A Preliminary Discussion on the Effectiveness of Shallow Geothermal Fresh Air Systems in Green Buildings for Improving Indoor Thermal Environments

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Abstract. With the progress of carbon neutrality in the construction industry, most of the existing research focuses on improving the efficiency of energy supply side, while the indoor thermal comfort of occupants is relatively neglected. Therefore, the synergistic mechanism between clean energy system and thermal comfort is not clear enough. Evidence-based review using a scoping review method, based on literature found in databases such as Scopus over the last 30 years, addressing the gap between technical performance and human comfort considerations. It develops a standardised evaluation framework suitable for various climatic settings, determines significant coupling processes, and suggests methods for synergistic improvement. The results show that shallow geothermal fresh air systems can lower the summer indoor temperature by as much as 9.12°C and raise the winter indoor temperature by 5.53°C when combined with passive soil preparation and active precise control, keeping the indoor temperature within the range of 18-26°C and PMV between 0 and 1. Furthermore, it achieves an energy efficiency ratio of 4.5-7.0 and regulates humidity well. By broadening the analysis to include the interaction between energy systems, people's comfort, and buildings, this study gives backing for more integrated green building designs. However, there are still some limitations such as a small scope of climate and no long-term empirical data, so it need a unified monitoring system and longitudinal studies in different climates.

Keywords: Low-Carbon Building, Thermal Comfort, Synergistic Optimization, Coupling Mechanism, Shallow Geothermal Fresh Air System, Indoor Thermal Environment.

1. Introduction

1.1. Background and context

As the world works towards carbon neutrality in the building sector, making buildings more energy-efficient and using clean energy are key ways to control carbon emissions. Existing research [1] has developed a complete framework for analyzing building energy consumption, which guides later studies to take an energy efficiency perspective and creates a technology system focused on improving energy efficiency.

But at present, most of the existing studies and applications emphasize improving efficiency on the energy supply side, but there is not enough systematic consideration for the demand side, especially the actual indoor thermal environment and the thermal comfort experience of building users [2-3]. This shows that the key problem about how to protect and improve indoor thermal environment quality when making energy saving is still not fully explored and needs more study.

1.2. Research problem

Although there is an increasing amount of clean energy technologies being used within the green building sector, such as shallow geothermal energy, there has been no review of the literature that addresses this key issue. A human-centred, systematic way to understand how clean energy technologies affect the indoor temperature environment is still missing. Indoor thermal comfort is a complex system idea; it is not just about basic physical conditions, but also includes people's physical reactions, feelings, and actions. Existing studies show that materials such as aerogels and phase change materials, along with smart technology such as dynamic shading systems, can help improve the thermal environment [4], but the actual effect of these auxiliary thermal control technologies often does not match the prediction, because of social and technical obstacles and users' behavioral changes [5]. And at the same time, the main focus of the current evaluation framework on energy efficiency makes academics even more confused about the synergies between clean energy technologies and thermal comfort parameters. So, the difficulty of aligning green building low-carbon goals with human-centered comfort needs is not well solved. In particular, the existing literature reviews do not address the following research gaps:

1.No standardized, long term performance evaluation framework for clean energy systems in different climates, and the related thermal comfort indicators.

2. There is no systematic research result about the efficient coupling mechanism and optimization strategy for integrated clean energy-building system in different climate conditions.

1.3. Objectives of the study

This is a study that makes a summary of research based on facts, trying to make people feel more comfortable when using clean energy by looking at how well it works with numbers and careful study. The specific objectives are:

Create a standardized evaluation framework: Create a quantitative metric system that is applicable to different climatic conditions over a long period of time to comprehensively evaluate the regulatory effectiveness of clean energy systems on indoor thermal environments.

Key coupling mechanisms: Look into and combine important technical (for example, system parameters) and non-technical (such as climate adaptability, operation plans) coupling elements that affect the thermal comfort advantages of clean energy systems.

Integrated Optimisation Strategies: From the above analysis, summarize the design and operation optimization strategies that can improve both the energy efficiency of buildings and human thermal comfort, to provide direct guidance for engineering practice.

1.4. Significance of the study

Theoretical Dimension: This research widens the scope from a single source of energy supply to a system of interactions among energy, people, and the environment. Behavioral adaptation theory and life-cycle assessment metrics have been incorporated into this study to fill a void in human-centered approaches for examining clean energy applications in buildings.

