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Review

A Review of the Current Status and Prospects of Improving Indoor Environment for Lightweight Buildings in High-Altitude Cold Regions

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Abstract: Lightweight structures, characterized by rapid assembly, are vital for creating habitats in outdoor environments, but their implementation in high-plateau cold regions encounters significant challenges in heating and ventilation. This paper systematically introduces the environmental characteristics and reviews the demands and primary influencing factors of indoor environments in these regions. The advantages and limitations of underground lightweight construction are also discussed. Current research indicates that evaluation methods for air quality in high-altitude cold regions require further development. Reducing building heat loss and minimizing cold air infiltration can enhance indoor environments and lower energy consumption. However, it is essential to establish effective ventilation strategies to prevent the accumulation of air pollutants. Then, potential passive ventilation improvement measures suitable for the environmental characteristics of high-cold plateaus are outlined. The application potential and possible limitations of these measures are summarized, providing references for future research. Finally, the main research methods for ventilation and heating within building interiors are organized and discussed. Findings indicate that computational fluid dynamics models are predominantly used, but they demonstrate low efficiency and high resource consumption for medium- to large-scale applications. Integrating these models with network models can achieve a balance of high computational accuracy and efficiency.

Keywords: plateau cold climate; lightweight buildings; indoor environment; energy saving; ventilation calculations

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1. Introduction

Lightweight structures such as panel houses, tents, and some prefabricated houses are characterized by their quick assembly, convenience, and mobility. They feature simple designs that facilitate installation and disassembly. Compared to traditional buildings, panel housing offers unique advantages such as lightweight construction, low cost, and the ability to be quickly erected and disassembled in outdoor conditions. It can be repositioned as needed and is widely used in various scenarios, including field construction, camping, and emergency relief, playing a vital role in these applications. Researching and improving ventilation and heating in temporary structures like panel housing is significant for expanding living space, enhancing emergency response, and promoting economic development [1,2]. During wartime, these structures become essential for national defense, field training, and military operations. For remote areas or frontline conditions, lightweight housing serves as a critical refuge, providing shelter in extreme environments. While there is extensive research on the residential applications of panel housing in livable conditions, studies on ventilation in camping spaces for lightweight housing in high-altitude cold regions remain limited.

A high-altitude region is characterized by thin air and low atmospheric pressure, which differs significantly from livable plains. The low-pressure conditions in extreme climates affect airflow under thermal and wind pressure, influencing humidity and the dispersion of pollutants [3]. Additionally, a high-altitude environment features strong solar radiation, large diurnal temperature variations, and high winds, all of which significantly impact the heating and ventilation of lightweight structures like panel housing. The pronounced temperature differences and strong winds create notable thermal and wind pressure coupling, allowing cold air to enter through ventilation openings. Extreme low temperatures, combined with the relatively low thermal resistance of lightweight structures, pose significant challenges to maintaining indoor temperatures. Substantial heat loss results in massive energy consumption. To reduce building energy consumption, maintain indoor environmental stability, and promote the sustainability of lightweight structures in extreme conditions, lightweight housing solutions in high-altitude areas usually try to minimize the impact of external environmental fluctuations in practical application and limit ventilation in camping spaces to reduce cold wind penetration [4].

However, the relatively enclosed space created may lead to a decline in air quality within the camping area [5], resulting in issues such as elevated concentrations of pollutants like CO_2, which pose serious health risks to residents. Excessive ventilation can also lead to increased heating loads and excessively low humidity levels. Analyzing the heating and ventilation characteristics of lightweight structures, employing effective research methods, and exploring viable solutions can help develop efficient and rational ventilation strategies for lightweight buildings in high-altitude cold regions, thereby improving air quality and living conditions within camping spaces. Currently, mechanical ventilation is widely used in civil buildings such as garages and shopping malls to remove pollutants and enhance thermal comfort, which consumes significant electrical resources [6–8]. However, in certain outdoor camping areas of high-altitude cold regions, stable electrical resources are limited. Effectively utilizing natural ventilation in lightweight buildings can significantly reduce energy consumption [9]. Discussing effective passive natural ventilation strategies to leverage these natural conditions is crucial for developing efficient and energy-saving ventilation solutions in lightweight buildings in high-altitude cold areas.

This paper provides a review of ventilation issues in lightweight housing within high-altitude cold regions. It begins by outlining the current state of building ventilation in these areas, detailing the climatic characteristics and key factors affecting the indoor environment. The paper summarizes major ventilation types and the specific thermal environment requirements within buildings in high-altitude cold regions and examines the feasibility of developing underground lightweight structures. Subsequently, given the unique indoor and outdoor environmental characteristics of high-altitude cold regions, the potential passive natural ventilation improvement measures for lightweight housing in these areas are focused on. Research methods related to ventilation experiments, theoretical calculations, and optimization models in building areas are categorized and reviewed. Finally, the paper summarizes the challenges of and developments in improving the indoor environment for lightweight buildings in high-altitude cold regions. This provides an important reference for further research on improving indoor environments and enhancing the sustainability of lightweight buildings in extreme conditions.

2. Current Status of Building Ventilation in High-Altitude Cold Regions

2.1. Climate Characteristics

High-altitude cold regions typically refer to areas with an elevation exceeding 3000 m. In these regions, the unique climatic conditions significantly impact the ecological environment, distribution of flora and fauna, and human activities. The Tibetan Plateau, due to its elevated altitude and climatic conditions, is the most representative high-altitude cold region, with an average elevation exceeding 4000 m. It has climatic characteristics such as strong solar radiation, low average temperature, large daily temperature difference, low air pressure, low oxygen content, low relative humidity, and high wind speed [10].

- High solar radiation intensity and prolonged duration. As solar radiation passes through the atmosphere, some energy is absorbed, while the rest is either directly transmitted or scattered to the ground. The amount of solar energy received at the surface is influenced by elevation and other factors. In high-altitude areas, lower atmospheric density, greater elevation, reduced atmospheric thickness, and decreased water vapor and dust increase sunlight transmittance. Additionally, longer sunshine duration means that buildings in these regions must contend with intense solar radiation [11]. The annual direct solar radiation intensity in certain areas of the Tibetan Plateau is illustrated in Figure 1. Higher altitudes experience longer durations of intense solar radiation.

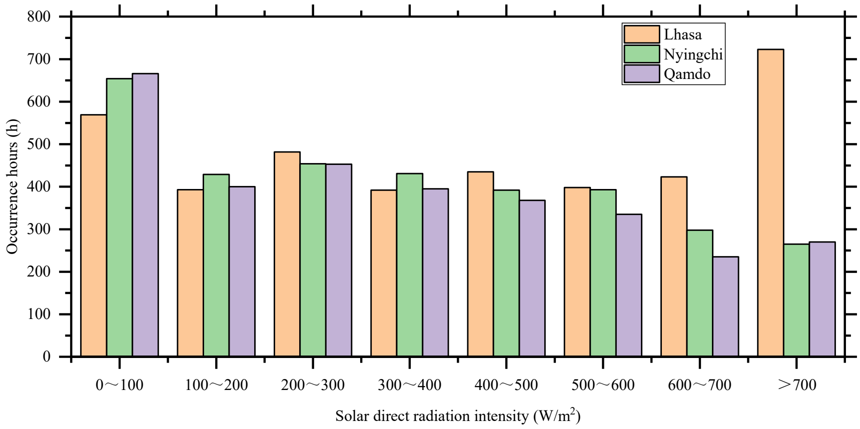


Figure 1. Annual solar radiation conditions in certain areas of the Tibetan Plateau.

- Low temperatures and significant diurnal temperature variation: In high-altitude environments, temperatures decrease with elevation approximately 1 °C for every 150 m gained [10]. The diurnal temperature range is pronounced due to the lack of vegetation. At night, high-altitude areas cool rapidly without an insulating layer. The coldest monthly temperature variations for some regions of the Tibetan Plateau are illustrated in Figure 2, with daily temperature differences exceeding 20 °C. In areas above 4500 m, summer maximum temperatures can drop below 0 °C, while the annual average temperature remains below 0 °C, with extreme lows reaching −35 °C to −45 °C [12,13].

