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EARTH-COUPLED COOLING STRATEGIES ACROSS REGIONS: A REVIEW TOWARD ADAPTATION IN HOT AND HUMID CLIMATES

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ABSTRAK

Sistem pendinginan dengan bumi memanfaatkan suhu tanah yang stabil pada kedalaman tertentu yang dipertahankan oleh inersia termal bumi untuk mengurangi beban panas dalam ruangan, sehingga menawarkan solusi pasif maupun hibrida untuk mencapai kenyamanan termal secara hemat energi. Studi ini menyajikan tinjauan pustaka komprehensif terhadap 30 publikasi kunci terpilih mengenai pendingin dengan bumi di berbagai iklim, dengan tujuan memperjelas definisi, menetapkan klasifikasi sistematis, dan menilai potensi penerapannya di wilayah beriklim tropis yang panas dan lembap seperti Indonesia. Berdasarkan mekanisme pertukaran panas, studi ini membedakan pendinginan dengan bumi ke dalam dua kategori utama: pendingin langsung, yang mengandalkan konduksi melalui kontak langsung antara struktur bangunan dan tanah; serta pendingin tidak langsung, yang menyalurkan udara atau air melalui pipa yang ditanam di bawah tanah untuk pendinginan konvektif dan radian. Sistem tidak langsung ini diklasifikasikan lebih lanjut menjadi Pemindah Panas dari Udara ke Bumi (*Earth–Air Heat Exchanger*/EAHE) dan Pemindah Panas dari Air ke Bumi (*Earth–Water Heat Exchanger*/EWHE), di mana EAHE lebih umum digunakan karena desainnya yang lebih sederhana. Faktor-faktor yang memengaruhi kinerja EAHE meliputi diameter pipa, panjang pipa, susunan pipa, kedalaman penanaman, kecepatan aliran udara di dalam pipa, dan konduktivitas termal tanah. Lebih lanjut, integrasi dengan sistem pasif lainnya seperti atap hijau atau cerobong surya, maupun bantuan mekanis juga dapat meningkatkan performa pendinginan. Hasil kajian menunjukkan bahwa meskipun sistem hibrida yang kompleks banyak ditemukan di iklim kering dan sedang, penerapan di iklim tropis masih terbatas, dan umumnya masih menggunakan konfigurasi EAHE standar. Studi ini menekankan pentingnya meninjau kembali teknik-teknik yang jarang digunakan, seperti yang mengandalkan massa termal atau pendinginan dengan evaporasi, untuk menilai potensi penerapannya pada kondisi tropis. Dengan menyajikan definisi yang jelas dan kerangka klasifikasi terstruktur, penelitian ini diharapkan menjadi landasan bagi adaptasi, inovasi, dan penerapan yang lebih luas dari sistem pendingin dengan bumi di berbagai konteks iklim.

Kata-kata kunci: Pendinginan dengan Bumi, Pendinginan Pasif, Pertukaran Panas dari Tanah ke Udara

ABSTRACT

Earth-coupled cooling systems harness the stable subsurface temperature maintained by the earth's thermal inertia to reduce indoor heat loads, offering a promising passive or hybrid solution for energy-efficient thermal comfort. This study presents a comprehensive literature review of 30 selected key publications on earth-coupled cooling across diverse climates, aiming to clarify definitions, establish a systematic classification, and assess potential applications in hot and humid tropical regions such as Indonesia. The review distinguishes two primary categories based on heat exchange mechanisms: direct earth-coupled cooling, which relies on conductive contact between building structures and soil; and indirect earth-coupled cooling, which circulates air or water through buried pipes for convective and radiant cooling. Indirect systems are further classified as earth–air heat exchangers (EAHE) and earth–water heat exchangers (EWHE), with EAHEs being more prevalent due to their simpler design. Performance factors for EAHEs include pipe diameter, length, arrangement, burial depth, airflow velocity inside the tubes, and soil thermal conductivity, while integration with other passive systems (e.g., green roofs and solar chimneys) or mechanical assistance can further enhance performance. Findings show that while complex hybrid systems have been implemented in arid and temperate climates, tropical applications remain limited, often relying on basic EAHE configurations. The study highlights the importance of reassessing underutilized techniques, such as those based on thermal mass or evaporative cooling for tropical conditions. By providing a clear definition and structured classification, this research offers a foundation for future adaptation, innovation, and broader implementation of earth-coupled cooling systems in tropical climatic contexts.

Keywords: *Earth-coupled cooling, Earth-Air Heat Exchange, Passive Cooling*

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1. INTRODUCTION

Climate change and rising global temperatures have led to a significant increase in cooling demands across many regions, including the hot and humid tropical Southeast Asian countries. Active cooling systems, e.g., air conditioners (AC), have become the dominant solution, whose usage directly contributes to high electricity consumption and increased carbon emissions (Roche, 2022). Therefore, it is crucial to develop more environmental-friendly and energy-efficient cooling solutions, with little or no dependance on mechanical systems, to support sustainable building practices.

Passive cooling technologies have demonstrated significant potential, with temperature reductions ranging from approximately 1°C to 24°C, leading to annual energy savings of about 2 to 300 kWh (Nqoro, et al., 2025). Among these, earth-coupled cooling techniques, which utilize the stable temperature of the earth at certain depths to reduce incoming air temperatures into buildings, have emerged as a promising passive or hybrid approach for enhancing thermal comfort with minimal energy input (Grondzik, et al., 1981). These systems exploit the principles of heat conduction and convection between air, soil, and structural components, with various configurations adapted to different climates, topographies, and building typologies.

A growing body of research across various regions and climatic conditions has exhibited the potential of such systems to reduce indoor temperatures. For instance, studies by Rivero et al. (2023) and Mahmoud et al. (2024) have demonstrated the cooling performance of earth-air heat exchangers (EAHE) in combination with thermal siphons and buoyancy-driven flows. Meanwhile Bourouis et al. (2019) and Pierrès et al. (2022), investigated hybrid systems combining earth-air exchangers with evaporative cooling under hot-dry and temperate climatic conditions. Additionally, Bhandari (2024) provided a broader view of system integration at community scales, highlighting their potential beyond single residential applications.