On a practical level, these results give us ways to make indoor spaces feel better and use less energy in buildings. By improving the user experience, it may help increase the market acceptance of clean energy technologies [6], which can provide references for low-carbon transformation, design, and decision-making in the building industry.

1.5. Overview of the paper structure

This study is based on the context of building carbon neutrality, and it solves the existing knowledge gap of clean energy application. Each chapter's main function is as follows: Firstly, the core research questions are determined via background analysis and literature review; secondly, the research methodology and data collection methods to bridge this gap are stated; thirdly, the results derived from the literature evidence are presented and analyzed in an organized manner; lastly, the research findings are explained in the discussion and conclusion parts, which summarize the theoretical and engineering practical values of the research.

2. Literature Review

2.1. Overview of the existing research

Existing review literature has investigated the efficiency of clean energy use in green buildings to improve indoor thermal conditions from various aspects such as technical efficiency, climate adaptability, and interdisciplinary integration. Clean energy and indoor thermal environment reviews in green buildings (solar-driven systems, passive/active envelope solutions using phase change materials, geothermal energy, ground source heat pump systems) [7-8], three main research directions can be identified: First is a technology-centered method that concentrates on enhancing the efficiency of particular technologies or combined systems, with the main goal being the promotion of low-carbon and net-zero energy building development while also guaranteeing occupant health and comfort [9]; Second is climate-oriented methods which stress regional applicability of technologies, pushing research advancement from separate techniques to all-encompassing climate-adaptive solutions; Third is people-centered approaches which gradually incorporate occupants' requirements into research structures, encouraging a development pattern that blends technological integration, exact fitting, and people-oriented concern. At the same time, the long-term reliability, durability, and maintenance costs of many cutting-edge technologies in actual settings have become constraints for large-scale industrial application [10].

2.2. Identification of gaps in the literature

Building carbon neutrality is underway, and current studies have looked into how shallow geothermal fresh air systems affect indoor temperatures in green buildings. But there are still three big research holes that it can be summarized as:

Firstly, there is no uniformity in the evaluation metrics. There is currently no standardized way to evaluate the effectiveness of shallow geothermal fresh air systems. Some related researches only stress on the energy efficiency indicators such as the reduction rate of system energy consumption, while others merely observe indoor thermal environment physical parameters such as temperature and humidity. Without an all-encompassing evaluation system that includes thermal environment, comfort, and low-carbon advantages, it is difficult to compare different studies, which makes it hard to do a thorough check of how well the whole system works.

Secondly, the research coverage is insufficient for both climate and time. Existing studies mostly concentrate on one type of climate region, so there’s not much information about how well these shallow geothermal fresh air systems work in different climates. At the same time, studies often depend on brief monitoring data, without conducting systematic, multi-period evaluations of the system's reliability, longevity, and operating expenses. This lack of information hinders a thorough comprehension of the system’s long-term usage efficiency, which is an important obstacle preventing it from being widely used industrially.

And thirdly, human-centred thermal comfort considerations have not been sufficiently integrated. Thermal comfort is often considered a secondary indicator rather than an important goal for system optimization. Many studies do not take into account the human body's physiological reactions, mental impressions, and behavioral modifications when assessing shallow geothermal fresh air systems. This restricts the capacity to link the system’s performance to the real user experience and prevents a natural blending of energy-efficiency goals with human-comfort needs.

2.3. Relevance to the current study

Compared with earlier studies on shallow geothermal or fresh air system, this study has three new aspects: Firstly, it investigates the combination of shallow geothermal and fresh air systems, which is a systematic analysis of the two systems working together; Secondly, it includes the most recent research results and covers various regional applications; Lastly, it goes beyond just describing technology and focuses on improving the indoor temperature environment. This method not only fills in the blanks in research, but also creates a theoretical basis for later studies.

3. Methodology

3.1. Research design

This study uses a scoping review method. Following PRISMA-ScR guidelines, it systemically outlines the extent, nature, and scope of existing studies, with an emphasis on recognizing important ideas and gaps in knowledge instead of quantitatively assessing particular results. It successfully pinpointed and distinguished various technical routes (tunnel ventilation, soil-air heat exchanger, etc.) covered by the general term "shallow geothermal ventilation," making major research gaps apparent. This creates a firm and dependable base for later more thorough research and gives a comprehensive overview of how the present state of research is organized so that talks may move toward central problems from a big picture standpoint. The criteria for including and excluding literature will be explained in the following parts.

