.74% to 8.62%.	[8]

Table 1. Cont.

Title	Authors	Main Findings	Citation Numbers
Retrofitting of a pig nursery with solar heating system to evaluate its ability to save energy and reduce environmental pollution.	Mun H.S.; Ahmed S.T.; Islam M.M.; et al.	The solar-powered pig house reduced electricity usage by 15% (261 kWh) compared with the conventional house, resulting in a 15% decrease in CO ₂ emissions (128 kg).	[9]
Evaluation of the radiometric properties of roofing materials for livestock buildings and their effect on the surface temperature.	Vox G.; Maneta A.; Schettini E.	Roofing materials with a solar reflectivity coefficient higher than 22% and an emissivity coefficient higher than 90% can greatly reduce surface temperatures in livestock buildings, especially during the warmest periods.	[10]
Evaluation of solar energy on the roofs of livestock houses.	Liberati P.; Zappavigna P.	The annual energy absorption of a shed roof was 2.5% higher than that of a gabled roof.	[11]
Research on the application of energy saving design of green buildings based on Ecotect.	Cui Z.; Guo Z.M.; Zhang J.P.	Ecotect software enables simulation and analysis of lighting, acoustics, thermal conditions, visibility, and other aspects of architectural designs.	[21]
Optimization of Photovoltaic external shading structure based on Ecotect.	Chen H.F.; Wang Y.J.; Cai B.R.; et al.	The Ecotect software can be utilized to study the daylighting and power generation performance of external photovoltaic panels.	[22]
Building energy conservation in atrium spaces based on Ecotect simulation software in hot summer and cold winter zone in Iran	Nima A.	The Ecotect software can effectively assist in energy-saving design research for buildings.	[23]
Simulation Analysis of Different Enclosure Materials for Pig Welfare Breeding	Peng H.; Yun H.X.	The Ecotect software analysis suggested that adding insulation materials and architectural coatings to the enclosure structure of pig housing improves animal welfare in farming.	[24]
Study on the change rule of solar radiation in solar greenhouse group based on Ecotect.	Luo M.Y.; Wu X.; Liu K.; et al.	Ecotect software accurately simulated daylighting conditions, with a relative error range of −0.54% to 7.92%.	[25]
Analysis of luminous environment of photovoltaic greenhouse using Ecotect models.	Wang B.; Chen J.L.; Ying J.Y.	Comparing the simulated values of Ecotect software with the measured values, the average difference in solar radiation at each testing point was within 10%.	[26]

2. Materials and Methods

2.1. Experimental Pig Housing Model and Parameters

The experimental pig house is located in Qian Guo County, Songyuan City, Jilin Province, China (124°28' E, 44°51' N). The annual total solar radiation in this area is approximately 5064 MJ/m². The pig house has a length, width and height of 50.6, 18.5, and 2.6 m, respectively. The roof has a slope angle of 13.32°. The pig house interior consists of one pig-fattening room, two piglet rooms, and one sow room, with a total of 48 fattening pigs, 40 piglets, and five sows. The main load-bearing structure is consists of steel, and the wall material consists of a 10 mm plastic flame-retardant plywood + 20 mm polyethylene foam layer + 290 mm foam concrete wall panel + 20 mm cement mortar layer. The north-side roof is composed of a 25 mm wooden board + 2 mm asphalt felt layer + 10 mm polystyrene foam board + 0.5 mm blue color steel tile; the south-side roof is

constructed with double-layer polycarbonate (PC) sheets, and the glass section consists of fully enclosed double-layer insulated glass windows (Figure 1).