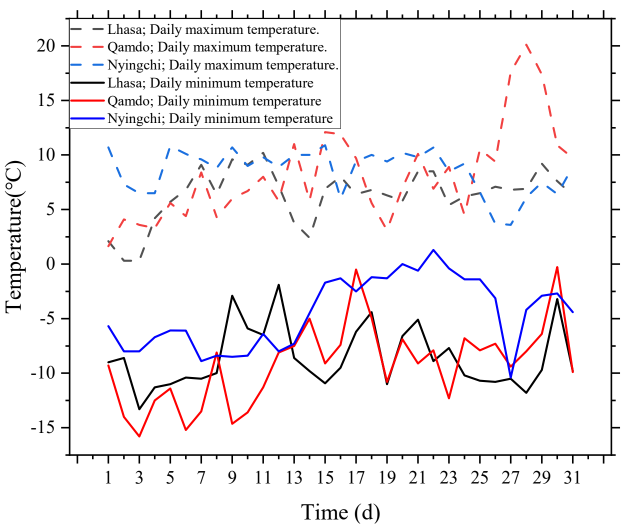


Figure 2. Temperature variation in the coldest month of the year in certain regions of the Tibetan Plateau.

- Low air pressure and oxygen content: A key characteristic of the thermal environment in high-altitude regions is the thin air with lower oxygen levels compared to plains. As elevation increases, the air becomes thinner and atmospheric pressure decreases. Since the proportions of atmospheric components remain constant, the partial pressure of oxygen decreases proportionally. For instance, the average oxygen content in the Tibetan Plateau is only about 60% of that in flatlands [14], which can impact human comfort significantly.
- Dry air and strong winds: Elevation significantly affects humidity, with absolute humidity decreasing as altitude increases. In the Tibetan Plateau, indoor air can be extremely dry during winter, with average relative humidity as low as 15% in the coldest month and minimum values dropping to 3–5% [15]. Additionally, the average wind speed along the Qinghai–Tibet Railway in January exceeds 3 m/s [16]; in the Ngari Region of Tibet, measured wind speed exceeds 10 m/s at 2 m above ground, as shown in Figure 3. The complex terrain, coupled with low pressure, results in unstable and transient airflow, leading to strong winds and turbulence.

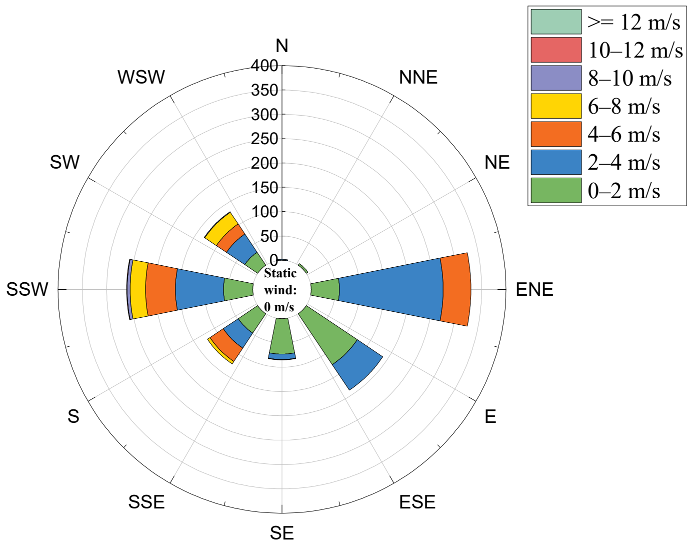


Figure 3. Winter ambient wind speed distribution measurement in the Ngari Region of Tibet (4300 m above sea level).

2.2. Indoor Air Environment Requirements

Based on the characteristics of high-altitude environments, the air quality in camping spaces in cold plateau regions faces numerous challenges, significantly affecting the comfort of occupants. A comfortable air environment is crucial for maintaining health and restoring energy. Currently, researchers have conducted in-depth analyses of the air quality requirements for buildings in high-altitude cold regions.

Current research indicates that temperature, humidity, wind speed, and atmospheric pressure significantly impact thermal comfort in high-altitude cold regions. Wang et al. [17] conducted a survey revealing that human sensitivity to changes in air velocity decreases with lower atmospheric pressure and increases with lower indoor air temperature. Toe and Kubota [18] analyzed data from the ASHRAE RP-884 database on naturally ventilated buildings, finding significant differences in neutral temperatures across various climates, suggesting that applying the same thermal adaptation model to extreme climate regions is inappropriate. Hu et al. [19] recommend that indoor relative humidity not fall below 30%. Addressing the issue of cold and dry winters in the Tibetan Plateau, extensive experimental tests in Lhasa during winter conditions revealed the fundamental distribution patterns of indoor humidity influenced by factors such as humidity sources, humid component states, temperatures, and source locations. Liu [20] found that the lower limit of thermal comfort temperature in the Tibet region is 14.25 °C. Wang [15] conducted field research on the indoor thermal environment of residential buildings in high-altitude areas such as Lhasa, Shigatse, and Chamdo, utilizing computational predictions. The study found that the acceptable indoor temperature range for residents in these regions during winter is between 12.74 °C and 23.15 °C.

Fan et al. [21,22] conducted human thermal comfort experiments using a high-pressure chamber to simulate low-pressure conditions typical of high altitudes. They found that within the simulated minimum pressure of 0.75 atm (74.790 kPa), the factors significantly affecting subjects' average thermal sensation, in order of influence, were temperature, pressure, and wind speed. Lan et al. [23] established a multi-hazard composite environment testing platform and developed an evaluation index system for disaster relief tents' environmental adaptability using a value function method. They proposed an assessment method for tent adaptability in windy and low-temperature, and rain–snow composite environments. Amaripadath et al. [24] suggested spatial assessments during early architectural design and personalized evaluations post-occupancy, recommending a time-integrated multi-zone humid heat comfort index that should incorporate operational temperature and relative humidity in the future. Zheng et al. [25] conducted an in-depth evaluation of thermal comfort in temporary buildings, revealing widespread dissatisfaction among users regarding the thermal environment. There is a noted discrepancy between the PMV-PPD model predictions and field study results for the thermal comfort of temporary structures.

It is evident that the low atmospheric pressure in high-altitude areas results in reduced air density, significantly diminishing the intensity of both natural and forced convection heat transfer. This alteration affects the heat-exchange characteristics between the human body and the environment. Consequently, the ventilation methods and the determination of fresh air volume for buildings in cold, high-altitude regions may change. Additionally, the decreased oxygen concentration in low-pressure environments significantly impacts human metabolic rates, indicating that the air-quality demands for camping spaces in such conditions are unique [26].

Moreover, high levels of air pollutants in indoor spaces can severely compromise the quality of life and health of occupants. Ventilation within buildings must ensure that oxygen levels are maintained within an appropriate range while reducing indoor CO_2 and other pollutants. Zhao et al. [14] studied the spatial distribution characteristics of indoor oxygen concentration under actual natural ventilation conditions and analyzed various ventilation methods at different oxygen levels. Hang et al. [27] utilized computational fluid dynamics (CFD) simulations to explore the effects of indoor–outdoor temperature differences and elevated bridge configurations on the diffusion of gases and particulates in an idealized street canyon. Their results indicate that increasing the temperature gradient and optimizing elevated bridge layouts can enhance pollutant dispersion and reduce concentrations. Panagopoulos [28] adopted CFD methods, providing predictions for airflow, volatile organic compounds, and formaldehyde distribution within apartments.

In summary, the air-quality demands for camping spaces in high-altitude cold environments significantly differ from those for residential buildings in plains. Current research primarily focuses on the distribution and characteristics of indoor air quality in civilian buildings, with limited studies on the air environment of lightweight structures under extreme conditions. There is also a lack of suitable and systematic air-quality assessment methods for ventilation in camping spaces in these regions. Developing specific evaluation methods for air quality in high-altitude cold camping spaces will be crucial for establishing scientifically sound ventilation strategies.

2.3. Factors Influencing Indoor Environment

Users in lightweight panel houses can enhance their comfort by adjusting physiological activities and changing clothing thermal resistance, demonstrating some degree of adaptability. However, this improvement is limited in extreme conditions, necessitating appropriate measures to enhance the thermal environment within lightweight structures [29]. Winter indoor thermal conditions in high-altitude buildings are often inadequate, with cold radiative effects negatively impacting thermal comfort. Therefore, it is essential to investigate improvement measures and their impacts, while modern building practices primarily focus on optimizing the heat insulation and airtightness of enclosures.

As shown in Table 1 regarding related studies on factors affecting the indoor environment, key factors influencing the creation of a healthy indoor air environment and effective building layout from an architectural perspective include the materials used for building envelope structures, structural forms, shading methods, heating systems, the orientation of doors and windows, and so on. Architectural design primarily impacts radiant heat, heat transfer, and space utilization [30]; adjustments in shading methods significantly affect radiant heat gain indoors [31]; and the arrangement of windows and doors [32], as well as heating methods [33,34], also significantly influence the indoor environment.