Despite these advancements, the studies and applications of earth-coupled cooling systems in hot and humid climates, especially in Indonesia, remains relatively underexplored. Despite the demonstrations of earth coupled cooling system potential by Sanusi (2011) and Sanusi et al. (2014) in Malaysian context, the explored systems only represents a standard earth-to-air heat exchanger (EAHE) using circulated air through buried pipes underground, while other systems such as direct conduction or hybrid systems that incorporate other passive cooling techniques are still missing. This is important, since even though the more complex and hybrid systems have been investigated, implemented, and performed well in arid, hot or temperate climates, they may not apply effectively to high-humidity contexts without significant adaptation.

Consequently, this study aims to critically review and categorize existing earth-coupled cooling strategies across climatic regions, with a particular focus on their mechanisms, design configurations, and application systems. By identifying key gaps in the literature, particularly regarding earth coupled cooling systems in hot and humid climates, this review lays the groundwork for future research tailored to climate-responsive building design in Indonesia and similar tropical regions.

2. METHODOLOGY

This study adopts a systematic literature review approach to explore and synthesize researches on earth-coupled cooling systems across various climatic contexts, with emphasis on providing an extensive and comprehensive perspectives of earth-coupled cooling systems and particular intention to assess their relevance and adaptability to hot and humid tropical climate like in Indonesia. The review was conducted by collecting, filtering, and analyzing various relevant scientific publications, from conceptual reviews to computer simulations and experimental studies.

Data collection was carried out through searches on international academic databases such as Scopus, ScienceDirect, SpringerLink, and Google Scholar using keywords such as “earth-air heat exchanger”, “passive cooling”, “subsurface cooling”, “tropical climate”, and “ground-coupled systems”.

To ensure focus and quality, the following inclusion criteria were applied:

- Relevance to earth-coupled or subsurface cooling systems in building.
- Based on empirical, experimental, numerical, or theoretical research.
- Addressing certain climatic conditions, system configurations, or performance outcomes.
- Published in peer-reviewed journals or recognized academic repositories.

On the other hand, exclusion criteria were also included:

- Solely focused on heating or geothermal applications without relevance to cooling.
- Only reviewing articles without original contribution or methodology.

- Incomplete publications lacking accessible data or methodology.

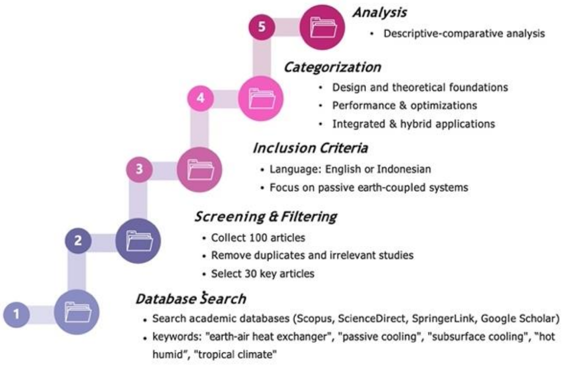

Figure 1: Systematic Literature Review Process

The initial search yielded over 100 peer-reviewed journal articles, book chapters, conference papers, and technical reports, which were later filtered based on the inclusion and exclusion criteria, resulting in a curated selection of 30 key articles. The selected articles were then studied in sequence, based on the publication year, examined in depth to capture both contextual and technical information, including:

- Cooling system typology, terms used and definition
- Location and climatic relevance
- Research methodology
- System configuration and parameters
- Key findings and conclusions

As a result, proper comprehension, categorization and classification can be applied, despite the usage of different terms and definitions for arguably similar systems, e.g., earth-air heat exchanger (EAHE or EAHX), earth pipe cooling (EPC), Earth Tube Heat Exchanger (ETHE), and so on.

As this research is conducted using literature review approach, it is essential to provide a clear overview of the sources examined. Displaying a table that lists the selected key references used, including each study's title, author(s), and key summaries, would enhance the transparency and traceability of the review process. This approach allows identification and verification of the scope and diversity of the literature studied. Presenting this information in this results section also ensures that the foundation of the study's findings is clearly visible and accessible before detailed interpretations are made in the results and discussions sections.

Table 1: Selected 30 Key Articles

No.	Article & Summary
1	Earth coupled cooling techniques (Grondzik, et al., 1981)
	• Conducted in The United States, particularly relevant to hot and arid to semi-arid climates. • Discussing multiple systems of earth coupled cooling techniques, specifically outlining two main types: o Direct Earth Coupling: using the thermal mass of the earth directly in contact with the building structure (e.g., earth-sheltered walls or floors) to moderate interior temperatures. Elements: Subsurface walls, slab-on-grade foundations, soil temperature modeling. o Indirect Earth Coupling: pre-cooling or pre-heating air by passing it through buried ducts or earth tubes before entering the building. Elements: Earth-air heat exchangers (EAHX), underground ducts or tubes, ventilation fans or natural stack-driven airflow.
2	Earth-coupled radiant heating and cooling system for hot, humid climates (Akridge, et.al., 1990)
	• Conducted in Atlanta, Georgia (hot, humid Southeast U.S.), examines an Earth-Coupled Radiant Heating and Cooling System: a hybrid passive HVAC approach that uses the earth's stable subsurface temperature to heat or cool water, which is then circulated through radiant concrete panels indoors. • The system has two main components: (1) Earth-Side Wells: Three vertical wells (45.7 m deep) in clay and granite subsoil, serving as thermal sinks/sources, and (2) House-Side Radiant Panels: 46 concrete wall panels functioning as both structure and radiant surfaces, with water from the wells circulating inside. • Although largely passive in heat exchange, the system uses pumps, controls, and occasionally fans for circulation and regulation.
3	Passive cooling systems in residential buildings (Ingersoll, et al., 2008)
	• Reviewing earth-coupled cooling systems in diverse climates (Israel, U.S., India, etc.), representing temperate, hot-humid, and hot-arid climates. • Examining two system types: o Direct Earth-Coupled Cooling: Passive conductive cooling via direct contact between building structures and earth (e.g., bermed walls, subterranean floors) with shading and soil treatments to regulate soil temperature. o Indirect Earth-Coupled Cooling (Earth Tubes): Pre-cooling of incoming air through buried pipes, requiring minimal mechanical assistance (fans). Performance depends on pipe size, length, depth, material, and airflow rate.
4	Cooling by thermal earth inertia (Almusaed, 2011)
	• A conceptual review of cooling by thermal inertia: using the stable subsurface temperature for conduction, radiation, or convection-based cooling. • Discussed key approaches: o Underground structures: Building elements in direct contact with soil for thermal buffering. Design considerations: waterproofing, drainage, and structural integrity. o Thermal mass cooling: Using bedrock or other mass layers to store and release coolness.