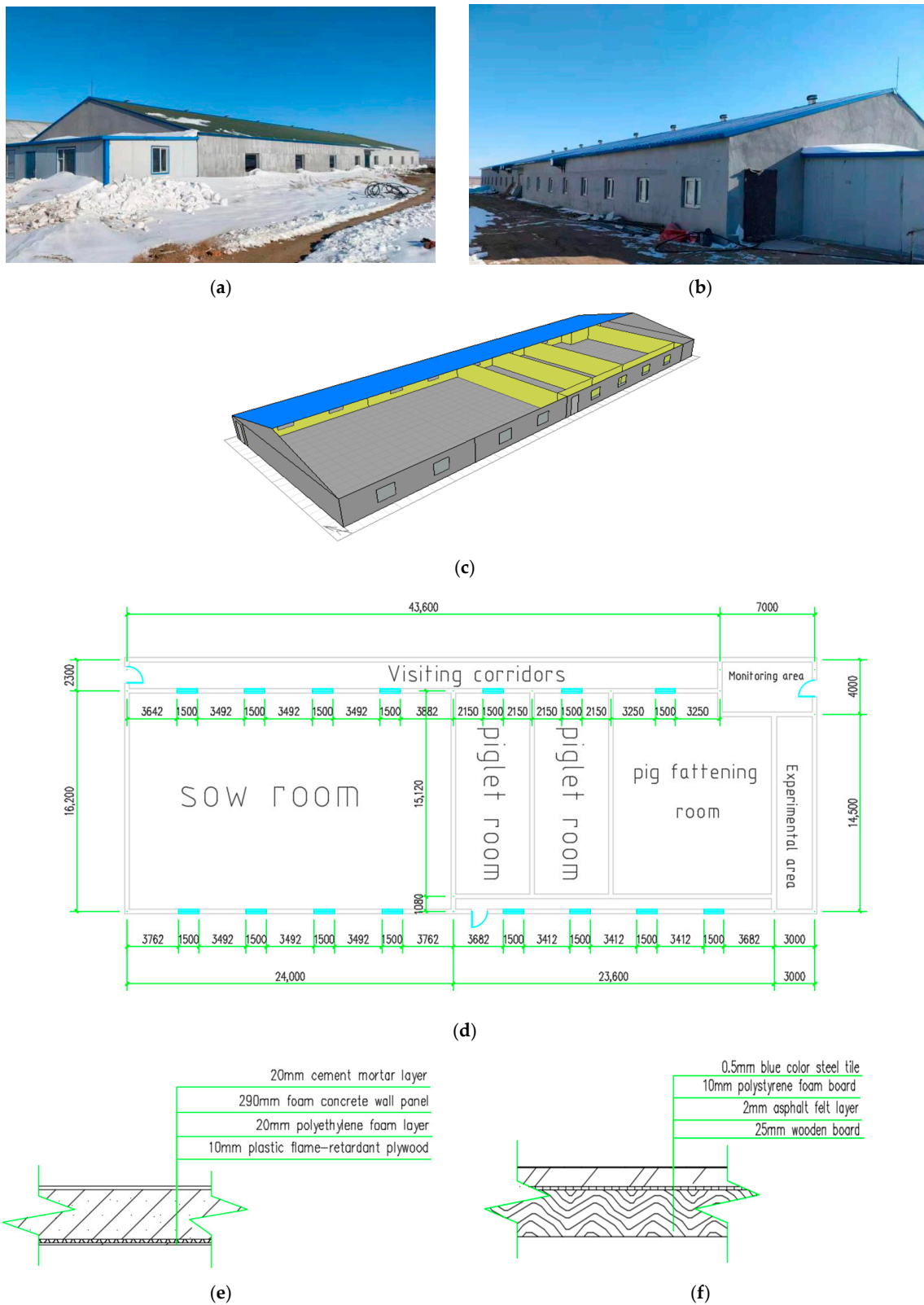


Figure 1. Overview of the experimental pig house: (a) south wall; (b) north wall; (c) Ecotect model; (d) floor plan; (e) detailed drawing of the wall construction (f) detailed drawing of the roof construction on the north side.

The working principle of a solar-energy-insulated pig house with a heat collection shed involves sunlight penetrating the south-facing roof, heating the air inside the shed, and storing the heat in phase change materials located at the bottom of the shed. The heated air then enters the pig house through internal pipelines within the heat collection shed. The phase change material used in this study was Hexadecane wax ($C_{16}H_{34}$). The material has a phase change temperature of 40–50 °C, melting point of 48 °C, density of 0.8–0.9 g/cm³, and latent heat of 150–200 J/g.

Ecotect was used for proportional modeling. The pig house model is shown in Figure 1c, and the calculated parameters for each component are listed in Table 2.

Table 2. Parameters of various components of the pig house.

	Components	Heat Transfer Coefficient	Access Coefficient	Solar Absorptivity/%	Attenuation Coefficient	Delay Time/h	Solar Transmittance/%
Wall	10 mm plastic flame-retardant plywood + 20 mm polyethylene foam layer + 290 mm foam concrete wall panel + 20 mm cement mortar layer.	0.56	3.12	50.00	0.30	11.36	-
North side roof	25 mm wooden board + 2 mm asphalt felt layer + 10 mm polystyrene foam board + 0.5 mm blue color steel tile.	0.50	2.42	80.00	0.80	3.12	-
South side roof	Double-layer PC sheets (Various polycarbonate fillers adopted from Ecotect material library).	3.00	6.00	-	-	-	78.00
Glass	Fully enclosed double-layer insulated glass windows (Using Ecotect prototype double-layer aluminum alloy glass mode).	2.70	2.80	-	-	-	63.00

2.2. Experimental Method

Using Ecotect software, meteorological parameters such as annual temperature, solar radiation, relative humidity, and wind direction for the Songyuan area were determined. An energy consumption simulation analysis for the pig house was also conducted.

Ecotect software, as a civil building software, is used to analyse the lighting environment, energy consumption, sunlight, shading, etc., of buildings by setting parameters including building occupants, building structure, and environmental factors. In the analysis of building energy consumption for pig houses, it is necessary to simulate pigs by selecting the human state in the software. For simulation purposes, choosing a person in a sitting position with uncovered body parts to represent the pigs is possible. Under the chosen state, the sensible heat dissipation of humans and pigs may differ. According to the heat balance principle, quantitatively converting the sensible heat-power relationship between humans and pigs is necessary [8]. In the software, the default sensible heat power for a person in a sitting position with uncovered body parts is 70 W, which is equivalent to 252 kJ/h. The sensible heat power is 100.24 kJ/h for a 9.0 kg piglet, 968.04 kJ/h for a 179 kg sow, and 288.05 kJ/h for a 91 kg fattening pig. Using Equations (1)–(3), 40 piglets, 5 sows, and 48 fattening pigs inside the pig house can be converted into the equivalent of 90 selected individuals.

$$Q_p = Q_c \quad (1)$$

$$P_p \cdot N_p \cdot t = P_c \cdot N_c \cdot t \quad (2)$$

$$N_p = \frac{P_c}{P_p} \cdot N_c \quad (3)$$

In the equations above, Q_p and Q_c represent the total heat dissipation of pigs and humans, kJ; P_p represents the heat dissipation per hour for each pig, kJ/h; N_p represents the number of pigs; t represents time, h; P_c represents the heat dissipation per hour for each person, kJ/h; and N_c represents the number of participants.

