



PLANNING MALAYSIA:

Journal of the Malaysian Institute of Planners

VOLUME 23 ISSUE 6 (2025), Page 119 – 135

PASSIVE COOLING IN EARTH-SHELTERED HOMES: NATURAL STRATEGIES FOR ENERGY EFFICIENCY IN COOBER PEDY, AND YAODONG

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Abstract

The growing demand for energy-efficient architecture has led to renewed interest in passive cooling techniques, particularly in earth-sheltered homes. These structures, built partially or entirely underground, leverage the thermal stability of the earth to maintain comfortable indoor temperatures with minimal energy consumption. This study examines underground homes in Coober Pedy, Australia, and Yaodong, China, focusing on their natural cooling mechanisms and architectural strategies. Using a mixed-methods approach, including a literature review, architectural analysis, and interviews with architects familiar with these structures, the research identifies key design elements such as thermal mass, subterranean depth, and ventilation systems that contribute to their energy efficiency. The findings reveal that these strategies effectively reduce temperature fluctuations, making them a sustainable alternative to conventional cooling systems. Additionally, the study discusses the feasibility of adapting these passive cooling techniques to modern urban settings. The research concludes that underground architecture offers significant potential for energy conservation and sustainable housing solutions in a warming climate.

Keywords: Earth-Sheltered Homes, Energy Efficiency, Natural Ventilation, Passive Cooling, Sustainable Design, Thermal Mass, Underground Architecture.

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INTRODUCTION

As global temperatures rise and energy consumption escalates, the quest for sustainable architectural solutions becomes increasingly critical. Buildings account for a significant portion of global energy use, with cooling demands contributing substantially to carbon emissions and environmental degradation (R. Baydoun & Sapian, 2022a, 2022b). While extensive research exists on passive cooling in conventional buildings, few studies have examined the long-term efficiency of underground dwellings in extreme climates. Earth-sheltered homes are buildings that are constructed partly or entirely below ground to use surrounding soil as natural insulation, those buildings offer an alternative approach to temperature regulation by reducing reliance on mechanical cooling systems (Milanović et al., 2018). Despite their potential to enhance energy efficiency and sustainability, these strategies remain underutilized in contemporary construction practices.

This study aims to bridge this research gap by examining two well-established underground housing typologies: Coober Pedy (Australia) and Yaodong (China). Coober Pedy's underground residences, developed in response to extreme desert conditions, the strategy of underground structures is characterized by the high leverage thermal mass which refers to the capacity of a material to absorb and store heat. Which some earth sheltered structures are classified as subterranean structures which refers to the insulation and the protection provided by surrounding soil layers to maintain stable indoor temperatures. Similarly, Yaodong dwellings, constructed within loess soil, utilize high thermal mass and natural ventilation to achieve passive cooling with minimal energy consumption. While both cases illustrate the potential of underground architecture for energy-efficient cooling, there is limited comparative research analyzing their architectural strategies within the broader context of contemporary sustainable design. To address this gap, the study investigates the following research objectives:

1. Examine how underground homes maintain cool temperatures without artificial cooling.
2. Identify key architectural techniques that enhance their energy efficiency.
3. Explore the applicability of these passive cooling methods to modern sustainable housing.

By analyzing these case studies, this research aims to extract valuable design principles that can inform contemporary architecture, particularly in regions experiencing extreme climate variations. Findings from this study will contribute to a deeper understanding of how earth-sheltered homes can serve as

a viable solution for reducing energy consumption while ensuring indoor comfort, aligning with global sustainability efforts.

LITERATURE REVIEW

Underground Architecture and Thermal Performance

Earth-sheltered buildings utilize the insulating properties of soil whose high thermal resistance limits heat transfer, those properties help to maintain stable indoor temperatures, thereby reducing reliance on mechanical heating and cooling systems. The high thermal mass of soil buffers temperature fluctuations, leading to improved energy efficiency. While Ashrafian et al. (2011) argue that underground housing primarily relies on thermal inertia to regulate indoor climates, Milanović et al. (2018) emphasize that air ventilation strategies play an equally significant role. This study examines both perspectives through real-world cases.