  - Underground earth tubes: Buried pipes that pre-cool air before it enters the building. Types include: open-loop (fresh air intake), closed-loop (recirculated indoor air), vertical loops (45–60 m boreholes), and horizontal loops (2 m deep).
- Design notes: Small-diameter, deeper-buried tubes perform better; wings or internal obstacles can improve heat exchange; ground thermal resistance is the main limiting factor.
- Cautions: Odor, mold, bacterial growth, and pest entry (preventable with proper construction and drainage).

5 Low energy ground cooling system for buildings in hot and humid Malaysia (Sanusi, 2011)

- Conducted at a Kuala Lumpur university campus in a hot-humid tropical climate, examining low energy earth pipe cooling: a passive system where ambient air passes through buried polyethylene pipes to exchange heat with cooler soil.
- Setup: Pipes buried at 0.5, 1.0, and 1.5 m depths, with soil and air temperature sensors at inlet/outlet points.
- Findings: At 1.0 m depth, soil was cooler than peak outdoor temperature by 6 °C (wet season) and 9 °C (dry season); outlet air cooled by up to 6.4 °C (wet) and 6.9 °C (dry).
- Simulations using EnergyPlus closely matched experimental results.

6 Comparison of earth-air and earth-water ground tube heat exchangers for residential air-conditioning application (T'Joen, et al., 2012)

- Comparing Earth Air Heat Exchangers (EAHE) and Earth Water Heat Exchangers (EWHE) without specifying location or climate.
- EAHE: Ambient air passes through buried tubes, exchanging heat with soil before entering the building. Performance depends on tube length/diameter, airflow rate, and soil conductivity.
- EWHE: Water circulates through buried tubes, exchanging heat with soil, then cools indoor air via a compact heat exchanger. Efficiency relies on soil–water conduction, water flow rate, and heat exchanger effectiveness (≥ 0.8).
- Key insights: Soil thermal resistance limits both systems. EAHEs are simpler but constrained by soil conductivity; EWHEs may achieve higher performance in smaller layouts if the air–water exchanger is efficient. Selection depends on soil type, cooling needs, and mechanical complexity.

7 Simulation of a passive ground-coupled cooling system for a room in a hot humid climate (Onyango, 2012)

- Examining a passive earth-air heat exchanger (EAHX) for hot-humid climates (South Florida, USA): Warm, humid outdoor air is directed through buried plastic ducts (200 mm diameter) at 1 m depth, sloped for condensate drainage into a sump. As air passes underground, it exchanges heat with cooler soil (28 °C), lowering its temperature and reducing reliance on mechanical cooling. The process also dehumidifies the air.
- System modeled: 178 m² single-story residence (2.44 m ceiling height), typical of U.S. hot-humid homes.
- Key takeaway: Passive EAHX can provide both cooling and dehumidification in high-humidity regions, but requires careful design for drainage and soil-air heat transfer.

8 Application of earth tube heat exchanger and solar chimney for natural cooling system in Basrah City (Hammadi, et al., 2014)

- Presenting a numerical/analytical evaluation for Basrah's hot climate, integrating an Earth Air Heat Exchanger (EAHE) and a Solar Chimney (SC).
- EAHE: Buried pipes (up to 4 m depth) pre-cool ambient air via soil heat exchange. Cooling improves with deeper burial, smaller diameter, and lower airflow rates.
- SC: Vertical shaft heated by solar radiation induces stack ventilation; performance increases when paired with pre-cooled EAHE air.
- Key takeaway: Combining EAHE and SC can enhance passive cooling and ventilation, with optimal results achieved by balancing pipe geometry, depth, airflow, and chimney dimensions.

9 Materials for the earth-air pipe heat exchanger (EAPHE) system as a passive ground cooling technology for hot-humid climate (Ariffin, et al., 2014)

- Conducted in Malaysia's hot-humid climate, using EnergyPlus simulations to assess Earth-Air Pipe Heat Exchanger (EAPHE) performance with different pipe materials.
- System parameters: 25 m length, 50 mm diameter, 1 m depth, 0.5 m/s airflow, max inlet temp 36.46 °C.
- Tested configurations: single-material pipes (PVC, PE, Cu, St), hybrid-material pipes, and insulated hybrid pipes (water or rockwool).
- Findings: Across all configurations, maximum cooling potential varied minimally (6.23–6.24 °C drop). PE and steel combinations performed slightly better, but overall material choice had negligible effect.
- Key takeaway: In hot-humid climates, pipe material selection has limited influence on EAPHE cooling performance compared to system geometry and operating parameters.

10 Achieving cooler soil as an effective heat sink for earth-to-air heat exchanger (EAHE) cooling technology in Malaysia tropical climate (Sanusi, et al., 2014)

- Conducted in Malaysia's hot-humid climate, testing ways to improve Earth-Air Heat Exchanger (EAHE) performance by lowering surrounding soil temperature.
- Method: Pipes buried at 1.0 m and 1.5 m depths; soil surface treated with either bare soil, timber pallet shading, or used tyre shading. Soil temperatures were monitored with embedded sensors and a data logger.
- Findings: Used tyre shading yielded the coolest soil, followed by timber pallet shading, then bare soil.
- Impact: EnergyPlus simulations confirmed that cooler soil improves EAHE heat exchange efficiency, enhancing overall cooling performance.
- Key takeaway: Surface shading boosts EAHE performance by reducing soil temperature around buried pipes.