In addition, many researchers have found that selecting materials with high thermal mass and resistance [35,36] or incorporating phase-change materials and reflective materials into the building envelope [37–39] can effectively enhance the internal environment. Coatings with varying thermal performance are particularly suitable for rapidly constructed temporary buildings. Phase-change materials with excellent energy storage properties are also widely used in lightweight buildings. They can effectively accumulate environmental cold or heat, release it when needed, and reduce the spatio-temporal mismatch between heat storage and heat release [40]. It is especially suitable for use in high-altitude cold regions where temperature and radiation fluctuate violently throughout the day and radiation fluctuations are relatively cold at night. Phase-change materials can be used to accumulate heat energy during the day and release it at night, which has great application potential.

Table 1. Factors affecting the indoor thermal environment in buildings.

Author	Architectural Typology	Influencing Factors	Main Conclusions
Ullal et al. [30]	Tent	Building structure	This study compared the thermal performance of two types of standard humanitarian tents: a standard family tent (SFT) and a geodesic family tent (GFT). The GFT outperformed the SFT in terms of radiative heat gain, conductive heat loss, air tightness, structural stability, and space utilization.
Jia et al. [31]	Plateau architecture	Shading methods	Under identical heating performance conditions, shading strategies can significantly enhance the thermal environment's uniformity and reduce heating energy consumption, with fully shaded buildings realizing up to 26.27% in equivalent energy savings.
Cheng et al. [38]	Residential and tent	Building materials	Studies show that the combination of phase-change material (PCM) and cool paint (CP) on the south wall and CP on the roof is the most effective way of integrating PCM and CP into building envelopes. This roof application of PCM and CP can extend the thermal comfort zone by over 8.05 h.
Zhang et al. [39]	Tent	Building materials	When integrated with reflective materials, the peak indoor air temperature in tents can be reduced by over 7.7 °C, while the internal surface radiant temperature can decrease by up to 4.8 °C during the day. This indicates that reflective materials can enhance the indoor thermal environment of tents.
Raushan Kumar et al. [37]	Tent	Building materials	The study discusses the use of various reflective materials to reduce the internal air temperature of canopies. Results indicate that the use of phenolic foam as a reflective material yields a minimum temperature change of 4.8 °C, achieving a temperature change rate of 18.74% compared to other reflective materials.

Table 1. *Cont.*

Author	Architectural Typology	Influencing Factors	Main Conclusions
Shen et al. [35]	Prefabricated houses	Building materials	A comparison of the average indoor air temperatures between prefabricated classrooms and brick–concrete classrooms reveals that the low thermal inertia and poor insulation of the light steel enclosure in the prefabricated buildings result in an indoor thermal environment that does not meet students' thermal comfort requirements.
Wang et al. [32]	Prefabricated houses	Window arrangement	The analysis of heat gain distribution in the building shows that adding a thin, movable fabric layer with a reflectivity of 0.9 to the walls, roof, and external shutters significantly reduces the percentage of unacceptable periods.
Li and Chen [34]	Residential building	Heating methods	Field tests revealed that the heating status of neighboring rooms directly affects the surface temperature of interior walls and total heat consumption. Wall-mounted radiant heating provides the highest heat output and heat flux density when adjacent rooms are unheated, indicating its superior effectiveness in enhancing the indoor thermal environment.
Purev et al. [33]	Yurt	Heating methods	The use of direct radiation from stoves in yurts results in temperatures exceeding the lower limit of the comfort range over 70% of the time. This indicates that the current design of yurts and the use of fuel stoves are effective in achieving a comfortable indoor environment during winter, even with lightweight enclosures that have poor insulation performance.

The factors mentioned above primarily enhance the indoor living environment by modifying the heat transfer through the building envelope. Moreover, differences in airtightness can lead to varying degrees of cold air infiltration, significantly affecting the indoor environment. Air infiltration in buildings is closely linked to indoor thermal conditions, air quality, and energy consumption, with significant impacts from air movement through the building envelope on the indoor environment and energy use. However, the level of airtightness largely depends on construction quality, particularly the sealing at window/wall joints, as well as the quality of brick or block walls and roof/wall interfaces. This makes it challenging to accurately assess cold air infiltration. The calculation of cold air infiltration may vary significantly across different building configurations. Lu et al. [41] found that the room heat load calculated using the percentage method exceeded that calculated using the ventilation rate method. The infiltration heat loss calculated by the aperture method closely aligns with the national standard area heat index. It is advisable to use either the ventilation rate method or the infiltration heat loss calculation when assessing room heat loads for more accurate results. Jokisalo et al. [42] discussed the evaluation of a multi-zone infiltration model for existing two-story detached houses, which integrates energy simulation and infiltration modeling, allowing for realistic predictions of pressure conditions in detached houses under cold climates, suitable for detailed infiltration and energy analysis.

Wang et al. [43] utilized a multi-zone network airflow model to simulate the air permeability of 111 rural housing samples across 13 provinces in China. The results indicated that rural homes have a higher average air infiltration rate than urban residences, generally following a log-normal distribution across different climatic zones. Ji et al. [44] highlighted the need to consider air infiltration when designing HVAC systems for public buildings and tested the airtightness of three typical public building zones in China, finding that the air frequency in all three areas also follows a log-normal distribution. Hu et al. [45]

conducted measurements and simulations based on a typical office building in Changsha, China. The findings revealed that the operation of the air-conditioning system significantly influenced air infiltration, with each unit change in setpoint air temperature resulting in an average variation of one-third or more in the air infiltration rate. The cold wind penetration performance of lightweight buildings is undoubtedly of great significance for improving the internal environment of lightweight buildings in plateau and alpine areas.

However, since cold wind penetration is closely related to structure and construction technology, the current cold air penetration model cannot be directly applied to the estimation of air penetration in lightweight buildings. It is necessary to carry out relevant research specifically on the cold air penetration characteristics of lightweight buildings in subsequent research. Implementing measures to reduce environmental air infiltration can lower energy consumption for heating and cooling supply air; however, the reduced influx of fresh air may lead to a significant increase in indoor carbon dioxide levels or other pollutants [46], negatively impacting human health [47]. It is equally important to create appropriate ventilation strategies to prevent indoor pollutant levels from exceeding standards.

2.4. Underground Lightweight Building

Similar to optimizing the heat transfer characteristics of building structures and improving their airtightness to reduce cold air penetration, there have been some new developments in lightweight buildings for field camping in high-altitude cold regions; users place lightweight buildings shallowly underground to improve their internal environmental quality, as shown in Figure 4. The outermost periphery of this lightweight building form is earth walls, the interior is an active area built with steel tile maintenance structures, and the upper part is a shallow soil covering. The active area is equipped with container prefabricated panel houses.

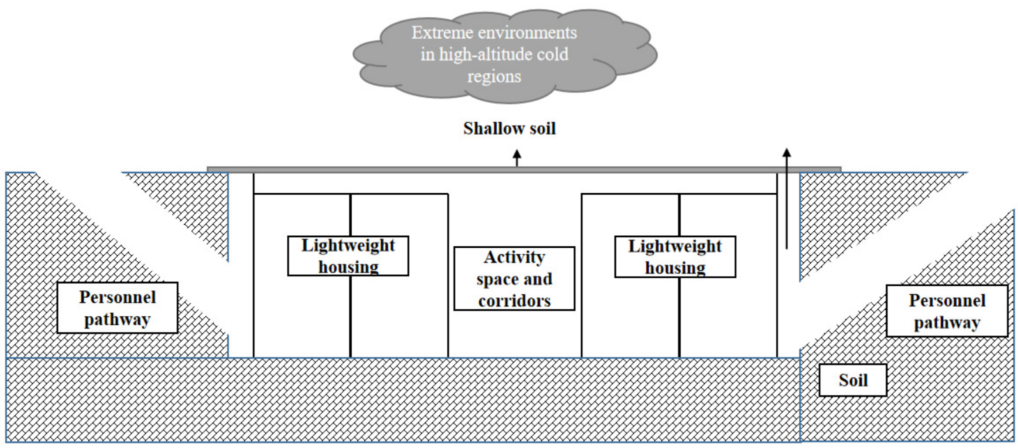


Figure 4. Schematic diagram of the layout of underground lightweight prefabricated houses in cold plateau regions.

Field investigations found that this practice avoids direct cold air blowing from the external environment and can reduce cold air penetration to a certain extent. At the same time, the mound structure around the building has good thermal inertia. As illustrated in Figure 5, without additional heating or ventilation, the indoor temperature fluctuations of a lightweight underground building in the Ngari Region of Tibet are markedly smaller than those of the external environment. This effectively mitigates the risk of indoor extreme temperatures caused by the low thermal inertia of the lightweight structure; the impact of violent fluctuations, such as external environmental temperature radiation, on the internal environment is reduced and heat loss is minimized, so heating energy consumption is decreased.