3.2. Data sources and search strategy

This study uses authoritative databases such as Scopus that cover almost 30 years of research output with no language restrictions to get the most global coverage of relevant scholarly contributions. Keyword Framework is created according to logic structure including technology platform, application field and assessment index. Thermal comfort, ground-air heat exchangers, green buildings, and thermal comfort performance are included in it. This method makes sure all tech ways, how they're used, and how well they work are covered.

3.3. Data collection methods

This study focuses on three core areas: new energy utilization in buildings, indoor thermal environment regulation, and thermal comfort assessment. The literature screening criteria are as follows.

Inclusion criteria:

Core relevance: Research must cover at least two of the aforementioned core areas.

Empirical basis: Studies must provide empirical data or case studies (e.g., measured, simulated, or experimental data).

Academic Quality: Sources must be formally published peer-reviewed academic works.

Exclusion Criteria:

Irrelevant Subject Matter: Failure to address any core dimension of 'building energy utilization', 'indoor thermal environment', or 'thermal comfort'. Discussion confined to isolated building elements (e.g., envelope structures, materials) without addressing synergistic optimization between thermal environments and energy systems.

Missing Core Elements: Focuses solely on building energy efficiency without addressing specific indoor thermal environment parameters or thermal comfort evaluation. Discusses only theoretical principles, policies, or technical concepts without application data validation in actual buildings.

Deviation in Scope: Studies specialized buildings (e.g., data centres, industrial facilities) where the technology or conclusions lack applicability to residential/ordinary buildings. Focuses exclusively on energy technologies without contextualizing them within specific building applications.

Substandard quality: Research methodologies are unclear, or samples/data are incomplete. Lack of explicit core conclusions or research findings. Classified as non-academic literature (e.g., news reports, commercial briefings) or lacking peer review.

Duplication and obsolescence: Highly redundant with core content already included in the literature. Research conclusions overturned or superseded by subsequent, more reliable studies.

3.4. Data analysis techniques

Data analysis that focuses on getting and making standard important information such as the main parts of books, kinds of buildings, how they are used, different ways to make energy, how warm or cool it feels inside places, what people want to learn about, how they will do their work, and the most important results. Extraction done separately and checked together, based on first sources, lots of other people looked at it too. This process makes sure everything is the same, right, and complete, giving organized and regular information to help with looking into things more.

4. Results

4.1. Presentation of key findings

Note: The content in this section is summarized based on the existing literature, and it is not an original experimental result of this study.

Geothermal ventilation systems are a kind of passive building technology that uses underground pipes to let outside air go through a heat exchange with the ground, which has a steady temperature, before it goes into the house. This makes the air cooler in summer and warmer in winter. The system greatly reduces the load on the air conditioner by doing such an effective preliminary treatment. Often combined with active control technologies for better building energy efficiency and indoor thermal comfort.

4.2. Use of tables, figures, and charts

The main advantage of geothermal fresh air systems is that they combine passive pre-treatment and active accurate control. First, it takes advantage of the large thermal inertia of the soil to do "basic temperature adjustment" on the incoming fresh air in an efficient and energy-saving way. Then it's combined with technologies such as radiant terminal units and independent dehumidification for separating and precisely regulating temperature and humidity [11-12]. This method greatly cuts down on the amount of energy used by air conditioners (the system's energy efficiency ratio can be as high as 4.5-7.0) [11-12], but what's even better is that it improves the quality of the air being supplied (drafts are eliminated and temperatures are consistent). It makes a big jump from just controlling the temperature to making sure people feel comfortable all over people's body, which helps people understand how good something is for them without needing to know about complicated technology [13-14].

4.3. Statistical analysis

Table 1. Temperature Regulation

Enhancement Dimension	Specific Effects	Date	(Comparative Study)
Temperature Regulation	Summer cooling by using the cooling power of the topsoil	Ductwork system reduces the incoming air temperature on average by 9.12 °C	Indoor average temperature could be reduced by 5.9°C
	Winter Heating: Using the heat from shallow soil layers	During the winter operation, the tunnel ventilation system can raise the temperature of the incoming fresh air by about 5.53 degrees Celsius on average	Average indoor temperature increases by 4.29°C
	Temperature stability and uniformity	The integrated system maintains a stable year-round temperature of 18–26°C	Minimal vertical temperature variation indoors ensures a more uniform thermal distribution.