2.2.1. Analysis Method for Evaluating Different Orientations of Pig Houses in Terms of Received Solar Radiation

The typical orientation of pig house buildings is between 45° east of south and 45° west of south [27]. In this simulation design, 19 sets of experiments were conducted at 5° intervals within the orientation range. The focus of this research was to investigate solar radiation received on the south roof and wall during the heating season (20th October to 10th April of the following year). Using the Ecotect software, models were built for different orientations of the pig house and analysed based on the climate characteristics of the Songyuan area.

2.2.2. Analysis Methods for Energy Consumption of Pig Houses with Different Translucent Materials

To analyse energy consumption of a pig house using Ecotect software, the following parameters were set: clothing index to 0, humidity level to 60%, wind speed to 0.1 m/s, and indoor temperature to 24 °C. An equal number of pigs of the same mass were placed in pig houses with different translucent materials. The heat gain/loss of the roof and energy consumption of the pig house were analysed by changing only the type of translucent material on the south side of the roof while keeping other enclosure structures and materials constant.

The analysis focused on translucent materials commonly used in local pig house construction, such as fibreglass-reinforced plastic (FRP) daylighting boards, double-layer polycarbonate (PC) sheets, and flat and organic glass. The parameters of the translucent materials are presented in Table 3.

Table 3. Parameters of the translucent materials.

Roofing Translucent Materials	FRP Daylighting Board	Double-Layer PC Sheet	Flat Glass	Organic Glass
Thickness (mm)	8.00	8.00	8.00	8.00
Density (kg/m ³)	1400.00	1200.00	2500.00	1190.00
Specific heat capacity (J/kg·K)	840.00	1172.00	800.00	1164.00
Thermal conductivity (W/m·K)	0.16	0.17	0.76	0.19
U-value (W/m ² ·K)	4.37	4.42	5.30	4.54
Access coefficient (W/m ² ·K)	4.34	4.39	5.26	4.51
Solar absorptivity (%)	24.00	22.00	10.00	18.00
Visible light transmission rate (%)	76.00	78.00	90.00	82.00

2.2.3. Analysis Methods for Energy Consumption of Pig Houses with Different Roof Forms

Based on the experimental pig house structure dimensions, four different roof designs were considered: front and rear unequal-slope roofs, upper and lower staggered unequal-slope roofs, and four-equal-slope roofs (Figure 2). Utilising the best available translucent material, Ecotect software was used to simulate and compare the heat gain/loss of the existing equal-slope roof and three newly designed roofs, as well as the energy consumption of the four designs.