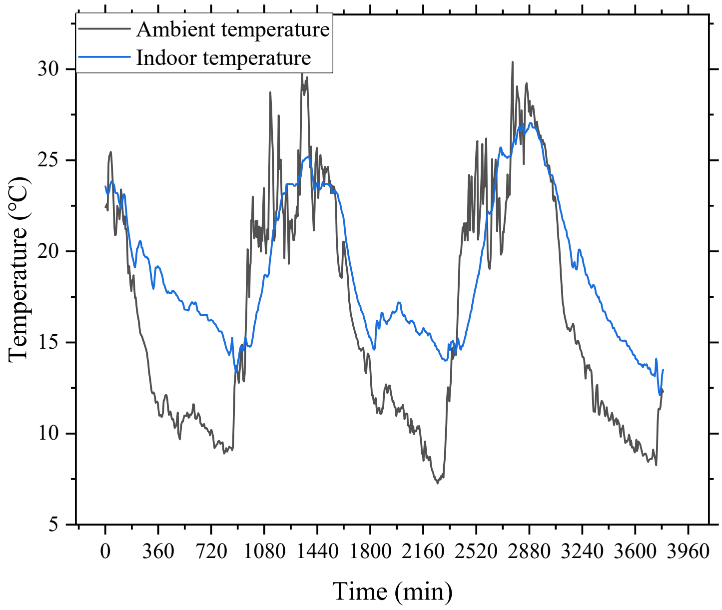


Figure 5. Comparison of indoor and outdoor temperatures in a lightweight underground building in the Ngari region of Tibet during summer.

The review of relevant research on underground building structures reveals that as depth increases, underground temperatures exhibit reduced fluctuations [48], and the surrounding geotechnical medium is less affected by outdoor weather conditions, offering excellent thermal stability and energy-saving potential [49]. Additionally, the surrounding atmosphere and soil can naturally regulate the traditional underground environment to provide the necessary thermal conditions and ventilation for basic living or storage needs [50].

Utilizing natural caves and other underground spaces offers benefits such as protection from cold, heat, rain, and enemy threats [51]. Placing housing underground not only enhances security, concealment, thermal stability, and energy efficiency but also meets the strategic requirements of high-security urban areas, effectively serving as civil defense spaces. Dronkelaar et al. [52] conducted a year-round energy consumption analysis of underground buildings, revealing that 11% of these structures approach zero energy consumption, with annual energy needs below 10 kWh/m^2. S. Choi and Krarti [53] applied interval temperature curve estimation methods to heat transfer calculations in building enclosures, identifying optimal insulation configurations for underground buildings. Tinti et al. [54] conducted tracking tests on temperature distributions in an underground wine cellar, demonstrating that its thermal mass significantly reduces air-conditioning energy demands. Yang Bo employed energy simulation software to analyze cooling, heating, fan, and equipment energy consumption for both underground and surface buildings, finding that the stable soil temperatures and thermal mass of underground structures result in significantly lower total energy consumption.

However, the development of underground spaces faces some significant challenges. Occupants in underground buildings are confined indoors. Due to the unique geographic location of these structures, they primarily rely on ventilation and air-conditioning systems to improve indoor air quality. This reliance means that occupants cannot easily ventilate rooms by opening doors and windows, leading to the accumulation of carbon dioxide and other pollutants and relatively poor air quality [55]. As depicted in Figure 6, when a lightweight house accommodates about seven people with limited door and window openings during rest periods, although outdoor carbon dioxide levels are around 400 ppm, the indoor carbon dioxide concentration peaks exceed 2000 ppm, impacting residents' health.

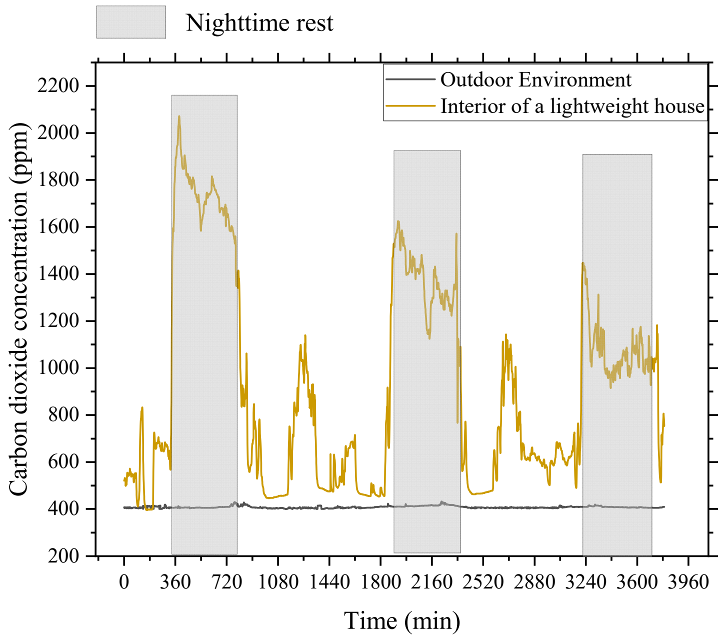


Figure 6. Comparison of indoor and outdoor carbon dioxide levels in a lightweight underground building in the Ngari region of Tibet during summer.

In summary, placing buildings underground effectively mitigates temperature fluctuations caused by external environmental changes. The favorable thermal mass characteristics of the surrounding soil reduce reliance on air conditioning and auxiliary heating systems, relieving the issues of temperature extremes and instability often seen in lightweight structures like panel houses, which have low thermal resistance and poor thermal inertia. However, underground buildings could lead to higher concentrations of air pollutants and relatively poor air quality. The investigation in Section 2.1 reveals that high-altitude cold regions are characterized by large temperature variations, strong radiation, and high wind speeds. These conditions are favorable for developing wind and thermal pressure-driven passive natural ventilation. Given these characteristics, developing scientific passive natural ventilation strategies for maintaining a suitable air environment in lightweight building spaces warrants further attention and research.

3. Ventilation Improvement Measures

Building ventilation systems are categorized into natural and mechanical ventilation. Mechanical ventilation utilizes fans to impart energy to the air, generating pressure to overcome resistance, directing airflow along a predetermined path, and expelling contaminated air. Numerous studies have analyzed forced ventilation in various types of underground structures, such as parking garages, underground stations, mines, and retail spaces [56].

Luo et al. [57] investigated the impact of the layout of displacement ventilation air inlets/outlets and site temperature on the performance of localized environmental control systems. Their results indicated that displacement ventilation systems can achieve effective localized environmental control in large exhibition areas, ensuring uniformity and environmental stability. Wang et al. [58] noted that the greatest energy consumption in underground buildings comes from ventilation systems. By analyzing the indoor radon migration process, they proposed an intermittent ventilation strategy to reduce radon concentration in underground spaces. Their numerical model compared changes in radon levels under different ventilation strategies, revealing that during intermittent ventilation, reducing the fresh-air ratio significantly enhances heat recovery from return air, thereby lowering the power requirements of air-conditioning units. While mechanical ventilation allows precise control over airflow and rapid adjustment of indoor thermal and humidity conditions, it consumes substantial electrical resources and incurs high maintenance costs.

In remote, cold plateau areas with limited stable power resources and scarce manpower and equipment support, optimizing ventilation strategies should prioritize the effective use of natural ventilation in campsite spaces to reduce energy consumption and enhance operational capability and maintenance efficiency.

Natural ventilation systems are among the most effective passive cooling strategies for reducing energy consumption and greenhouse gas emissions. Natural ventilation relies on wind speed and the temperature difference between the building and its environment as natural driving forces, with its effectiveness depending on climate, building design, and human behavior. There are two fundamental methods for designing natural ventilation systems: wind-driven ventilation and thermal-driven ventilation. In wind-driven ventilation, airflow is driven by pressure differences [59]. Typically, positive pressure is established on the windward side (inlet) and negative pressure on the leeward side (outlet) [60]. Air enters through openings on the windward side and is expelled from openings on the leeward side. Cross-ventilation can occur when air enters from one side of a space and exits from the other.

When wind speed and direction are known, maintaining clear openings between the windward (inlet) and leeward (outlet) sides is recommended for wind-driven ventilation. Extensive research has been conducted on the performance [61], design optimization [61], and flow characteristics [62] of wind-driven ventilation systems, as well as the positioning of intake and exhaust openings [63,64]. Thermal-driven ventilation, driven by the temperature difference between indoor and outdoor environments, creates a pressure difference due to variations in air density, facilitating airflow within the building. When indoor temperatures exceed outdoor temperatures, warm air rises and exits through upper windows, replaced by cooler air from below. Thermal-driven ventilation is a crucial element of low-energy buildings, requiring a significant temperature differential between the interior and exterior. Current research on thermal-driven ventilation focuses on natural driving forces [65], the impact of ventilation methods on flow characteristics [66], and building applications [67].