Thermal stability in earth-sheltered structures depends largely on depth. According to Ashrafian et al. (2011), temperatures between zero- and 10-meters underground exhibit seasonal fluctuations, whereas beyond 10 meters, thermal conditions remain stable throughout the year as shown in figure 1. This principle underlies the cooling efficiency of underground dwellings, such as Coober Pedy's sandstone homes and Yaodong's loess-soil dwellings. However, Alwetaishi (2021) challenges this notion, arguing that depth alone is insufficient and must be complemented by strategic ventilation placement to optimize indoor comfort.

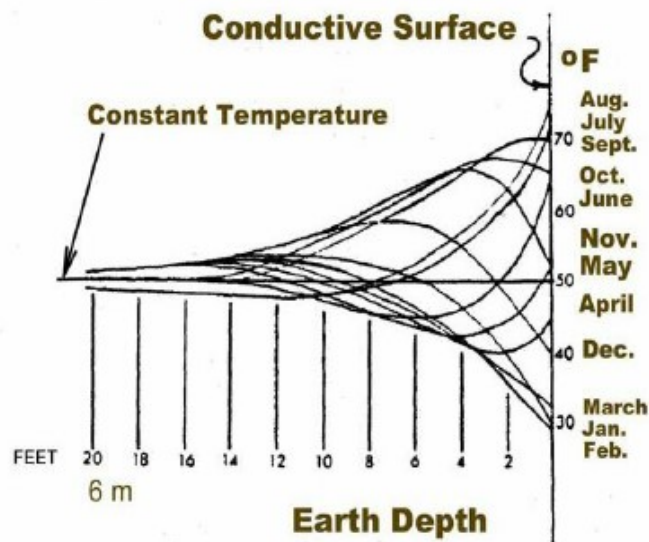


Figure 1: thermal stability in earth sheltered houses (Ashrafian et al., 2011)

Comparative Analysis of Passive Cooling Strategies in Earth-Sheltered Homes

Passive cooling refers to natural design techniques that minimize indoor heat gain and enhance heat dissipation without relying on mechanical systems. In earth-sheltered architecture, such strategies include optimizing thermal mass, ventilation systems, and surface insulation to improve indoor comfort (R. Baydoun & Sopian, 2022a). However, the effectiveness of these strategies varies depending on climatic conditions, soil composition, and construction methods. The comparative analysis highlights that while both Coober Pedy and Yaodong successfully employ earth-sheltered design that is defined as architecture that integrates the building envelope with the ground for insulation and temperature stability, their effectiveness is shaped by local geology, climate, and culture. In Coober Pedy, sandstone excavation ensures thermal buffering against extreme desert heat, a method that would be impractical in regions without stable rock formations. By contrast, Yaodong dwellings leverage the insulating qualities of loess soil to withstand both summer heat and winter cold, though soil fragility limits long-term durability. These findings underscore that the success of passive cooling strategies is context-dependent; transferring them to other climates or urban areas requires adaptation to local material availability, climatic conditions, and regulatory frameworks.

Thermal Mass vs. Ventilation Efficiency

One of the primary debates in passive cooling strategies concerns whether thermal mass or ventilation strategies contribute more significantly to indoor temperature regulation. Meir & Gilead (2002) assert that thermal mass is the dominant cooling factor in Coober Pedy's underground homes, where sandstone absorbs heat during the day and slowly releases it at night. This results in stable indoor temperatures ranging from 19°C to 25°C, even when external temperatures exceed 40°C. However, Liu et al. (2011) contend that in China's Yaodong dwellings, cross-ventilation mechanisms play a more critical role in maintaining indoor comfort. Due to the porous nature of loess soil, air circulation through well-positioned openings prevents excessive heat accumulation.

These contrasting findings suggest that passive cooling strategies must be adapted to local climatic conditions. Table 1 compares the cooling effectiveness of different strategies in Coober Pedy and Yaodong, highlighting their reliance on either thermal inertia or ventilation efficiency.