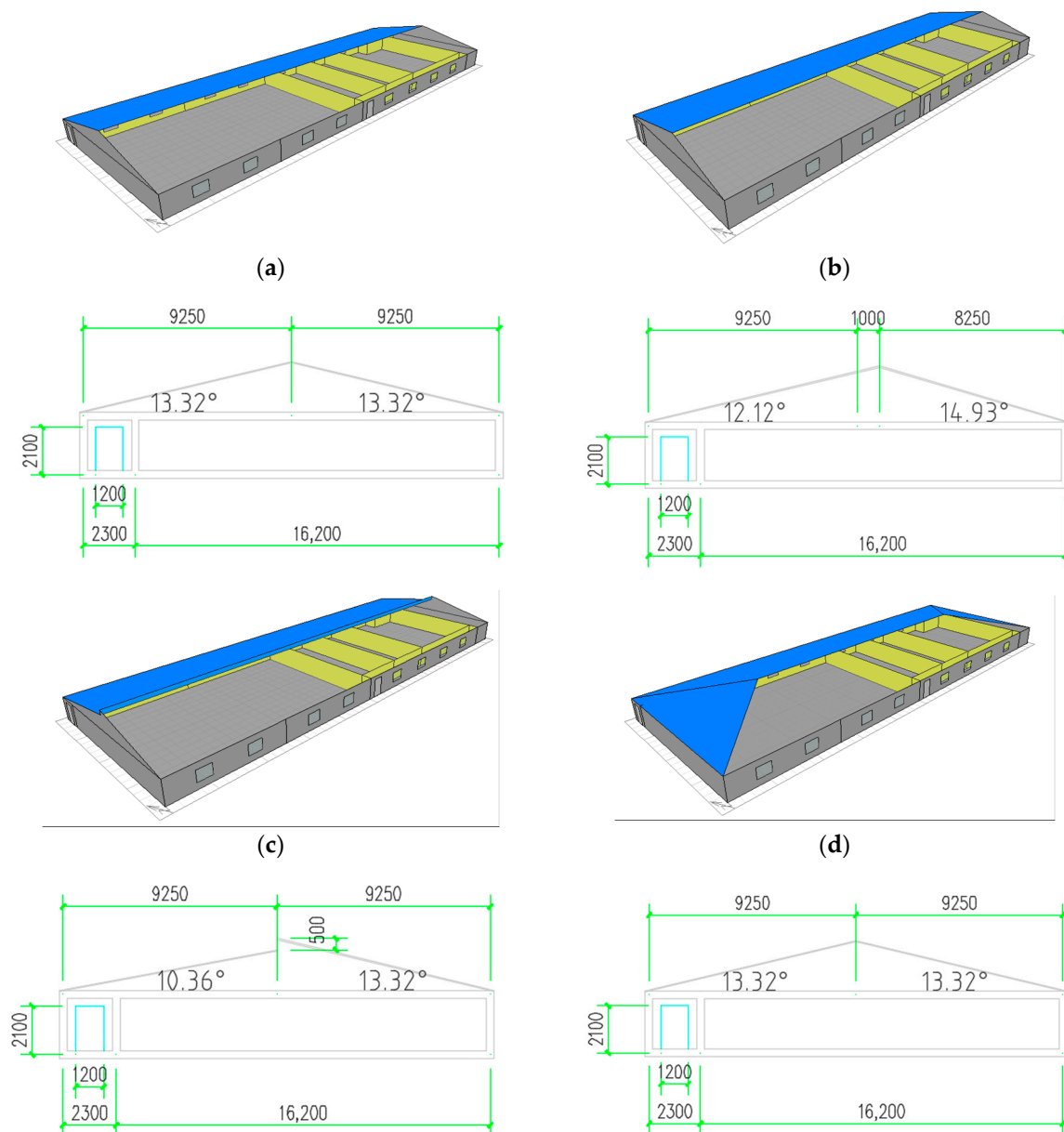


Figure 2. Modeling of pig houses with different roof forms: (a) equal-slope roof; (b) front and rear roofs with unequal slopes; (c) upper and lower staggered unequal-slope roof; (d) four-equal-slope roof.

2.2.4. Economic Analysis Methods

Electric heating was used to achieve heat compensation in the pig houses. With the assumption that the compensation heat is solely provided by air conditioning, the service life of a pig house is 10 years. The construction costs and heating expenses of the pig house roof were calculated based on different translucent materials and roof types using Equations (4)–(6). This analysis aimed to compare and evaluate the economic performance of different pig houses. Currency conversion was performed between RMB and USD during the calculations (1 USD = 6.5 RMB).

$$T_R = P_{cs} \cdot S_{cs} + P_{tm} \cdot S_{tm} \quad (4)$$

$$P_E = 0.484 \cdot Q_h \quad (5)$$

$$TLCC = T_R + 10 \cdot P_E \quad (6)$$

In the equations above, T_R represents the construction cost of the pig house roof, USD; P_{CS} represents the unit price of color steel sheet, USD/m²; S_{cs} represents the area of color steel sheet, m²; P_{tm} represents the price of translucent material, USD/m²; S_{tm} represents the area of translucent material, m²; P_E represents the electricity cost during the heating season, USD; 0.484 represents the electricity price for agricultural production in Songyuan City, USD/kWh; Q_h represents the additional heat supply during the heating season, kWh; and TLCC represents the total life cycle cost, USD.

3. Results and Discussion

3.1. Solar Irradiance Received by Pig Houses of Different Orientations

The daily average solar irradiance received by the south roof and south wall of the pig house is shown in Figure 3. Between 45° west of south and 45° east of south, the change in solar irradiance received by the south roof and wall shows a consistent increasing and then decreasing pattern, with the maximum values appearing at 25° west of south. At this orientation, the solar irradiance received by the south roof and wall was 4285.0 Wh/m² and 4221.8 Wh/m², respectively. When the orientation was between 35° west of south and 10° west of south, the change in solar irradiance received by both the south roof and south wall is mild. To improve solar energy utilisation efficiency, the optimal orientation of the pig house should be 25° west of the south, considering other building requirements. The recommended orientation variation range is between 35° west of the south and 10° west of south. The experimental pig house meets the requirements of the optimal orientation, ensuring that both the south roof and wall receive the desired solar irradiance.

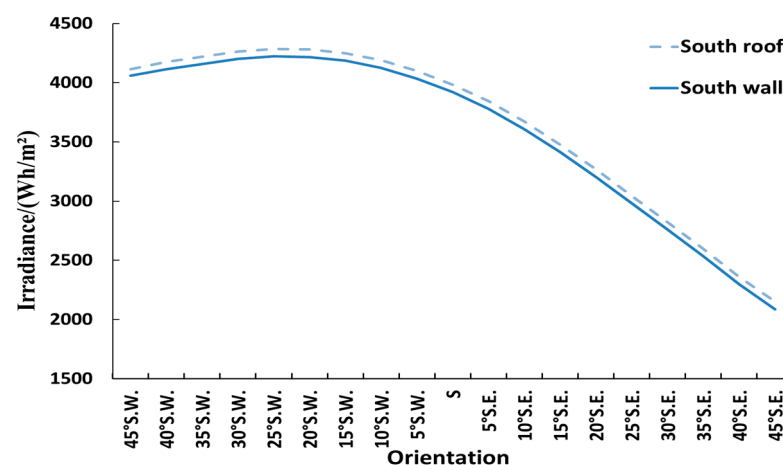


Figure 3. Solar irradiance received by the south roof and wall of the pig house.