This paper primarily focuses on ventilation improvement measures in cold plateau regions. As analyzed in Section 2.1, these areas exhibit strong radiation and significant wind speeds, along with substantial temperature fluctuations that create considerable indoor–outdoor temperature differentials. These conditions are conducive to both thermal-driven and wind-driven ventilation. Additionally, challenges such as limited electrical energy resources further emphasize the need for feasible passive ventilation improvement strategies.

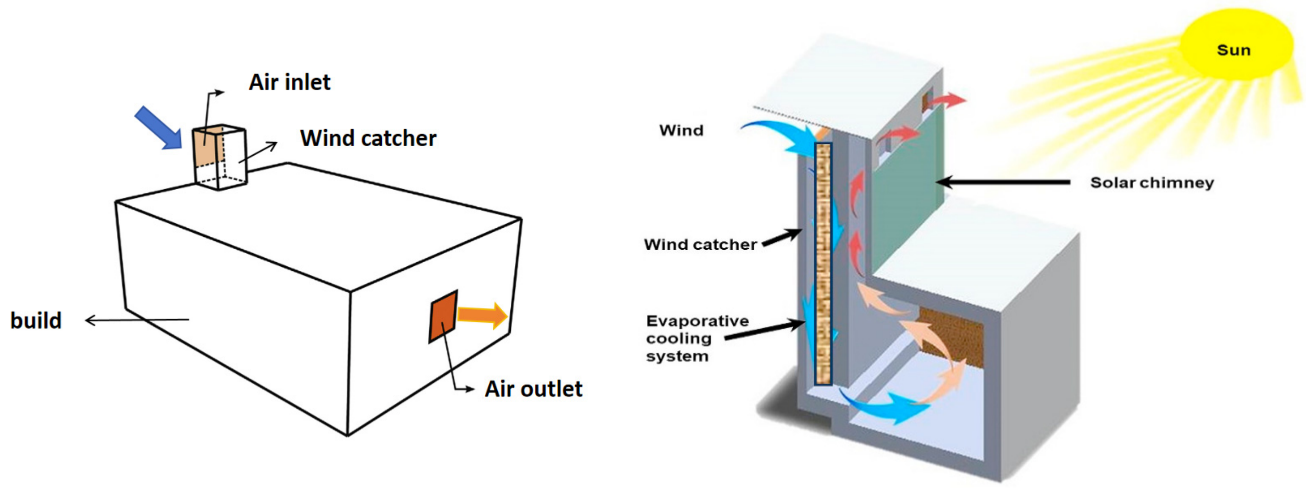
3.1. Ventilation Shafts

Ventilation shafts are common components of natural ventilation systems, serving as either supply or exhaust shafts in underground buildings [68]. Takeuchi et al. [69] investigated the natural ventilation performance of underground road tunnels using six vertical shafts, developing a model to predict smoke temperature based on multiple vertical shafts. Fan et al. [70] conducted a numerical study on the impact of shaft arrangement on natural ventilation performance during fires, indicating that better performance occurs with low longitudinal wind speeds and a higher number of shafts. Wang et al. [71] examined the effects of shaft geometry and layout on maximum smoke temperature beneath tunnel ceilings during fires, optimizing design parameters such as shaft quantity, spacing, height, and width for improved exhaust efficiency. Chu et al. [9] utilized wind tunnel experiments, large eddy simulation models, and time scale analysis to study natural ventilation in underground garages, finding that openings perpendicular to the wind direction enhance ventilation, while angled shafts effectively remove pollutants from garage corners. Kallianiotis et al. [72] simulated various fire scenarios using computational fluid dynamics, demonstrating that passive ventilation shafts can provide effective smoke control without additional control systems. Wang et al. [73] applied a complementary ventilation system to a segmented longitudinal ventilation model, analyzing design factors such as shaft positioning, airflow design, and ventilation ratios relative to pollutant concentrations.

Overall, vertical ventilation shafts are important elements to consider in the design of natural ventilation systems, particularly in underground buildings. However, they are often insufficient on their own and typically need to be integrated with other facilities, such as wind catchers, to effectively construct a natural ventilation system.

3.2. Wind Catchers

Wind catchers are key elements of passive ventilation systems in buildings, primarily designed to enhance indoor air quality by harnessing the natural wind effect created by wind pressure [74]. Their design aims to capture wind energy, allowing fresh air to enter through openings; when these openings are positioned opposite the wind direction, surrounding air is drawn in. The use for enhancing building ventilation to improve indoor air quality is shown in Figure 7a. This technology has gained widespread application and been the focus of more research in recent decades due to its sustainability, environmental benefits, and energy efficiency.



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

Figure 7. Schematic diagram of building ventilation assisted by a unilateral wind catcher [64]: (**a**) single-sided wind catcher; (**b**) wind catcher combined with solar chimney [75].

Research on wind catchers encompasses various types and configurations, including single-sided, double-sided, four-sided, six-sided, and eight-sided designs, with openings that can be unidirectional or omnidirectional [76]. The design of these openings is critical for wind catcher efficacy, as it directly affects airflow efficiency and direction. For example, Esfeh et al. [77] studied the airflow characteristics of single-sided wind catchers with different roof designs using smoke visualization techniques and evaluated the influence of wind speed and direction on wind catcher performance through analytical methods and wind tunnel experiments. Montazeri [78] tested a scaled-down model of a single-sided wind catcher in a wind tunnel and identified the surrounding flow field using smoke visualization. Additionally, Varela-Boydo [79] et al. examined various design configurations by altering the opening area of the wind tower and employing CFD numerical simulations, discovering that increasing the size of the opening area enhances the volumetric flow entering the wind tower, positively impacting performance. These studies indicate that adjusting the size and design of wind catchers can effectively regulate airflow into buildings, suggesting their potential as an effective passive ventilation strategy for lightweight buildings in high-altitude areas with significant natural wind speeds.

Recent studies have further expanded the application of wind catchers. Zaki et al. [80] analyzed the ventilation performance of double-sided wind catchers under varying wind speeds and directions using wind tunnel experiments and CFD simulations, finding that wind catchers significantly improve natural ventilation efficiency, particularly when the wind is directed towards them. Montazeri et al. [64] evaluated the impact of rooftop wind catchers on cross-ventilation in isolated buildings, indicating that using outlet openings close to the wind catcher does not increase airflow but can degrade indoor air quality. The study recommends combining single-sided wind catchers with windows to enhance ventilation efficiency and indoor air quality. Moreover, due to their simple structure and easy installation, wind catchers can be effectively integrated with other passive ventilation systems. As shown in Figure 7b, the combination of wind catchers, evaporative condensers, and solar chimneys in buildings achieves enhanced ventilation performance. Saifi et al. [75] demonstrated through experiments and numerical simulations that the passive system can effectively reduce indoor temperatures by approximately 3–7 °C in Algeria's semi-arid climate, enhancing indoor comfort and ventilation conditions.

In summary, wind catchers serve as significant passive ventilation elements that enhance the natural ventilation performance of buildings. Through ongoing research, design optimization, and synergy with other systems, the application of wind catchers can be further improved to accommodate various climatic conditions and building requirements. Future studies should investigate the performance of wind catchers under different climates and explore design optimizations to enhance their efficiency. Additionally, incorporating modern technologies such as CFD simulations will enable more accurate predictions and optimizations of wind catcher performance, providing a scientific basis for design. As the pursuit of sustainable architecture and green energy continues, research and application of wind catchers will remain a dynamic field.

3.3. Earth–Air Heat Exchangers

In addition to the application of passive natural ventilation components such as shafts and windcatchers, earth–air heat exchangers (EAHEs) demonstrate significant potential as an effective passive cooling and heating technology in lightweight buildings in high-altitude cold regions [81]. EAHE systems utilize the relatively stable underground soil temperature to pre-cool or pre-heat the air entering the building, thereby reducing energy consumption and enhancing indoor thermal comfort [82]. As shown in Figure 8, the EAHE system consists of underground pipes, which can be arranged horizontally or vertically. As air passes through these pipes, heat exchange occurs with the surrounding soil, facilitating temperature regulation [83,84].