11 Underground soil and thermal conductivity materials based heat reduction for energy-efficient building in tropical environment (Alam, et al., 2015)

- Using numerical modeling (COMSOL Multiphysics) to assess an underground soil–thermal conductivity pipe system for Malaysia's tropical climates.

- System: Thermal conductivity pipes are attached to interior walls and extended underground, transferring indoor heat into cooler subsurface soil.
- Key factors: Soil type (e.g., sandy loam vs. clay loam) strongly affects heat dissipation.
- Results: up to 3 °C indoor temperature reduction when paired with other passive or mechanical cooling.
- Insight: Ground-connected wall though thermal conductivity pipes can enhance passive cooling by using soil as a continuous heat sink.

12 Design of earth–air heat exchanger system (Bisoniya, 2015)

- Developing a 1D theoretical model for earth-air heat exchangers (EAHE) in arid and temperate climates, using simplified equations to estimate heat transfer, convective coefficients, pressure drop, and pipe length.
- Key variables: Pipe length, depth, diameter, airflow velocity, and earth's undisturbed temperature (EUT).
- Insight: Longer, deeper, smaller-diameter pipes with lower air velocity improve both cooling and heating performance.

13 Performance evaluation of hybrid earth pipe cooling with horizontal piping system (Ahmed, et al., 2016)

- Validated for Rockhampton, Australia (hot-humid subtropical climate), modeling Horizontal Earth Pipe Cooling (HEPC): buried horizontal pipes exchanging heat with soil, integrated with green roofs.
- Using thermal modeling (ANSYS Fluent) comparing three rooms: HEPC only, green roof only, and no system.
- Findings: HEPC alone reduced room temperature by 1.1 °C; HEPC + green roof reduced by up to 4.26 °C; Pipe length most strongly affected cooling (optimal: 10–20 m); Smaller diameters (100 mm) and moderate airflow (1–3 m/s) further improved heat exchange.

14 A review of underground building towards thermal energy efficiency and sustainable development (Alkaff, et al., 2016)

- Reviewing Earth-Sheltered or Underground Buildings (ESUB) across climates from hot-arid to temperate, leveraging soil's stable thermal properties for passive indoor temperature regulation.
- Scope: Historical/vernacular examples, thermo-physical factors (thermal mass, insulation, moisture control), and conceptual designs combining passive solar, ventilation, and daylighting.
- Findings: (1) ESUB maintains stable, moderate indoor temperatures year-round; (2) ESUB significantly lowers HVAC energy use, especially in extreme climates; (3) ESUB supports decarbonization, resource efficiency, minimal land use, and climate-resilient comfort.

15 Parametric study of an earth-air heat exchanger assisted by a green wall for passive cooling in hot climates (Bourouis, et al., 2019)

- The study models an Earth-Air Heat Exchanger (EAHE) integrated with a Green Wall-Air Heat Exchanger (GAHE) for hot-arid climates like Adrar, Algeria.
- System: Air is pre-cooled in underground EAHE pipes, then further cooled via a GAHE facade using shading and evapotranspiration.
- Findings: (1) GAHE notably boosts EAHE cooling, especially at low airflow or shallow pipe depths; (2) Coupling the systems can maintain performance with shorter EAHE pipes, reducing space and cost.

16 Utilization of earth-to-air heat exchanger to pre-cool/heat ventilation air and its annual energy performance evaluation: a case study (Zhang, et al., 2020)

- Modeling an Earth-to-Air Heat Exchanger (EAHE) for China's hot-summer, cold-winter climate. Ambient air is pre-cooled in summer and pre-heated in winter via buried pipes, easing HVAC loads.
- Key design variables: burial depth, pipe length, and pipe diameter.
- Optimal design: 5 m depth, 80 m length (balancing performance and cost).
- Performance: 19.6 kWh/day cooling and 19.3 kWh/day heating for ventilation air.
- Impact: Cutting ventilation cooling demand by 16% and heating demand by 50% annually.

17 A sustainable approach to improve the efficiency of earth pipe cooling system (Ishtiaque, et al., 2020)

- Modeling Earth Pipe Cooling (EPC) for Dhaka's hot-humid subtropical climate using CFD simulations. Ambient air passes through buried pipes to leverage cooler subsurface temperatures.
- Focus: Effect of inlet airflow dispersion and geometry on cooling performance.
- Key finding: Adding inlet turbulators boosts air circulation, improving temperature uniformity.
- Performance gain: ~0.8 °C extra cooling, saving ~0.84 kWh/day.
- Insight: Optimized inlet design can meaningfully enhance EPC efficiency.

18 Eco-efficient evaporative and ground-coupled system with terra-cotta evaporative walls (Pierrès, et al., 2021)

- Simulating an eco-efficient cooling system for a 100 m² house in Bordeaux's temperate climate, designed primarily for hot regions, integrating ground-coupled cooling and terra-cotta evaporative cooling to operate without mechanical refrigeration.
- Operation: Underground tank cools water via earth mass → cooled water circulates through radiant floor → warm water is diverted to porous terra-cotta walls for evaporative cooling → re-cooled water returns to tank.
- Performance:
    - Best in hot-dry climates (max evaporation efficiency)
    - Moderate in hot-humid climates (reduced evaporation)
    - Less suitable in cold climates
- Adaptability: Flow rate, burial depth, and wall porosity can be tuned to local conditions.
- Note: Ground-coupled component retains usefulness in most climates; further field validation recommended.

19 Performance analysis of an integrated cooling system consisted of earth-to-air heat exchanger (EAHE) and water spray channel (Ahmadi, et al., 2021)

- Targeting hot-arid conditions of Tehran, Iran, using EAHE + water spray channel system; ambient air is first pre-cooled underground via EAHE, then passes through a vertical spray channel for evaporative cooling.