3.2. Energy Consumption Analysis of Pig Houses with Different Translucent Materials

Building energy consumption refers to the energy consumed by a building during construction and operation. The energy consumption within a building can serve as an evaluation indicator for the energy efficiency of the building design, providing a reference for the heating, cooling, and other systems design within the building [28,29]. The monthly heating and air conditioning energy consumption of an entire building and specific areas within the building can be analysed using Ecotect. The building energy consumption simulated in this study refers to the energy required to maintain a set temperature within a pig house during the heating season.

Figure 4 shows the heat gain and loss analyses of equal-slope roofs with different translucent materials during the heating season. During this season, all roofs with different translucent materials experienced the greatest heat loss in January, in the following order: flat glass > organic glass > FRP daylighting board > double-layer PC sheet. In January, the FRP daylighting board, flat glass, and organic glass lost an additional 632 kWh, 1003 kWh, and 718 kWh of heat, respectively, compared with the double-layer PC sheet. The energy-

saving rates were calculated as -55.54% , -88.14% , and -63.09% for the FRP daylighting board, flat glass, and organic glass, respectively. The cumulative heat gain and loss of the equal-slope roofs with different translucent materials during the heating season are shown in Figure 5. The total heat gain and loss of different translucent materials for the roofs were in the following order: flat glass > organic glass > FRP daylighting board > double-layer PC sheet. Compared with the double-layer PC sheet, the FRP daylighting board, flat glass, and organic glass achieved energy savings of -2816 kWh, -4539 kWh, and -3228 kWh, respectively. The energy-saving rates were calculated as -55.81% , -89.95% , and -63.97% for the FRP daylighting board, flat glass, and organic glass, respectively. The translucent material used in the experimental pig house, the double-layer PC sheet, had the least heat loss and was more energy-efficient compared with the other translucent materials.

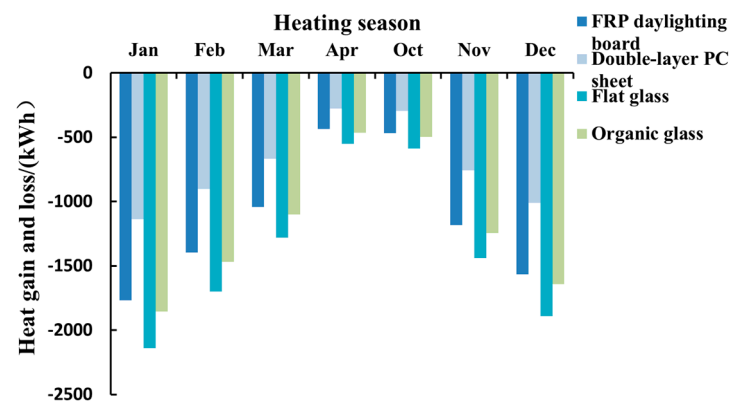


Figure 4. Heat gain and loss of the equal-slope roofs with different translucent materials during the heating season.

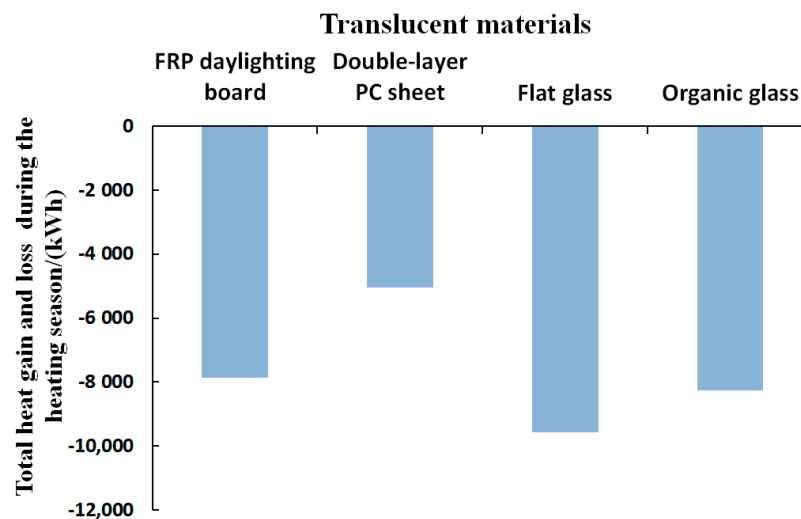


Figure 5. Total heat gain and loss of the equal-slope roofs with different translucent materials during the heating season.

A total energy consumption analysis of equal-slope roof pig houses with different translucent materials during the heating season is shown in Figure 6. The results indicate that the FRP daylighting boards, double-layer PC sheets, flat glasses, and organic glass pig houses required additional heat supplementation of 126,172 kWh, 62,109 kWh, 163,630, and 135,559 kWh, respectively, whereas the FRP daylighting board, flat glass, and organic glass consumed 103.15%, 163.46%, and 118.26% more energy, respectively, than the double-layer PC sheet. The month with the highest heat supplementation for all translucent materials was January. Heat supplementation in January accounted for 30.55%, 35.69%, 28.85%, and

30.01% of the total heat supplementation for the FRP daylighting board, double-layer PC sheet, flat glass, and organic glass pig houses, respectively, indicating that equal-slope roof pig houses with a double-layer PC sheet effectively reduce energy consumption.