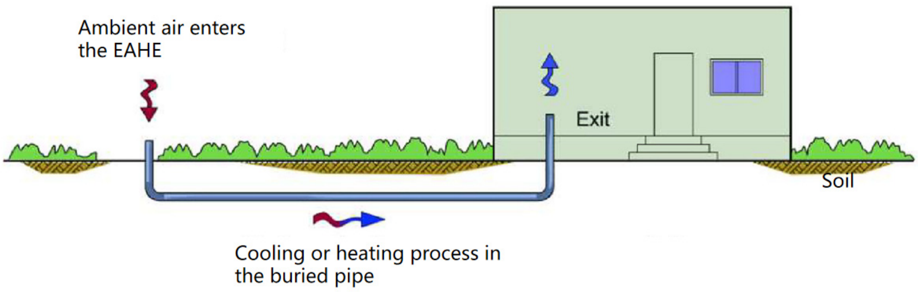


Figure 8. Schematic diagram of building ventilation assisted by an EAHE [85].

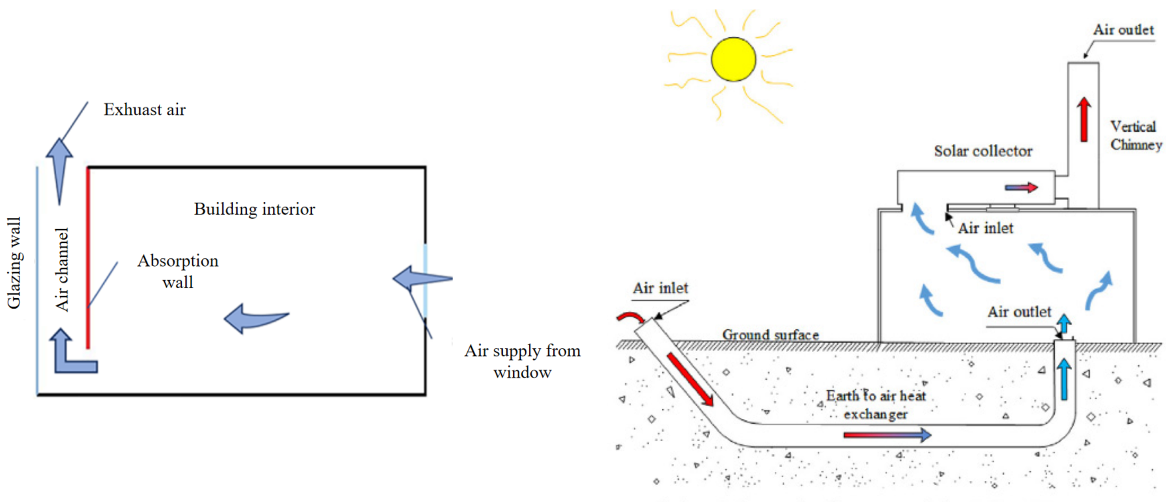
The study by Al-Ajmi et al. provided a theoretical model for EAHEs in desert climates, demonstrating the cooling potential in hot, arid conditions [84]. In high-altitude cold regions, EAHE performance is influenced by various factors, including the thermal properties of the soil, groundwater levels, and seasonal temperature variations. Gao et al. [85] further explored the impact of backfill materials on EAHE thermal performance, finding that the thermal conductivity of backfill significantly affects EAHE efficacy, though its effectiveness diminishes beyond a certain depth. Additionally, Zhong et al. [86] conducted long-term static air temperature and humidity tests, along with summer/winter ventilation experiments, on underground pipe frameworks in Guangzhou, revealing that air passing through a 200 m pipe framework could achieve maximum temperature reductions of 7.5 °C in summer and increases of 11.2 °C in winter, highlighting EAHE's significant effectiveness in improving ventilation. EAHE systems are often integrated with other passive or active building systems to enhance overall energy efficiency and thermal comfort.

Jakhar et al. [87] investigated the integration of EAHE with solar air heating ducts, finding that this combined system significantly enhances winter heating potential and improves the coefficient of performance. This integration not only boosts thermal comfort in buildings but also further enhances ventilation effectiveness. As an environmentally friendly building energy technology, EAHEs have a minimal impact on the environment, particularly in reducing fossil fuel consumption and greenhouse gas emissions. Ahmed's research assessed the performance of EAHEs in low-energy buildings [88], revealing that they can lower indoor temperatures by approximately 2 °C, resulting in energy savings of 866.54 kWh annually. This indicates that EAHEs not only improve ventilation but also contribute to substantial energy savings.

In summary, EAHEs hold significant potential for improving indoor heating and ventilation and reducing energy consumption in high-altitude cold regions. However, challenges remain, including issues related to pipeline frost heave and the long-term stability of soil heat-exchange efficiency. Moreover, constructing air channels with sufficient heat-exchange capacity in permafrost regions requires adequate burial depth, sufficient pipe length, and large underground space, and fans may be needed to provide air pressure, leading to higher initial costs [89–91]. Future research can focus on developing new EAHE materials suitable for extreme climate conditions, optimizing design and construction methods, and enhancing the intelligent control of EAHE systems. Additionally, comparative studies of EAHE performance across different climate regions and their integration with other renewable energy technologies are essential directions for future research.

3.4. Solar Chimneys

Solar chimneys (SCs) are a passive cooling and ventilation technology that harness solar energy to heat air, generating a thermodynamic pressure difference that drives natural ventilation, thereby effectively enhancing indoor thermal comfort and air quality. Constructing solar chimneys primarily requires the use of transparent glass, heat-absorbing materials, insulation, and steel frameworks, demanding a specific installation area. Although the initial cost is higher compared to wind catchers, their simple structure and ease of maintenance offer significant long-term energy-saving and carbon-reduction benefits [92]. In high-altitude regions with abundant solar resources and strong daytime solar radiation, SCs demonstrate considerable potential for development and application. The principle of solar chimney application in building ventilation is illustrated in Figure 9a.



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

Figure 9. Schematic diagram of solar chimney-assisted building ventilation: (**a**) solar chimney [93]; (**b**) solar chimney combined with an EAHE [94].

Zhang et al. [93] focused on the ventilation performance of solar chimneys in multi-story buildings. They found that optimizing geometric parameters, such as widening the air channel gap and increasing the chimney height, significantly enhances ventilation capacity in multi-story structures, thereby reducing reliance on mechanical ventilation systems and promoting energy savings. In harsh climatic conditions, natural ventilation using only solar chimneys is inadequate, prompting researchers to further analyze enhanced solar ventilation systems to improve cooling and heating efficiency in residential and non-residential spaces [95]. Elghamry et al. [96,97] presented experimental studies on the combination of solar chimneys and geothermal air pipe heat exchangers for heating and ventilation in buildings. With photovoltaic panels installed at a 45-degree angle within the chimney, the system could raise indoor temperatures by 6.4 °C, achieving an air exchange rate of 46 times per day, greatly improving indoor air quality. Bai et al. [94] demonstrated through experimental research that a system combining solar chimneys with earth-to-air heat exchangers provides effective natural ventilation in both summer and winter, as shown in Figure 9b. During summer, the airflow rate driven by the system could reach up to 252 m^3/h during the day, maintaining a rate of 50–70 m^3/h even at night or under low solar radiation, significantly enhancing indoor thermal comfort.

Li et al. [98] demonstrated that a system integrating solar chimneys and ground heat exchangers could achieve a maximum cooling capacity of 1398.0 W on typical summer days, significantly lowering indoor temperatures and enhancing thermal comfort. Wen et al. [99] proposed a system combining solar chimneys, photovoltaic–thermal technology, and ground-source heat pumps for hybrid ventilation in underground environments. This system effectively integrates energy from the atmosphere, shallow and deep soil, and solar and waste heat, providing stable thermal pressure ventilation for underground spaces. Moreover, solar chimneys alone can provide ventilation during the daytime but lose effectiveness at night, so researchers have proposed integrating phase-change materials with solar chimneys to store heat during the day and release it at night, ensuring more consistent passive ventilation for buildings [100,101]. However, the implementation of this technology is constrained by factors such as the cost of phase-change materials, their phase transition temperature range, and stability.

In conclusion, solar chimneys, as a passive building technology, hold significant application potential in lightweight structures in high-altitude cold regions. They effectively enhance natural ventilation and indoor environments while markedly reducing energy consumption, thereby promoting sustainable development in construction. Future research should further investigate the integration of solar chimneys with other renewable energy technologies and optimize their performance across various climatic conditions for broader applicability. The combination of these ventilation strategies facilitates more stable natural ventilation, enhances regional ventilation, and improves indoor air quality in lightweight buildings.

4. Research Methods for Ventilation in Building Areas

The formation of indoor air quality involves complex physical processes. Different ventilation components and building structures exhibit varying resistance to fluid flow and heat transfer, influenced by factors such as building layout and material properties. Scientific and systematic research approaches are needed to thoroughly analyze the indoor air environment and ventilation strategies across various building structures.