- Key performance: Achieved >100 % cooling effectiveness, outlet temperatures dropped below ambient wet-bulb temperature.
- Impact: Able to maintain summer comfort levels without mechanical AC.
- Suitability: Strong potential for hot, dry climates as an eco-friendly, low-energy cooling.

20 Ventilative cooling in combination with other natural cooling solutions: earth-to-air heat exchangers—EAHX (Chiesa, 2021)

- Exploring ventilative cooling combined with Earth-to-Air Heat Exchanger (EAHX), adaptable to many climates, with emphasis on temperate and warm regions.
- Ventilative cooling: Using natural/mechanical airflow (cross, stack, or night purging) to flush heat and reduce AC demand.
- EAHX: Pre-cooling outdoor air via underground pipes, enabling ventilative cooling even when ambient air is too warm.
- Key insights: (1) Pairing ventilative cooling with EAHX broadens climate applicability and boosts performance. (2) Most effective when integrated at early design stages. (3) Promising strong potential for comfort, energy efficiency, and climate adaptability in residential and commercial buildings.

21 Potential applicability of earth to air heat exchanger for cooling in a Colombian tropical weather (Peña, 2021)

- Conducted in Bucaramanga, Colombia (hot, humid tropical climate), evaluating an Earth-to-Air Heat Exchanger (EAHE) using TRNSYS simulation with local soil and climate data.
- System specs: 7 parallel pipes, 252 m total length, 0.2 m diameter, buried 1.5 m deep; Airflow: 1,560 kg/h
- Key insights:
    - Delivered air cooled by 3 °C (20.9–24.1 °C), meeting comfort needs.
    - Cooling COP ranged from 0.91–160.
    - Economically viable: 23% IRR, 6-year payback.
    - Effective for tropical climates with stable underground temperatures and limited night-time cooling.

22 Comparison of single- and multipipe earth-to-air heat exchangers in terms of energy gains and electricity consumption: a case study for the temperate climate of Central Europe (Amanowicz, et al., 2021)

- Conducted in Katowice, Poland (temperate continental climate), using TRNSYS simulation to compare single-pipe and multi-pipe (3, 5, 7 branches) mechanically assisted Earth-to-Air Heat Exchanger (EAHE).
- Key insights:
    - Multi-pipe systems: up to 56% higher energy gain and more stable outlet temperatures in extreme summer/winter, but slightly higher electricity use from fan operation.
    - Single-pipe systems: lower energy use and simpler, cheaper setup, but less thermal performance.
- Best applications:
    - Single-pipe: moderate climates, low electricity priority, retrofits, low-cost systems.
    - Multi-pipe: net-zero/passive houses, hot or cold extremes, new builds with available space.

23 Applications of earth-to-air heat exchangers: a holistic review (Mihalakakou, et al., 2022)

- A global review of Earth-to-Air Heat Exchanger (EAHE) applications across hot, temperate, and arid climates synthesizes theory, experiments, parametric designs, and hybrid systems.
- Key insights:
    - Performance depends on climate, soil properties, pipe design (length, radius, depth, airflow, material), and surface conditions (shading/insulation).
    - Hybrid systems (e.g., evaporative cooling, solar-driven ventilation, renewable heat recovery) can markedly improve performance in challenging climates.
    - Many EAHE designs show positive ROI when climate suitability is high.
    - Calling for more long-term experimental validation and physical testbeds to strengthen design guidelines.

24 Parametric performance analysis of the cooling potential of earth-to-air heat exchangers in hot and humid climates (Bughio, et al., 2022)

- A parametric simulation for Karachi, Pakistan's hot-humid climate optimized Earth-to-Air Heat Exchanger (EAHE) design using a BIM–DesignBuilder model.
- Tested system parameters: Pipe material: HDPE; Pipe lengths: 1,160 m, 1,547 m, and 1,418 m; Pipe diameters: 0.10 m, 0.15 m, 0.20 m; Burial depths: 1 m, 2 m, 3 m, and 4 m; Air velocity: constant at 5 m/s
- Key insights:
    - Smaller pipe diameters (0.1 m) improve cooling by increasing surface area-to-volume ratio.
    - Deeper burial (3–4 m) leverages more stable soil temperatures.
    - Tested configurations achieved up to 15.2 °C temperature reduction between outdoor and conditioned indoor air.

25 Earth-to-air heat exchanger for cooling applications in a hot and dry climate: numerical and experimental study (Albarghooth, et al., 2023)

- An EAHE performance study in Karbala, Iraq (hot, dry climate) using combined simulation & experimental validation with a polynomial correlation model, linking outlet air temperature to air velocity, pipe length, diameter, and soil conductivity.
- Key insights:
    - Pipe length: strongest nonlinear influence; nearly linear for 75–100 mm diameters.
    - Soil conductivity: saturated soil (k = 1.5 W/m·K) requires 25% shorter length than dry soil (k = 0.5 W/m·K).
    - Air velocity effect (7 m/s): 26 °C outlet needs 62.1 m length; 29 °C outlet needs 39.9 m length (55% more length needed per extra °C of cooling).
    - Performance drivers: longer pipes, higher soil conductivity, optimized airflow (must be balanced for cost-effectiveness).
- Implication: Site-specific soil properties and airflow control are crucial for sizing EAHE systems.

26 Earth-air thermal siphon as a passive air-conditioning system for an arid climate (Rivero, et al., 2023)

- Proposing passive vertical EAHE with natural convection designed for arid climates with large diurnal temperature swings.
- System description:
  - Vertically embedded pipes in thermally massive soil.
  - Airflow induced purely by buoyancy: hot air rises, cool underground air sinks.
  - Operates in daily cycles aligned with solar heating and nighttime cooling.
  - No fans or external power required.
- Key insights:
  - Pipe geometry dominates performance: Smaller radius results in faster airflow but less heat transfer; Longer pipes results in better cooling but slower airflow.
  - Soil properties (thermal conductivity/diffusivity) influence performance less than pipe geometry.
  - Cyclic operation: Daytime draws cool air upward; nighttime airflow slows or reverses depending on temperature gradients.
- Implication: Offering a low-energy cooling solution in arid regions where large day–night temperature differences can drive natural convection.