Table 1: Comparative effectiveness of passive cooling strategies in underground homes.

Cooling Strategy	Effectiveness in Coober Pedy	Effectiveness in Yaodong
Thermal Mass	High	Moderate
Cross-Ventilation	Low	High
Green Roofs	Limited	Moderate
Solar Chimneys	Requires adaptation	Effective in hot seasons

The Role of Green Roofs and Solar Chimneys in Passive Cooling

In modern applications, passive cooling strategies integrate green roofs, solar chimneys, and perforated screens to enhance indoor thermal comfort. Delaney Nolan (2024) highlights that green roof not only reduce indoor temperatures but also contribute to stormwater management and urban heat island mitigation. Similarly, solar chimneys utilize heat absorption principles to drive natural ventilation, expelling warm air and drawing in cooler air from lower levels. However, Al-Shamkhee et al. (2022) argue that while these methods enhance cooling efficiency, their effectiveness depends on climatic conditions and careful design considerations.

Adaptation of Earth-Sheltered Design in Modern Architecture

The he principles of underground architecture closely align with traditional Islamic cooling techniques, including badgirs (wind catchers), qanats (subterranean water channels), and mashrabiya screens (Z. Baydoun et al., 2023; Dariyadi et al., 2022). These techniques demonstrate an advanced understanding of passive cooling and natural ventilation, making them relevant for contemporary sustainable design. Badgirs, for example, harness wind currents to direct cool air into buildings, while qanats leverage underground water channels to cool surrounding spaces through evaporative cooling. Additionally, Mashrabiya screens regulate solar heat gain while allowing airflow, reducing internal temperatures.

Modern architectural applications of these principles emphasize the integration of passive house standards, which focus on airtight construction, superinsulation, and heat recovery ventilation (Al-Shamkhee et al., 2022). Hybrid models that combine underground dwellings with solar-driven cooling technologies have demonstrated 30–50% energy savings, underscoring the potential for blending traditional passive strategies with contemporary innovations (R. Baydoun & Sopian, 2022b) Table 2 presents a comparison between traditional and modern passive cooling methods and their respective applications.

Table 2: Traditional Islamic cooling methods adapted into modern architecture.

Traditional Cooling Method	Modern Application
Wind Catchers (Badgirs)	Stack ventilation in underground homes
Qanat Water Channels	Evaporative cooling integration
Mashrabiya Screens	Perforated facades for shading

The literature presents contrasting perspectives on the effectiveness of passive cooling in underground architecture. While some studies highlight thermal mass as the primary cooling factor, others emphasize the role of ventilation in maintaining indoor comfort. The comparison between Coober

Pedy's sandstone dwellings and Yaodong's loess-soil homes reveals that the dominant passive cooling strategy varies depending on climate, soil properties, and design approach. Additionally, the integration of Islamic passive cooling techniques with modern sustainable architecture suggests that underground dwellings remain highly relevant for contemporary energy-efficient construction. Future research should explore hybrid ventilation systems, material innovation, and climatic adaptation to enhance underground dwelling performance. Additionally, a deeper investigation into historical passive cooling strategies in Islamic architecture may provide further insights into sustainable architectural solutions for contemporary challenges.

RESEARCH METHODOLOGY

This study employs a qualitative research methodology, integrating case study analysis and semi-structured interviews to explore natural cooling mechanisms in earth-sheltered homes (Z. Baydoun et al., 2024). The focus is on two prominent examples: Coober Pedy in Australia and Yaodong in China. These sites are recognized for their passive cooling strategies, which allow underground dwellings to maintain stable indoor temperatures despite extreme external climatic conditions.

Case Study Selection

The selection of case studies for this research is based on their distinct approaches to earth-sheltered architecture and their effectiveness in passive thermal regulation. Coober Pedy, Australia, was chosen due to its extreme desert climate, where summer temperatures frequently exceed 40°C. To counteract these harsh conditions, residents have developed an extensive network of subterranean dwellings which capitalize on the insulating properties of the sandstone substrate. These underground homes maintain stable indoor temperatures ranging between 19°C and 25°C throughout the year, significantly minimizing the need for artificial cooling and demonstrating the viability of earth-sheltered housing in arid environments.