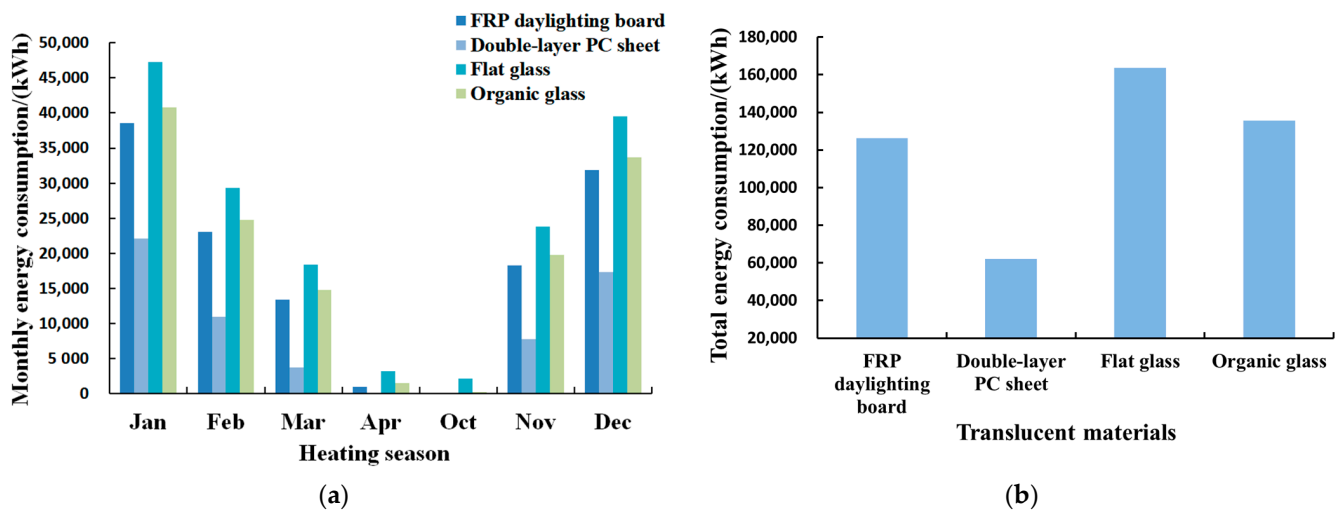


Figure 6. The comparison of energy consumption for equal-slope roof pig houses with different translucent materials during heating season: (a) Monthly energy consumption; (b) Total energy consumption.

3.3. Energy Consumption Analysis of Pig Houses with Different Roof Forms

The simulated calculations of the heat gain and loss for different roof forms during the heating season using a double-layer PC sheet as the translucent material are shown in Figure 7. All the four roof forms experienced the highest heat losses in January. The front and rear unequal-slope, upper and lower staggered unequal-slope, and four equal-slope roofs showed a reduction in heat loss compared to the equal-slope roof by 81 kWh, −4 kWh, and 151 kWh, respectively. The energy-saving rates of these roof forms were 7.1%, −0.4%, and 13.3%, respectively. The heat gain and loss sum for different roof forms during the heating season are shown in Figure 8, where the total heat losses for the different roof forms exhibited the following order: upper and lower staggered unequal-slope roof > equal-slope roof > front and rear unequal-slope roof > four-equal-slope roof. The front and rear unequal-slope, upper and lower staggered unequal-slope, and four-equal-slope roof showed a reduction in heat loss compared to the equal-slope roof by 368 kWh, −17 kWh, and 686 kWh, respectively. The energy-saving rates of these roof forms were 7.3%, −3.4%, and 13.6%, respectively.

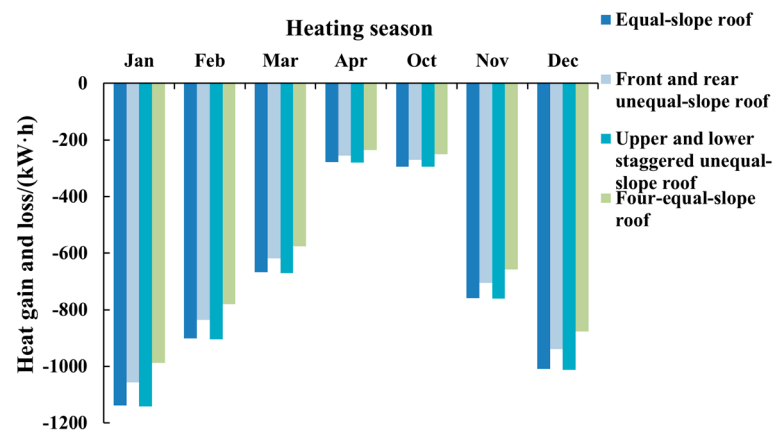


Figure 7. Heat gain and loss for different roof forms during the heating season.