27 Conduction shape factors for thermally active retaining walls (Gupta, et al., 2023)

- Simulation-based analysis of thermally active retaining walls with embedded heat exchanger pipes for heating/cooling in buildings with underground structures (e.g., basements, transit stations).
- System: Pipes: Ø 25 mm, embedded 75 mm from back wall face; Spacing: 0.3–0.8 m between pipes; Wall thickness: 0.4–1.2 m.
- Simulation: Constant heat flux of 12 W/m² applied for 1 year (transient model); Comparing analytical shape factor models: single buried pipe vs equally spaced pipes, validated against numerical simulation.
- Key insights:
  - Equally spaced pipes model best reflects steady-state performance for energy walls.
  - Pipe spacing: closer spacing improves thermal interaction and efficiency.
  - Wall thickness: minimal effect on steady-state heat transfer, but affects thermal response time, i.e., thinner walls reach equilibrium faster; thicker walls may take up to a year.
  - Heat transfer direction: pipe → wall → soil (heating) or reverse (cooling).
- Implication: Energy walls can double as structural and thermal exchange systems, with spacing optimization being more critical than wall thickness for performance.

28 Earth air heat exchangers (Mahmoud, et al., 2024)

- A comprehensive EAHE review: integrating analytical, numerical, and economic perspectives from global studies, no climate focus.
- System: Earth-to-Air Heat Exchanger (EAHE): buried ducts exchange heat between ventilation air and the earth's stable subsurface temperature, enabling passive cooling or heating depending on season.
- Key design parameters: Pipe geometry (diameter, length); Burial depth; Soil thermal conductivity & temperature; Climate variables (ambient temperature, wind speed, solar radiation).
- Key insights:
  - Passive EAHEs with natural airflow (e.g., solar chimneys, wind towers) can operate at near-zero running cost and extremely low energy consumption.
  - Embedding EAHE ducts into building foundations can lower capital cost and simplify installation.
  - Optimal EAHE design balances thermal performance, capital/operational costs, and environmental gains.
- Implication: EAHE systems are most impactful when integrated into building design from the outset, especially when combined with passive airflow drivers.

29 Performance measurement and configuration optimization based on orthogonal simulation method of earth-to-air heat exchange system in cold-arid climate (Zhang, et al., 2024)

- A real-world EAHE optimization in Lanzhou, China, conducted in a cold-arid climate with large seasonal swings and variable shallow soil temperatures, investigating standard earth-to-air heat exchanger (EAHE): buried pipes circulate ambient air for ventilation and air-conditioning.
- Method: Year-round monitoring (summer to winter); Orthogonal simulation to explore parameter interactions; Metrics: outlet air temperature, energy use, seasonal efficiency
- Key insights:
  - Peak heat exchange in extreme months (June–July, Dec–Jan)
  - Shallow soil temperature swings strongly affect performance
  - Parameter influence ranking: pipe length > diameter > burial depth > airflow velocity
  - Optimal setup: 20 m pipe length, 100 mm diameter, 4 m burial depth, 7 m/s airflow
- Implication: In cold-arid regions, EAHE performance hinges on precise tuning of geometry, especially pipe length, to handle strong seasonal soil temperature variability.

30 Sustainable cooling solutions for building environments: A comprehensive study of earth-air cooling systems (Bhandari, 2024)

- Investigating a community-scale EAHE in Budhanilkantha, Nepal, evaluating a multi-room community building in a humid tropical/subtropical climate.
- System: Earth-Air Cooling System (EACS): buried pipe heat exchangers deliver precooled air to interiors for passive cooling.
- Design & tools: LMTD method for pipe sizing; TRNSYS for annual load simulation; ANSYS CFD for airflow & thermal visualization
- Optimal setup (field + simulation): 12 pipes × 46 m each; Air velocity: 4.5 m/s
- Performance: 33% temp reduction (vs 23% predicted), 53.2 kW cooling (exceeding peak load)
- Significance: One of the few documented, real-field, community-scale EAHE systems in a humid climate, proving feasibility for meeting peak cooling demands.

3. RESULTS

The selected key articles are grouped into three categories:

- **Design and theoretical foundations**, aimed to extract proper definitions and classifications of earth coupled cooling systems and to gain solid understanding about the key principles on how they actually work, which eventually allows further implementations and improvements of the systems.
- **Performance and optimizations**, exploring relevant and significant parameters that might result in optimum performance of earth coupled cooling systems.
- **Integrated and hybrid applications**, exploring additional measures, passive or active, that can be combined with earth coupled cooling systems to improve the systems' performance.

It is important to note that several of the reviewed studies could reasonably fall into more than one category, as many combine conceptual development, performance evaluation, and hybrid integration. However, for clarity and to align with the objectives of the present study, each work is placed into the category that best reflects its primary emphasis and contribution. This approach allows for a structured synthesis without overlooking the cross-cutting nature of the research field.

3.1 Design and Theoretical Foundations

Referring to Almusaed (2011), earth-coupled cooling is defined as a set of techniques that harness the stable thermal properties of the ground at certain depth to moderate air or surface temperatures for building cooling purposes. The approach relies on the fact that, below a certain depth, soil temperature remains relatively constant throughout the year, uninfluenced by daily and seasonal air temperature fluctuations, often described as thermal earth inertia. This phenomenon occurs due to the ground's large heat capacity and low thermal diffusivity, allowing it to absorb, store, and release heat at a slow rate over time (Almusaed, 2011).

The study by Grondzik et al. (1981) becomes the oldest literature referred in this study, serving as the basis for classifying earth coupled cooling systems into two major types, which are (1) direct earth cooling; the system in which the earth (soil) is used to absorb heat through direct contact with building structure conductively, and (2) indirect earth cooling; the system in which air (or water) is pre-cooled using tubes (pipes) buried underground before entering the interior and moderating the temperature convectively and radiatively.