Similarly, Yaodong, China, was selected as a representative example of semi-subterranean architecture in a semi-arid climate. Constructed from compacted loess soil, Yaodong dwellings utilize the high thermal mass of earth to regulate indoor temperatures, remaining cool in summer and warm in winter. The inherent insulation properties of loess soil contribute to energy efficiency by reducing dependence on mechanical heating and cooling systems. By examining these two case studies, this research aims to compare their passive cooling mechanisms and evaluate their applicability in modern sustainable housing design.

Data Collection Methods

This study employs a multi-faceted approach to data collection, integrating both qualitative and analytical methods to ensure a comprehensive understanding of underground homes and their passive cooling strategies. A literature review was conducted to analyze open-access academic articles, and architectural studies on earth-sheltered dwellings, passive cooling techniques, and energy efficiency. This review provided a theoretical foundation for assessing the effectiveness of underground architecture in maintaining thermal comfort.

Additionally, semi-structured interviews were conducted with two architects and researchers who have either studied or visited these underground settlements regarding their comfort levels and adaptive cooling behaviors.

The interviews aimed to gather expert insights on the observed performance of passive cooling mechanisms, challenges associated with adapting these techniques to modern urban environments, and recommendations for integrating underground housing principles into contemporary sustainable architecture. This triangulated methodology ensures a well-rounded evaluation of the subject matter, combining theoretical knowledge with practical observations. To clarify the workflow of this study, a schematic diagram in figure 2 is provided, illustrating the sequence of research steps from literature review and case study selection to expert interviews and comparative analysis of cooling strategies.

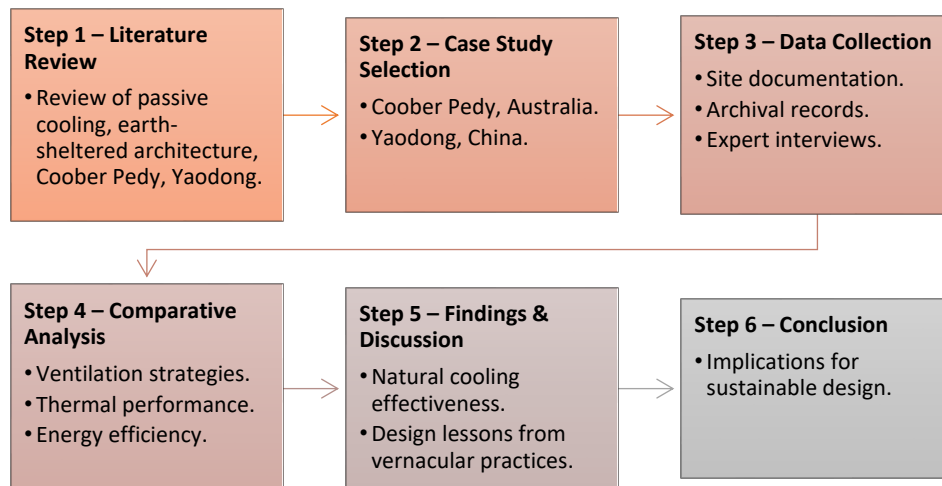


Figure 2: Research Methodology Process

Limitations

1. **Data Availability:** The study relies on existing literature and expert opinions, which may limit access to first-hand empirical data.
2. **Interview Scope:** The number of professionals familiar with these underground homes may be restricted, potentially narrowing the perspectives gathered.
3. **Generalizability:** Findings from Coober Pedy and Yaodong may not be universally applicable, as climatic, cultural, and geological conditions differ across regions.
4. **Beyond methodological constraints,** broader limitations include regulatory barriers, cultural preferences for above-ground living, and the high initial costs of excavation, which may hinder the adoption of earth-sheltered cooling strategies in modern urban contexts.