4.1. Experimental Research

Experimental research provides the most direct understanding of ventilation conditions in building areas, typically divided into full-scale and scaled model experiments. Rey-Hernández et al. [102] analyzed the performance of a mixed ventilation system incorporating ground-to-air heat exchangers, free cooling, and evaporative cooling air-handling units. The system operated 70% of the time using the heat exchangers, successfully achieving the specified parameters. Furthermore, analyses based on measured monitoring data indicated that optimal control and operation of the mixed ventilation system allowed for high energy recovery values with minimal additional electricity consumption, significantly reducing carbon emissions and operational costs. Nasrollahi et al. [103] investigated the use of passive strategies in naturally ventilated high-rise office buildings in hot, dry climates. Through field studies and numerical simulations, the research demonstrated that cooling energy demands in hot climates are substantial, and natural ventilation systems can effectively provide cooling and enhance thermal comfort by increasing volumetric flow rates when openings are strategically positioned.

Additionally, Liu [104] conducted detailed experiments on pollutant dispersion and airflow characteristics in multi-room buildings under cross-ventilation conditions, using a scaled multi-room setup to simulate cross-ventilation environments. The study indicated that the location of the pollution source and ventilation paths significantly influenced pollutant dispersion and airflow characteristics, providing quantitative differences. Shirzadi et al. [105] utilized a smoke generator for flow visualization to investigate the flow patterns in and around cross-ventilated buildings, employing tracer gas methods to measure airflow rates through openings. Their findings revealed significant differences in cross-ventilation mechanisms between medium- and high-density building arrangements. Meng et al. [106] established a scaled mixed-ventilation experimental model with heat sources, exploring four mixed-ventilation patterns. Their research indicated that excessively high mechanical ventilation rates could lead to increased energy consumption and potential airflow short-circuiting, resulting in poor thermal environments.

Experimental research on building ventilation methods yields the most accurate and reliable ventilation effects for various scenarios, allowing for preliminary analysis of ventilation conditions. However, both full-scale and scaled experiments involve high costs and extended durations, along with challenges such as numerous uncontrolled environmental parameters, limiting the availability of extensive data for in-depth comparative analysis and optimization. Therefore, computational modeling for simulation studies and predictive optimization remain the primary research approaches currently employed.

4.2. Ventilation Calculation Methods

Current methods for calculating building ventilation primarily include analytical methods, empirical models, network calculation models, and CFD numerical models. These approaches are widely employed in various ventilation scenarios; however, each method exhibits distinct computational characteristics, application scopes, and limitations [107].

4.2.1. Analytical Methods and Empirical Models

In the field of building ventilation, analytical methods and empirical models are grounded in the fundamental theories of natural ventilation, derived from the analysis and simplification of fluid dynamics and heat transfer equations. These methods are particularly crucial in the early stages of ventilation design, as they allow for rapid assessments of ventilation performance. In earlier studies, Baines and Turner [108] first examined the impact of continuous convection from small buoyant sources within a limited area on environmental properties. They obtained effective asymptotic solutions for plume behavior from point and line sources, as well as for periodically released heat flow over extended time periods. Subsequently, Manins et al. [109] expanded the existing models to more accurately describe the behavior of turbulent buoyant convection generated by buoyant sources in enclosed spaces, deriving new analytical solutions under steady-state conditions for single sources. Li et al. [110] proposed a novel pressure-based formula for large-opening buildings, effectively predicting natural ventilation in both single- and multi-zone structures. Additionally, Li et al. [111] developed an analytical model to predict the natural ventilation rate for a single zone with two openings. By incorporating parameters such as thermal buoyancy, wind pressure, and heat loss, this model enables designers to forecast and optimize ventilation performance under varying environmental conditions.

Fitzgerald and Woods [112] focused on the effects of chimneys on flow patterns and stratification in natural ventilation systems with two openings. They established analytical solutions for room temperature and heat flux, enhancing the understanding of natural ventilation dynamics in specific geometries, such as multi-story structures. Mazumdar and Chen [113] developed a model using the superposition principle and separation of variables to predict pollutant concentration distribution in aircraft cabins. Their model incorporates diffusion and convective transport of pollutants, as well as the effectiveness of cabin air recirculation and high-efficiency particulate air filters. Guo et al. [114] concentrated on heat transfer in underground transportation tunnels, simplifying the heat transfer process to a one-dimensional model. They derived temperature distribution models along the tunnel and calculation models for the convective heat transfer coefficient based on energy conservation and boundary layer theory.

In the realm of empirical models, Wang et al. [115] established a novel empirical model to predict the average and pulsating airflow rates induced by single-sided wind-driven natural ventilation and vortex penetration in buildings. Hayden et al. [116] established and validated an empirical model that describes the relationship between flow rate, pressure differential, and effective leakage area in enclosed spaces. Niehaus et al. [117] proposed a semi-empirical model to predict the mass transfer rate of moisture in humid air under mixed convection in a new experimental setup, along with the overall heat transfer. Tariku et al. [118] conducted long-term monitoring of wind speed, relative humidity, and temperature within three wall cavity configurations, as well as the humidity and temperature of plywood and wood-framed studs. Based on the analysis of these monitoring data, they established an empirical model of cavity ventilation that relates wind pressure to the temperature differences between outdoor spaces and cavity spaces under combined wind and solar effects.

The models and methods presented in these papers simplify and analyze complex physical phenomena, enabling the prediction of ventilation performance under various building and environmental conditions. However, these models are generally applicable only to specific or similar geometric structures and rely on simplified geometric and thermal–fluid boundary conditions, making direct application in more complex engineering situations challenging. Consequently, analytical or empirical models are primarily suited for rapid calculations of typical structures or complex ones supported by similar data, while applying them to ventilation airflow in unique complex building structures is difficult.

4.2.2. Ventilation Network Calculation Model

Currently, network computational models are a common and effective method for calculating ventilation in multi-zone systems, including multi-zone or regional modeling approaches [119]. Software such as CONTAM, COMIS, and SPARK employs multi-zone models, which assume uniform air parameter distribution within each room, treating each room as a node connected to others or the outdoors via windows, doors, and gaps, and solving based on Bernoulli's principle. Building on the multi-zone model, the regional model divides rooms into finite macro-regions, assuming uniform parameters within each region and considering heat and mass exchange between regions. By establishing mass and energy conservation equations and accounting for pressure differentials and flow relationships, this model studies temperature distribution and airflow within rooms [120]. Network models have been extensively researched and applied in building ventilation [121–123].

While network models effectively simulate regional ventilation and offer good convergence and computational efficiency by assuming uniform air parameter distribution within each room, this assumption limits the model's precision and makes it challenging to capture the specific airflow dynamics within regions [121,124]. Moreover, ventilation network models are generally more suitable for buildings with fixed geometric shapes. For innovative building forms, the building shape may change, and local resistance and heat transfer coefficients are unknown. These network models can be applied to optimize existing buildings under different environments or ventilation strategies but are challenging to accurately calculate during the initial structural optimization phase of building design.

4.2.3. Numerical Computation Model

In contrast to experimental studies, analytical methods, or network models, computational fluid dynamics (CFD) provides a more accurate numerical analysis of complex internal flows in building ventilation scenarios. Current status of ventilation calculation models is shown in Table 2, CFD applications are more versatile and can effectively compute and predict local physical quantities such as temperature, humidity, and airflow velocity and distribution. The heat transfer and fluid flow in new localized building structures can be effectively simulated and calculated. This approach not only reduces experimental equipment and labor costs but also enables accurate predictions and evaluations of building ventilation system performance under varying conditions, thereby optimizing system design and improving indoor air quality.

However, employing CFD numerical models for simulating ventilation in large open spaces presents challenges such as high computational costs, long simulation times, and difficulties in achieving convergence. To address these issues, researchers have proposed coupling multi-zone network models with CFD calculations, validating this coupled approach using experimental data. This framework has been used to investigate the effectiveness of emergency ventilation in protecting building occupants during toxic gas releases [121,125–127], simulate indoor airflow and temperature distribution [124], and improve building ventilation design [128]. Nonetheless, the coupling procedure is complex, requiring the prior establishment of the existence of the numerical solution. When integrating CFD simulations with multi-zone models, it is crucial to select appropriate physical quantities for coupling to avoid conflicts. For instance, predefined velocities can be used as known quantities to prevent flow conflicts at the boundaries [128,129].

Currently, the analysis of ventilation in regional buildings cannot rely solely on analytical or empirical models. The combination of network models and CFD models enables effective ventilation calculations for regional buildings. Network models require less computational effort and provide an overview of the building's macro ventilation but do not yield airflow patterns within individual zones. Conversely, CFD models can predict airflow and temperature distribution within each zone, though they involve significant computational demands and difficulties in handling boundary conditions. By integrating and developing network models to calculate overall natural ventilation and using these results as known boundary conditions for field models, the strengths of both approaches can be effectively leveraged. The coupling procedure remains complex, with challenges related to solution existence, convergence, and reliability. However, integrating network models for areas with well-defined resistance and heat transfer characteristics with CFD models for less defined regions is an effective strategy for ventilation calculations in large spaces.