Almusaed (2011) further classifies direct earth cooling based on thermal mass employed in the heat exchange process, which are (1) using underground building's exterior walls; where the cooling process happens through thermal exchange facilitated by direct contact between building's external elements and the soil mass, and (2) using dedicated thermal mass/conductivity; in which additional structures inside the building (e.g., bedrock installation under the floor) are used as the thermal mass that store heat exchange capacity gained conductively from the soil to perform radiant cooling in the interior.

Another instance of direct earth-coupled cooling is shown in a study by Alam et al. (2015), where square thermal conductivity pipes are fixed on the inner side of a building's walls while their lower ends are extended into the ground to allow conductive heat exchange between the pipes and the soil. Direct earth-coupled cooling can work fully passive without any mechanical equipment, but requires careful design related to waterproofing, drainage, and structural support (Almusaed, 2011).

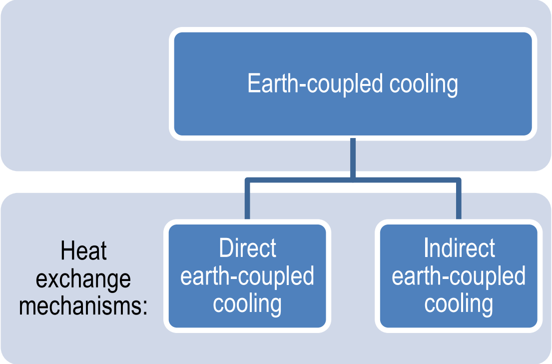

Figure 2: Classification of Earth-Coupled Cooling based on Heat Exchange Mechanisms

On the other hand, more sophisticated classifications can be applied to indirect earth-coupled cooling, which can be defined as a system that uses flowing substances, mainly air or water, circulated in tubes buried underground to facilitate heat exchange between interior spaces and the ground. Accordingly, based on the substance circulated in pipes, indirect earth cooling can be classified into (1) earth-to-air heat exchanger (EAHE or EAHX) and (2) earth-to-water heat exchanger (EWHE), as in a study by T'Joen et al. (2012), which reported that the first system might be simpler while the later offered better performance with smaller underground layout.

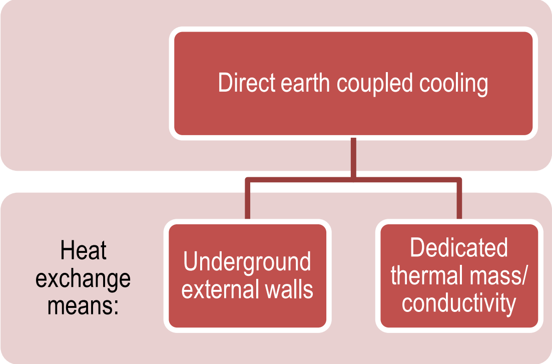

Figure 3: Classification of Direct Earth-Coupled Cooling based on Heat Exchange Means

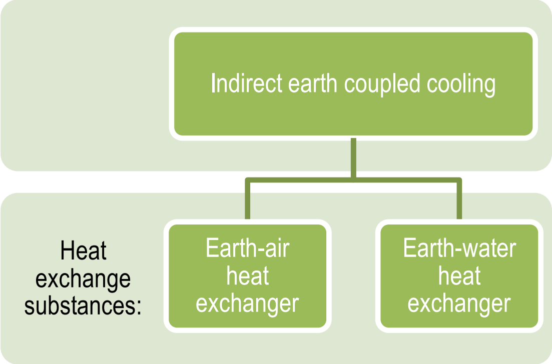

Figure 4: Classification of Indirect Earth-Coupled Cooling based on Heat Exchange Substances

Unlike EAHE that can operate either fully passive or with mechanical elements (fan), EWHE absolutely requires mechanical elements (pump) to keep the system working. Indeed, simplicity is a crucial factor that determines how easily the systems can be adopted and implemented in wider contexts, as it also translates into more efficient, less complicated, and cheaper installations. Unsurprisingly, this also impacts on the quantity of researches examining EAHE to be massively higher than those exploring EWHE found in this review. Both cooling substances, however, can be circulated in both (1) horizontal and (2) vertical loop systems (Almusaed, 2011).

Moving on with EAHE specifically, in terms of the loop system, it can be divided into (1) open loop system, in which outdoor air is drawn into underground pipes before entering the interior, and (2) closed loop system, which circulates air through the underground pipes without exchanging it with the outdoor air (Almusaed, 2011). The closed loop system might be more efficient in terms of heat exchange, but might lead to air quality issues if proper air regulation is absent. It is worth noting that this review found multiple terms and acronyms used to represent earth-air heat exchanger (EAHE or EAHX), such as earth pipe cooling (EPC) (Sanusi, 2011; Ishtiaque, et al., 2020), earth tube heat exchanger (Hammadi, et al., 2014), and earth-air pipe heat exchanger (EAPHE) (Ariffin, et al., 2014).

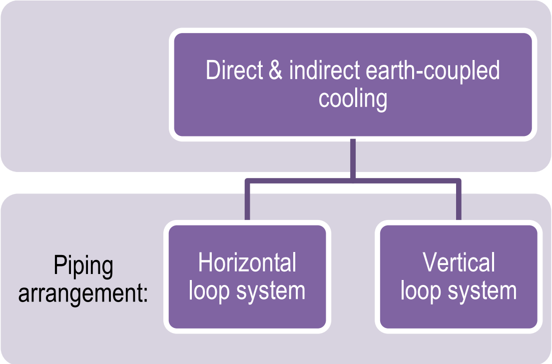

Figure 5: Classification of Direct & Indirect Earth-Coupled Cooling based on Piping Arrangement