ANALYSIS AND DISCUSSION

This section presents the key findings from the case studies of Coober Pedy and Yaodong homes, supported by insights from the literature review and two architects' validations. These underground dwellings demonstrate how thermal mass, ventilation strategies, and material selection contribute to passive cooling, reducing reliance on artificial climate control. The architects' input further supports the practical applicability of these strategies in modern sustainable housing.

As shown in figure 3 and 4, Coober Pedy's underground residences and China's Yaodong dwellings provide significant insights into the effectiveness of earth-sheltered homes in maintaining thermal comfort with minimal energy use. The analysis of Coober Pedy's underground homes and Yaodong dwellings directly addresses the study's objective of evaluating passive cooling in earth-sheltered architecture. Both case studies demonstrate that leveraging thermal mass, strategic ventilation, and natural insulation significantly reduces energy consumption, key principles that can inform modern sustainable housing designs.



Figure 3: Coober Pedy underground structure (Erinna Giblin, 2018)

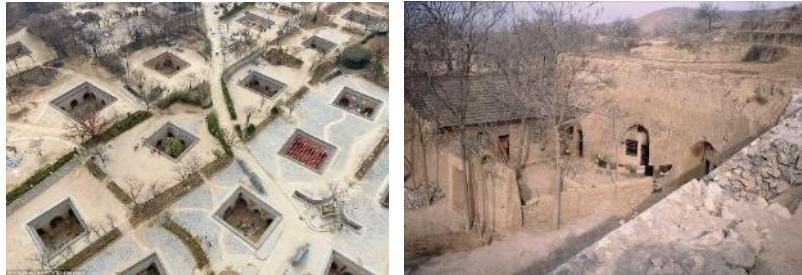


Figure 4: Yaodong dwellings courtyards (Kaushik Patowary, 2018)

In Coober Pedy, Australia, residents have adopted underground living to cope with extreme desert heat. The sandstone substrate acts as an insulating layer, keeping interiors cool during scorching summers and retaining warmth in winter (Zaria Gorvett, 2023). Similarly, in China, Yaodong homes, constructed within compacted loess soil, exhibit superior thermal regulation by maintaining stable indoor temperatures despite external climate variations. The thick earthen walls absorb heat during the day and release it at night, effectively mitigating temperature fluctuations.

To systematically compare these two underground housing typologies, analytical table 3 has been developed, summarizing their key characteristics, environmental adaptation strategies, and architectural techniques. This comparative analysis provides a structured evaluation of how each case study achieves energy-efficient cooling and highlights their relevance for modern sustainable housing solutions.

Table 3: Analytical table summarizing key characteristics

Criteria	Coober Pedy (Australia)	Yaodong (China)
Year Established	1915	Over 2000 years ago
Location	Hot desert climate, South Australia	Semi-arid/temperate regions, Northern China
Typology	Underground town	Semi-subterranean cave dwellings
Material Used	Sandstone	Loess soil
Thermal Strategy	Thermal mass insulation; stable underground temperatures	High thermal mass; soil insulation for passive cooling
Cooling Mechanism	Protection from extreme heat via earth coverage	Natural ventilation and heat absorption from thick walls
Energy Use	Minimal air conditioning needed	Little to no reliance on artificial cooling
Sustainability	Reduces energy consumption, adapts to harsh climate	Passive cooling reduces energy demand

Natural Cooling Mechanisms in Underground Homes Thermal Mass and Insulation

One of the most critical takeaways from the study is that thermal mass plays a dominant role in passive cooling, reinforcing Givoni's (1994) "thermal buffering" concept, which argues that materials with high heat storage capacity help regulate indoor temperatures by absorbing excess heat during the day and releasing it at night as shown in figure 5.

- Coober Pedy: Homes are carved into sandstone, a material with high thermal inertia. Indoor temperatures remain between 19–25°C, even when external temperatures exceed 40°C (Meir & Gilead, 2002).
- Yaodong: These cave dwellings, built into loess soil, utilize thick earth walls to maintain thermal stability, keeping interiors cool in summer and warm in winter (Liu et al., 2011).