Table 2. PMV

Enhancement Dimension	Specific Effects	Date	(Comparative Study)
PMV	Significantly improve general comfort by improving temperature, humidity, and air flow organization so that the PMV value is in the comfortable range.	Systems that use groundwater for radiant cooling or heating, and have PMV control, keep the indoor PMV value in the comfortable range of 0-1 (slightly cool to neutral).	Integrated floor supply air and radiant heating systems make sure that the PMV-PPD numbers match up with what people need to feel comfy in temperature

Table 3. Humidity Control

Enhancement Dimension	Specific Effects	Date	(Comparative Study)
Humidity Control	Independent temperature and humidity control: Obtaining a more accurate and effective way of regulating the humidity by means of solution dehumidification.	The solar-geothermal hybrid solution dehumidification system maintains indoor relative humidity within the comfortable range of 50%-65% during summer and 40%-60% during winter.	Tunnel ventilation increases the humidity of fresh air in summer while reducing it in winter.

Table1-3 shows the Statistical analysis.

5. Conclusion

5.1. Summary of key findings

The current research has shifted away from a single focus on “energy efficiency optimization” to a more comprehensive approach of “energy efficiency-comfort-health” synergy. The literature consensus is that passive geothermal ventilation technologies such as the Earth Air Heat Exchange (EAHE) system can close the “cognitive gap” between technical performance and human comfort in clean energy application via a path of “passive soil pretreatment plus active precise control.” Field measurements show it improves both energy efficiency and thermal comfort at the same time (such as making PMV values more comfortable), and plans for the future will be equal emphasis on low-carbon buildings and people-oriented designs.

5.2. Comparison with previous studies

Compared to the traditional compressor air conditioning system which uses high-grade electricity for coupled temperature-humidity treatment, the main advantage of the geothermal fresh air system is its use of low-grade geothermal energy efficiently and separating thermal load from moisture load. The conventional systems will have energy loss because of the heat-cold cancelling out and it has an uneven air flow that could make people uncomfortable. On the other hand, geothermal fresh air systems offer a softly pre-conditioned air via steady ground heat exchange. Together with radiant terminal units and individual dehumidification, they can get exact temperature and humidity control, giving more energy-saving, even air flow, and better indoor environment directly from the source.

5.3. Implications of the findings

Green building design’s main implication is a change in the way people think about designing buildings: instead of focusing on systems that deal with loads, it moves toward an approach where the emphasis is on passive measures first and then fine-tuning with active ones, all centered around integrating these systems together. Passive resources such as soil and natural ventilation need to be incorporated into the planning process from the start. Performance targets have to go beyond just one aspect of energy efficiency and include all-around numbers that cover how much energy is used, feeling warm or cool inside, and the air people breathe indoors. It helps to put underground air pre-treatment + high-efficiency terminal units + smart control together when making plans and designs.

5.4. Limitations of the study

The current existing research has some limitations. First, the conclusion mainly relies on single building case study or short term measurements in certain climate zones such as hot summer and cold winter region, which leads to limited sample diversity and no cross-climate generalizability. Second, there is a serious deficiency of continuous monitoring data for over five years covering the whole system life cycle, especially regarding soil thermal balance and long-term performance degradation. Lastly, there are discrepancies in the metrics and methods used to assess energy efficiency and comfort, making it difficult to compare different studies' results, combine their outcomes, and create standardized design guidelines.

5.5. Suggestions for future research

In order to break through the current constraints, future studies should concentrate on the following three aspects: First, set up standardized monitoring procedures and common databases that cover soil thermal reactions, system energy effectiveness, extended indoor atmosphere situations, and consumer comments. Second, deploy long-term performance monitoring stations in all significant climate zones and building types so as to collect 3-5 years' worth of actual information, thus acquiring variations among various climates and building kinds. Lastly, more sophisticated simulation tools and AI technologies can be applied to explore the dynamic coupling relationship between ground source heat pump fresh air system and building environment. This will help develop adaptive predictive control strategies which would enable demonstration projects to move into large scale, high performance engineering application.

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