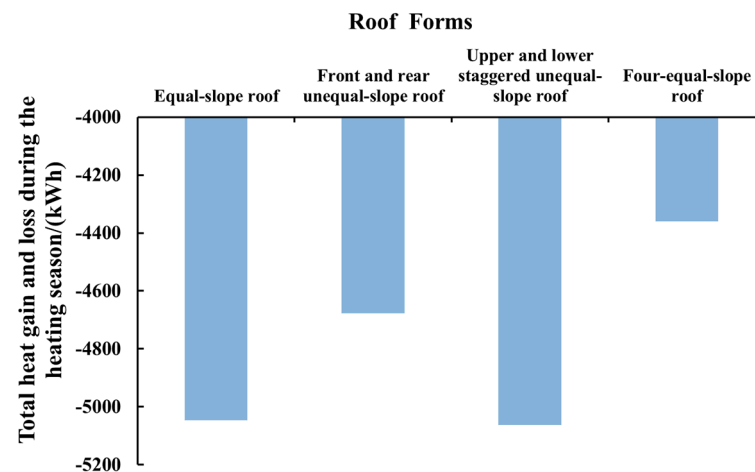


Figure 8. Heat gain and loss sum for different roof forms during the heating season.

An analysis of the monthly and total energy consumption during the heating season was conducted for the pig houses with different roof forms using double-layer PC sheets (Figure 9). The results indicated that during the heating season, the pig houses with different roof forms using double-layer PC boards did not require additional energy supplementation in April and October. In January, however, the highest amount of heat supplementation was necessary. In January, the equal-slope, front and rear unequal-slope, upper and lower staggered unequal-slope, and four-equal-slope roofs required heat supplementation, accounting for 35.69%, 36.53%, 36.00%, and 38.07% respectively of the total heat requirement. The heat supplementation required during the heating season for the equal-slope, front and rear unequal-slope, upper and lower staggered unequal-slope, and four-equal-slope roofs were 62,109 kWh, 56,116 kWh, 59,961 kWh, and 48,138 kWh respectively. Compared with the experimental pig house with an equal-slope roof, the front and rear unequal-slope, upper and lower staggered unequal-slope, and four-equal-slope roofs required 9.65%, 3.46%, and 22.49% less heat supplementation, respectively. The results indicate that the four-equal-slope roof had the most significant effect in reducing energy consumption in pig houses.

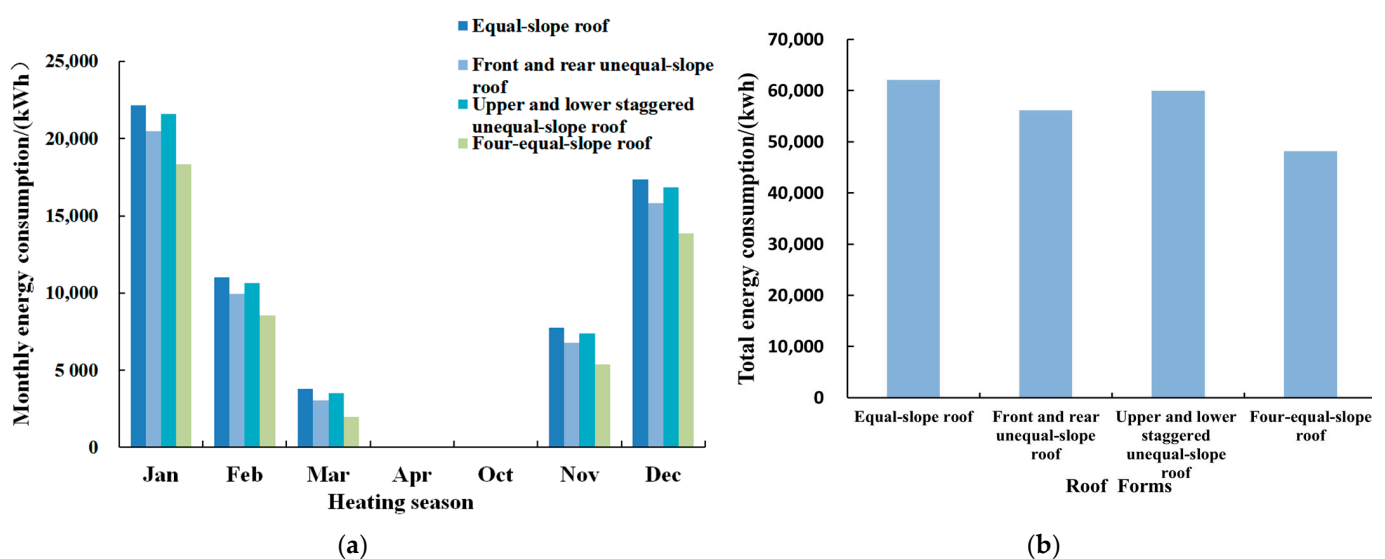


Figure 9. The comparison of energy consumption for pig houses with different roof forms using double-layer PC sheets during the heating season: (a) monthly energy consumption; and (b) total energy consumption.

3.4. Economic Analysis

Based on the agricultural electricity costs and market prices of building materials in Songyuan City, the heating costs for different translucent materials in equal-slope roof pig houses during the heating season were calculated according to the analysis in Section 2.2. Additionally, the material costs for heat-collection sheds with different translucent materials were analysed (Table 4). The results indicate that considering both material costs and operational expenses for the heating season, the double-layer PC sheet is the most economical option.

Table 4. Analysis of electricity heating cost and material costs for equal-slope roof pig houses with different translucent materials.