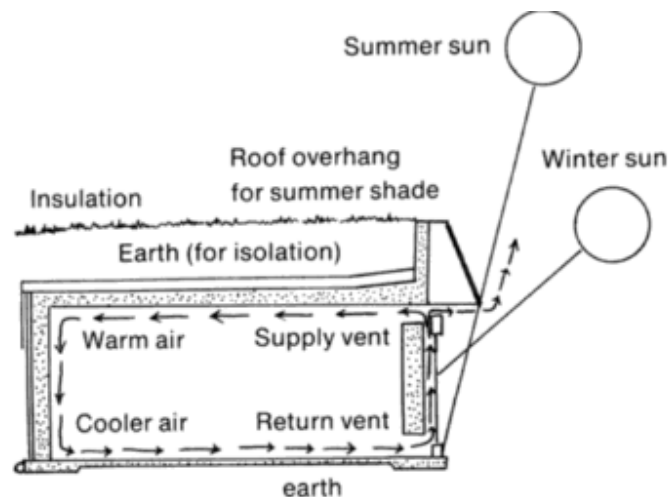


Figure 5: Sectional diagram of a traditional earth bermed dwelling showing passive cooling features, including earth insulation, ventilation shafts representing thermal stability (Terman, 2012)

Architect A highlighted that thermal mass is a crucial element in passive cooling strategies. Sandstone in Coober Pedy and loess soil in Yaodong exemplify how indigenous materials regulate temperature without mechanical systems. These principles are highly relevant for contemporary sustainable design.

Depth and Orientation

The effectiveness of passive cooling in underground homes is influenced by excavation depth and site orientation, which minimize heat gain.

- Coober Pedy: Dugouts are typically constructed 5–10 meters underground, reducing exposure to extreme temperature fluctuations (Meir & Gilead, 2002)
- As shown in figure 6, Yaodong dwellings are often partially or fully embedded in hillsides, leveraging natural shading to reduce heat absorption (Liu et al., 2011).

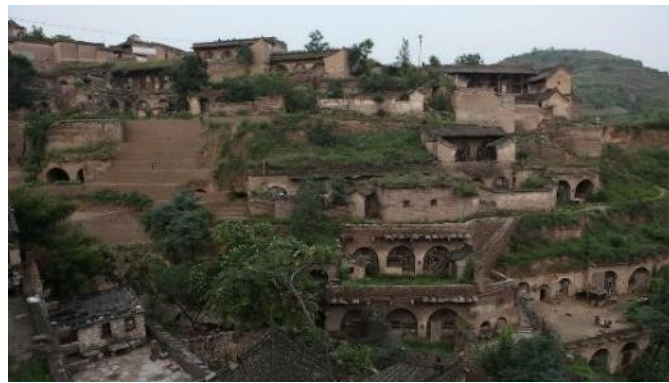


Figure 6: Yaodong cave dwelling (Mariabruna Fabrizi, 2021)

Architect B noted that strategic ventilation placement in underground homes is key to their energy efficiency. Coober Pedy's stack effect and Yaodong's wind-aligned openings showcase how passive ventilation can be optimized for different climates. These techniques should be incorporated into modern urban housing to reduce cooling energy demands.

Architectural Strategies for Energy Efficiency

Natural Ventilation and Airflow

Strategically placed ventilation shafts and openings facilitate natural ventilation, a passive process where air movement driven by pressure differences replaces indoor warm air with cooler outdoor air, reducing heat build-up.

- Coober Pedy: as shown in figure 7, many homes feature narrow shafts that promote stack ventilation, allowing cooler air to enter from below while expelling warm air from above (Meir & Gilead, 2002).
- Yaodong: Openings are aligned with prevailing winds, enhancing cross-ventilation and passive cooling (Liu et al., 2011).

Architect A emphasized that effective passive cooling relies not only on material properties but also on strategic ventilation design. The stack ventilation in Coober Pedy optimizes airflow in enclosed underground spaces, while Yaodong's cross-ventilation approach takes advantage of natural wind movement, making both systems highly adaptive to their respective climates. Architect B highlighted that modern architecture could incorporate similar principles by designing buildings with passive ventilation strategies, such as atriums and stack ventilation systems, which significantly reduce the need for mechanical cooling.