Table 2. Current status of ventilation calculation models.

Author	Architectural Typology	Calculation Models	Main Conclusions
Liu et al. [122]	Underground building	Ventilation network model and experimental methods	A dynamic flow network model is proposed to simulate natural ventilation in deeply buried underground structures. Small-scale experiments validate the model's potential for application in the study of natural ventilation in underground buildings.
Xiao [123]	Group of underground cavern of hydropower stations	Ventilation network model	The concept of branch thermal pressure, along with a branch temperature distribution model and calculation methods for branch thermal pressure, is proposed. A general network equation set is established, and a solution program is developed using MATLAB language.

Table 2. *Cont.*

Author	Architectural Typology	Calculation Models	Main Conclusions
Wang and Chen [121]	Multi-zone building	Ventilation network model	The assumptions used in multi-zone airflow network models were assessed, exploring the correlation between certain dimensionless air parameters and error. Key values were identified to determine when these assumptions become invalid.
Porras-Amores et al. [56]	Underground building	CFD numerical simulation	A CFD model incorporating terrain temperature gradients was developed to simulate natural ventilation in underground buildings accurately. The methodologies and adjustments presented in this model can serve as a reference for optimizing ventilation in other underground projects.
Mohammadshahi et al. [130]	Underground building (Shavadoon)	CFD numerical simulation	Numerical simulations were conducted to investigate the effects of components such as rooms, bases, and basements on natural ventilation in Shavadoon, leading to the identification of its optimal shape.
Moghtader Gilvaei et al. [131]	Residential building	CFD numerical simulation	A three-dimensional model was used to simulate the application of a novel hybrid system comprising a wind catcher, earth–air heat exchanger, and direct evaporative cooling system in residential buildings. The system reduced electricity consumption by 0.0194 kWh/m^2 compared to split air-conditioning systems.
Wen et al. [132]	Underground building	CFD numerical simulation	CFD simulations were utilized to analyze the principles and challenges of passive ventilation. Furthermore, the coupling of "space–airflow" in multiscale environments was proposed, optimizing the spatial layout and design to effectively enhance natural ventilation.
Zhang [133]	Underground building	CFD numerical simulation	A CFD-based method was developed to design reliable and efficient ventilation systems and layouts for irregular heritage sites, potentially reducing the number of ducts by up to 25%.
Wang and Chen et al. [121,125–127]	Multi-story building	CFD numerical simulation and network model	A coupled approach using a multi-zone network model and CFD simulations was proposed for ventilation calculations and validated accordingly. Building on this, the effectiveness of emergency ventilation in protecting occupants during toxic gas releases was investigated.
J.A. Clarke [124]	Residential building	CFD numerical simulation and network model	An airflow network model was established to handle flow within rooms and HVAC systems, while a CFD model was employed for more precise simulations of indoor airflow and temperature distribution, enhancing the accuracy and efficiency of building performance predictions.
Tan and Glicksman [128]	Large naturally ventilated building	CFD numerical simulation and network model	A strategy was proposed to integrate multi-zone models with CFD to improve the prediction and design of natural ventilation. The study examined the effects of large openings and atrium configurations on naturally ventilated buildings.

4.3. Optimization Algorithm

Optimization is the process of manipulating several variables subject to certain constraints to achieve the minimum or maximum value of a function, specifically to identify the best solution from a set of variables. While numerical methods such as network models or CFD models allow for effective comparative optimization of structural layouts and ventilation strategies, each alternative necessitates recalculation, and individual parameters are optimized sequentially, resulting in a significant workload and challenges in identifying the optimal solution. Currently, building optimization methods can integrate building simulation models with optimization tools or directly employ heuristic algorithms for predictive optimization, potentially involving one or more optimization algorithms [134]. Additionally, this approach can be utilized to evaluate various building design issues, including thermal comfort, indoor air quality, and energy consumption.

Genetic algorithms (GAs) have been integrated with building simulation programs. Typically, a GA is a population-based algorithm categorized as a global optimization search method involving operations for finding and improving optimal solutions. The iterative process of a GA converges to better solutions by breeding parent solutions with higher performance. For instance, Tuhus-Dubrow and Krarti [135] coupled a GA with a building energy simulation engine to identify optimal values for a comprehensive list of parameters associated with the building envelope, thereby minimizing energy usage in residential buildings. Lee [136] developed an optimization design tool that combines a GA and CFD using a two-step optimization search method, significantly reducing computation time and generating optimal designs. Park [137] et al. proposed a structural optimization framework based on integrating computer-aided design, computer-aided engineering, and metamodeling techniques. This framework achieves seamless integration of CAD and CAE software through the use of generic scripts and programming languages, automating the design–analysis–redesign optimization process.

Additionally, Hong et al. [138] compared two optimization methods: a GA and the analytical trial-and-error method (ATEM). The study introduced the ATEM based on order-of-magnitude analysis and system identification with a GA to optimize three parameters in the PID control algorithm, achieving effective optimization results. Prince et al. [139] proposed a novel algorithm that combines an adaptive neuro-fuzzy inference system with a GA for predicting energy consumption and airflow in underground mine ventilation systems. The genetic algorithm for automatically searching and configuring network architectures was investigated, aiming to reduce the manual adjustments required for optimizing network configurations.

Compared to ventilation simulation models like network models and CFD models, optimization algorithms do not require the establishment of complete mathematical models; they only need to abstract the system. This characteristic allows for speed and flexibility, enabling algorithms to progressively approach optimal solutions through continuous searching. These algorithms can efficiently handle multi-variable cooperative optimization problems in ventilation systems. However, their application necessitates a substantial amount of raw analytical data and often lacks detailed information (e.g., velocity, temperature, humidity, pressure) about the ventilation system. This limitation makes it challenging to intuitively reflect the system's flow effects, necessitating a combined analysis with experimental data and simulation results from ventilation calculation models.

5. Conclusions and Prospects

To sum up, this paper reviews ventilation issues affecting indoor air quality in lightweight houses in high-altitude cold regions. The climatic challenges and indoor environmental requirements of lightweight buildings in high-altitude cold regions are discussed. Subsequently, factors significantly impacting the indoor environment are discussed and analyzed. Potential building types and passive natural ventilation measures for improving indoor environments in lightweight structures in high-altitude cold regions are introduced and summarized. The key conclusions are as follows:

(1) The climatic environment of high-altitude cold regions is characterized by high radiation, strong wind speeds, large temperature fluctuations, low pressure, and low humidity. The air-quality requirements for camping spaces in high–cold plateaus are unique. There is a lack of studies on the air environment in shallow underground camping spaces under extreme conditions. A comprehensive evaluation method for assessing ventilation effects in buried camping spaces in high–cold environments needs to be established.
(2) Thermal loss in buildings can be minimized by adjusting structures, materials, and heating methods. Phase-change materials effectively reduce the impact of temperature fluctuations in high-altitude cold regions on internal ventilation and heating, indicating significant application potential. Enhancing building airtightness reduces cold air infiltration and heat loss but necessitates sufficient fresh air to prevent pollutant buildup. Therefore, to improve indoor environments and enhance building sustainability, developing a comprehensive ventilation strategy that minimizes cold air infiltration while ensuring adequate fresh air is essential.
(3) Underground lightweight buildings in high-altitude cold regions can utilize surrounding geology to reduce heat loss and cold air infiltration, offering significant development potential. However, they also face challenges related to poor air quality. Implementing effective natural ventilation strategies that leverage the unique environmental characteristics of these areas may provide a potential solution to simultaneously address heat dissipation and air pollution concerns.
(4) Natural ventilation offers significant energy-saving advantages compared to mechanical ventilation. Given the characteristics of high–cold plateau regions, there is potential to use passive ventilation components like shafts, wind catchers, soil–air heat exchangers, and solar chimneys to establish a natural ventilation strategy for lightweight buildings. Despite the higher initial cost, these strategies offer significant long-term energy savings and carbon reduction benefits, contributing to enhanced building sustainability. However, there is currently a lack of systematic research on optimizing ventilation improvement measures for lightweight buildings in specific high–cold environments.
(5) Current research methods for large spaces in buildings primarily utilize network models, CFD models, or a combination of both. Network models have limited accuracy, while CFD models face significant computational demands and convergence issues. The integration of these models can lead to complexity and challenges in solution existence and convergence. Integrating network models for areas with well-defined resistance and heat transfer characteristics with CFD models for less defined regions is an effective strategy for ventilation calculations in large spaces.

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