Pig Houses	Color Steel Plate Price (USD/m ²)	Color Steel Plate Area (m ²)	Translucent Materials Price (USD/m ²)	Translucent Materials Area (m ²)	Roofing Cost (USD)	Supplementary Heat Supply in the Heating Season (kWh)	Electricity Cost (USD)	TLLC (USD)
FRP daylighting board	18.62	481.00	6.15	481.00	11,914.37	126,172.00	9394.96	105,863.97
Double-layer PC sheet	18.62	481.00	8.62	481.00	13,102.44	62,109.00	4624.73	59,349.74
Flat glass	18.62	481.00	6.92	481.00	12,284.74	163,630.00	12,184.14	134,126.14
Organic glass	18.62	481.00	17.85	481.00	17,542.07	135,559.00	10,093.93	118,481.37

The analysis of electricity heating costs during the heating season for pig houses with different roof forms using a double-layer PC sheet and the material costs of the different roof forms is presented in Table 5. Among the pig houses with different roof forms using double-layer PC sheets, the equal-slope roof had the lowest construction cost of 13,102.44 USD. However, it had the highest electricity bill during the heating season, amounting to 4624.73 USD. In contrast, the four-equal-slope roof had the highest construction costs of 13,984.44 USD. However, it had the lowest electricity bill in the long run, totaling 3584.43 USD. Therefore, from an economic perspective, the combination of a four-equal-slope roof and double-layer PC sheet proved to be the most cost-effective for pig houses. Based on the calculation of the total life cycle cost, it can be concluded that the pig house with double-layer PC sheets and a four-equal-slope roof has the lowest cost within its lifespan at 49,828.74 USD. This design saves 9521 USD compared with the experimental pig house with double-layer PC sheets and an equal-slope roof.

Table 5. Analysis of electricity heating costs and material costs for double-layer PC sheet pig houses with different roof forms.

Pig Houses	Color Steel Plate Price (USD/m ²)	Color Steel Plate Area (m ²)	Translucent Materials Price (USD/m ²)	Translucent Materials Area (m ²)	Roofing Cost (USD)	Supplementary Heat Supply in the Heating Season (kWh)	Electricity Cost (USD)	TLLC (USD)
Equal-slope roof	18.62	481.00	8.62	481.00	13,102.44	62,109.00	4624.73	59,349.74
Front and rear	18.62	530.30	8.62	431.90	13,597.16	56,116.00	4178.48	55,381.96
Unequal-slope roof	18.62	501.10	8.62	481.00	13,476.70	59,961.00	4464.79	58,124.60
Upper and lower staggered	18.62	569.20	8.62	392.80	13,984.44	48,138.00	3584.43	49,828.74
Four-equal-slope roof	18.62	569.20	8.62	392.80	13,984.44	48,138.00	3584.43	49,828.74

Double-layer PC sheets exhibit good insulation properties, allowing for ample natural light while maintaining stable indoor temperatures and reducing heating demands [30]. The design of a four-equal-slope roof offers excellent insulation and airflow, thereby minimizing temperature fluctuations and facilitating rainwater collection and drainage [31]. In conclusion, the combination of double-layer PC sheets and a four-equal-slope roof design presents significant advantages in terms of improving energy efficiency, environmental quality, and resource conservation. This design can support the sustainable development of agricultural production.

4. Conclusions

According to the climatic characteristics of the Songyuan area in Jilin Province and using Ecotect software, simulations were conducted on the orientation and energy consumption of solar collector pig houses with different translucent materials and roof forms. The following conclusions were drawn from the economic feasibility analysis:

- (1) Through a comparative analysis of received solar irradiance of roofs at different orientations, it was determined that the optimal orientation for pig houses in the Songyuan area is 25° west of south. During construction, it is suggested that a range of orientation variations between 35° and 10° west of south be allowed.
- (2) Comparative analysis of energy consumption of pig houses with different translucent materials during the heating season. For pig houses with an equal-slope roof and different translucent materials, it was found that those with double-layer PC sheets consumed 103.15%, 163.46%, and 118.26% less energy than those with FRP daylighting boards, flat glass, and organic glass, respectively.
- (3) Analysis of energy consumption in pig houses with different roof forms during the heating season. Using double-layer PC sheets as the translucent material, it was found that pig houses with front and rear unequal-slope, upper and lower staggered unequal-slope, and four-equal-slope roofs required 9.65%, 3.46%, and 22.49% less heat supplementation, respectively, than those with an equal-slope roof.
- (4) The cost and expense analysis of pig houses with equal-slope roofs using different translucent materials and pig houses with double-layer PC sheets using different roof forms indicate that the combination of a four-equal-slope roof and double-layer PC sheets is the most economical option. The total life cycle cost is 49,828.74 USD, which represents a saving of 9521 USD compared with the experimental pig house.

This study primarily focuses on comparing the energy consumption and economic viability of pig houses with different translucent materials and roof structures during the heating season. The results indicate that the double-layer PC sheets pig house with a four-equal-slope roof exhibits the highest efficiency in utilizing solar energy. However, it should be noted that this study only considers the heating season. Further verification is required to assess the solar energy utilisation efficiency and economic suitability in other seasons or regions when promoting its application.

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