Figure 7: Coober Pedy shafts (Chris Weller and Erin McDowell, 2020)

Material Properties and Adaptability

Locally sourced building materials enhance the energy efficiency of underground homes.

- Coober Pedy: Sandstone is naturally porous, retaining moisture and further cooling interior spaces (Meir & Gilead, 2002).
- Yaodong: Loess soil has high thermal resistance, reducing heat transfer and stabilizing indoor temperatures (Liu et al., 2011).

Architect A stated that sandstone and loess soil are prime examples of materials that inherently regulate heat flow, reducing the dependency on artificial cooling. These materials should inspire modern sustainable architecture by integrating high thermal mass alternatives, such as rammed earth and bio-based insulation.

Architect B noted that beyond insulation, material selection in sustainable architecture should also prioritize moisture management, as underground structures require adequate waterproofing to balance humidity levels without compromising thermal efficiency.

Applicability to Modern Sustainable Housing Adaptation of Passive Cooling Techniques

Lessons from underground homes can inform modern architecture, especially in regions with extreme climates.

- Earth-sheltered housing can integrate underground thermal mass principles.
- Green roofs and bermed structures replicate the insulating effect of subterranean homes, mitigating urban heat island effects (Xie et al., 2023).

Architect A suggested that incorporating underground thermal mass strategies into modern urban housing can significantly reduce cooling demands. Techniques such as semi-subterranean dwellings, courtyard designs, and bio-climatic earth integration are viable adaptations.

Architect B emphasized that designers should explore hybrid solutions, such as integrating phase change materials (PCMs) with earthen walls, to achieve more dynamic and adaptable thermal performance.

Challenges and Considerations

- Structural challenges: Underground homes require advanced waterproofing to prevent moisture-related issues.
- Cultural adaptation: Many regions lack familiarity with earth-sheltered housing, necessitating public awareness campaigns and regulatory support.

Architect A highlighted that modern architect must balance the advantages of earth-sheltered design with contemporary building codes and urban development policies, ensuring that moisture control, ventilation efficiency, and cultural acceptability are adequately addressed.

Architect B noted that adapting underground housing to urban environments requires a shift in perception governments and architects need to advocate for alternative housing models that embrace energy-efficient earth integration rather than relying solely on conventional construction practices.

Summary of Findings

The comparative analysis of Coober Pedy's underground homes and Yaodong dwellings highlights the effectiveness of thermal mass, passive ventilation, and

natural insulation in maintaining indoor comfort while reducing energy demand. These strategies align with the study’s objective of evaluating passive cooling techniques in earth-sheltered architecture and their relevance to modern sustainable housing. The findings demonstrate that locally available materials, excavation depth, and ventilation design play a crucial role in achieving thermal efficiency in underground dwellings.

Table 2: Summary of the key insights from the study

Feature	Coober Pedy (Australia)	Yaodong (China)	Modern Adaptation
Thermal Mass	Homes carved into sandstone, a material with high thermal inertia, absorbing and slowly releasing heat.	Thick loess soil walls provide natural insulation, stabilizing indoor temperatures.	Rammed earth and high thermal mass concrete can replicate these effects in contemporary buildings.
Ventilation Strategy	Stack ventilation shafts facilitate airflow by drawing in cooler air and expelling warm air from the top.	Wind-aligned openings optimize cross-ventilation, leveraging natural air currents.	Hybrid ventilation systems, including passive air wells and atrium designs, can be integrated into modern buildings.
Cooling Effectiveness	Indoor temperatures remain between 19–25°C, even when external temperatures exceed 40°C.	Interiors maintain comfortable conditions throughout the year, keeping warm in winter and cool in summer.	Energy-efficient designs incorporating natural shading, thermal buffering, and ventilation zoning can improve indoor comfort while reducing reliance on HVAC systems.
Material Properties	Sandstone is porous, retaining moisture and aiding in cooling.	Loess soil has high thermal resistance, reducing heat transfer.	Bio-based insulation materials, phase change materials (PCMs), and green building technologies can enhance passive cooling.
Sustainability	Reduces reliance on artificial cooling and integrates well with the natural landscape.	Low-energy, time-tested housing strategy that remains culturally significant.	Earth-sheltered homes, green roofs, and bermed structures can replicate underground cooling mechanisms in modern urban environments.

The findings of this study align closely with its research objectives, providing a comprehensive evaluation of passive cooling mechanisms in underground architecture. This research aimed to analyze energy-efficient strategies employed in the underground dwellings of Coober Pedy and Yaodong, assess their applicability to modern sustainable housing, and highlight the role of

natural insulation and ventilation in reducing energy consumption. The study confirms that both Coober Pedy and Yaodong effectively utilize passive cooling strategies, significantly minimizing reliance on mechanical air conditioning. The high thermal mass of sandstone in Coober Pedy and loess soil in Yaodong plays a crucial role in regulating indoor temperature fluctuations, ensuring stable indoor climates, and preventing extreme variations.

Architectural strategies further reinforce the effectiveness of passive cooling in these underground dwellings. Coober Pedy employs stack ventilation, which facilitates airflow and removes excess heat, while Yaodong integrates wind-aligned openings that enhance cross-ventilation. Additionally, excavation depth and strategic site orientation contribute to reducing heat gain, demonstrating the importance of thoughtful spatial planning in energy-efficient building design. These principles, deeply embedded in the traditional architecture of underground homes, have significant implications for contemporary sustainable design (Givoni, 1994). Lessons from these dwellings can be applied to modern architecture through the integration of earth-sheltered housing, green roofs, and insulated structures. Moreover, advancements in construction materials, such as phase change materials (PCMs) and rammed earth, can further enhance the thermal performance of buildings, reinforcing the benefits of passive cooling systems.

Architectural validation supports the study's conclusions. Architect A emphasized that sandstone and loess soil regulate temperature effectively, while Architect B highlighted the importance of ventilation and suggested hybrid systems to enhance adaptability in modern housing. Together, their insights demonstrate the wider applicability of underground passive cooling to sustainable design.

This study confirms earth-sheltered housing as a viable, energy-efficient approach for extreme climates. The precedents of Coober Pedy and Yaodong show how thermal mass, insulation, and ventilation can reduce energy use and improve comfort, offering valuable strategies for contemporary sustainable architecture.

CONCLUSION

This study examined passive cooling in earth-sheltered dwellings in Coober Pedy, Australia, and Yaodong, China, demonstrating how thermal mass, orientation, and ventilation work together to maintain stable indoor conditions with minimal reliance on mechanical systems. Both case studies reveal the effectiveness of vernacular solutions in addressing climatic extremes. The findings highlight clear opportunities for modern architecture: underground and semi-underground housing strategies can inform sustainable design, particularly in regions facing rising energy costs and heat stress. Integrating elements such as

earth berms, optimized orientation, and selective natural ventilation can reduce energy demand while improving thermal comfort. Future research should expand to include quantitative simulations of energy performance, cross-cultural comparisons with other vernacular models, and assessments of user comfort and acceptability in modern contexts. Such work can bridge traditional knowledge with contemporary building technologies, advancing sustainable housing solutions in diverse climates.

ACKNOWLEDGEMENT

This work was supported by the Universiti Malaya under the Bantuan Khas Penyelidikan - Early Career Research Grant (BKP-ECRG) [Grant Number BKP050-2024-ECRG]. Also, a comprehensive collaboration between Tashkent University of Architecture and Civil Engineering and universiti Malaya helps to enhance this work.

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Glossary of Terms

Key technical terms used in this study are defined as:

- Thermal Mass: Ability of materials to store and release heat, moderating indoor temperatures.
- Subterranean Depth: Extent a structure is built below ground, influencing thermal stability.
- Passive Cooling: Natural methods (e.g., ventilation, shading, thermal mass) that reduce indoor heat without mechanical systems.
- Earth-Sheltered Housing: Buildings partly or fully below ground, using soil for insulation.

Received: 19th April 2025. Accepted: 28th August 2025