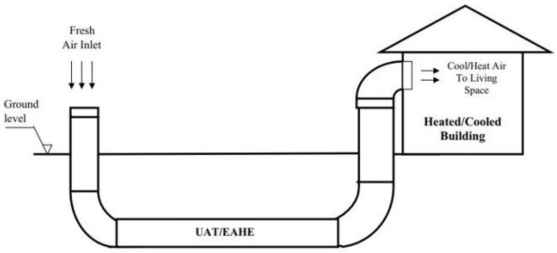

Figure 6: Open-Loop EAHE System
(Source: Kumawat et al., 2022)

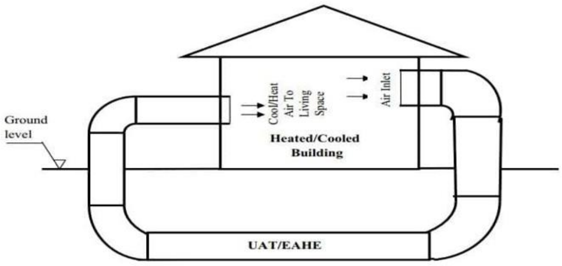

Figure 7: Open-Loop EAHE System
(Source: Kumawat et al., 2022)

3.2 Performance and Optimizations

Different measures are required to improve the cooling performance of both direct and indirect earth cooling systems due to their respective key mechanisms used for the heat exchange processes.

Related to direct earth coupled cooling, Alkaff et al. (2016) explore three types of vernacular architecture typology across regions, including (1) atrium/court yard plan, where buildings are fully submerged into the ground, (2) elevational plan, where all walls are bermed within earth except the south facing wall in cold regions and the northern wall in hot climatic zones, and (3) bermed plan, where earth is loaded up against exterior walls and piled to incline downwards away from the building. The study concludes that atrium plan excels in terms of thermal stability as well as wind and noise protection, while the other two have better passive solar and natural lighting potential, and still offer visual convenience. In terms of wall thickness, a study by Gupta et al. (2023) concludes that the thickness of a thermally active underground retaining wall has minimal effect on steady-state heat transfer, but affects thermal response time, i.e., thinner walls reach equilibrium faster while thicker walls may take up to a year.

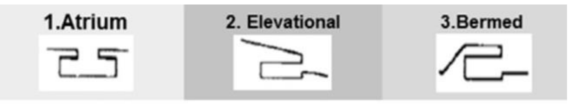

Figure 8: Underground Building Typology
(Source: Alkaff et al., 2016)

Sanusi (2011) provided one of the earliest empirical validations of earth pipe cooling (EAHE) in Malaysia's hot-humid climate, showing that pipe burial depth strongly influences cooling performance. In that study, at 1.0 m depth, soil remained up to 9 °C cooler than peak outdoor air during the dry season, enabling outlet air temperature reductions of 6–7 °C. Sanusi et al. (2014) later showed that surface shading, which in the study was done using tyre and timber pallets, further improves soil temperature stability and system performance. Furthermore, Alam et al. (2015), Albarghooth et al. (2023), and Mahmoud et al. (2024) demonstrated that soil's higher thermal conductivity also plays a decisive role in better thermal dissipation. Together, these studies highlight that burial depth, soil surface management (shading), and soil properties (temperature and thermal conductivity) are critical for enhancing the system's cooling performance.

On the other hand, Rivero et al. (2023) argue that pipe geometry (diameter and length) dominates the cooling performance over soil properties. Zhang et al. (2024) also suggest that precise tuning of pipe geometry, especially pipe length, might compensate strong seasonal soil temperature variability. An explanation provided by Bughio et al. (2022) says that smaller pipe diameters improve cooling by increasing surface area-to-volume ratio, making the material usage more efficient. Smaller pipe radius also results in faster airflow, while longer pipes allow the air to stay longer underground, which results in more heat being exchanged (Rivero et al., 2023). Furthermore, Amanowicz et al. (2021) demonstrated that multi-pipe configurations can increase thermal performance by up to 56% compared to single-pipe systems. With that being said, the design should emphasize on achieving balance between maximizing cooling and minimizing cost (Almusaed, 2011).

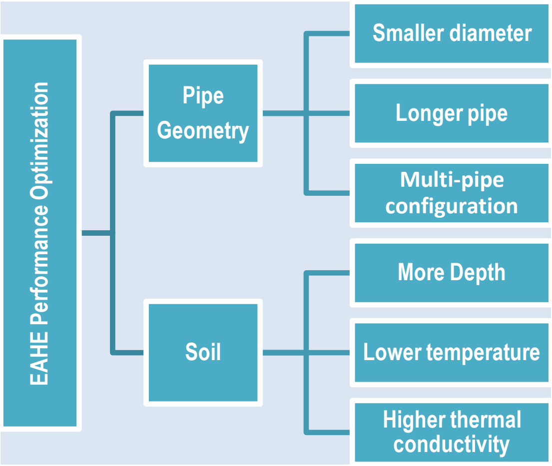

Figure 8: EAHE Performance Optimization

In contrast, Ariffin et al. (2014) found that pipe material contributed minimally to the earth coupled cooling performance, with only around 0.01 °C variation across various tested materials and configurations, i.e., single materials (PVC, Polyethylene, copper, and steel) and insulated combinations of those materials. This indicates that material selection is secondary to geometric factors and soil conditions, especially in hot-humid climates where the study was conducted. Insulated hybrid pipes provided negligible additional benefit, suggesting that investments in material upgrades may not yield proportional performance gains. Instead, the use of flow mechanics (fans) emerges as another significant performance booster, as shown by Ishtiaque et al. (2020), where inlet turbulators are used to improve air circulation and thermal uniformity, yielding measurable cooling gains.

3.3 Integrated and Hybrid Applications

The integration of earth-coupled cooling systems with other passive and renewable mechanisms has demonstrated significant potential in enhancing thermal performance and environmental adaptability across diverse climatic conditions (Mihalakakou, et al., 2022). A number of studies have explored the combination of Earth–Air Heat Exchanger (EAHE) systems with complementary natural or mechanical strategies to improve cooling efficiency and overall system resilience, among others by Hammadi et al. (2014), who investigated the use of an Earth Tube

Heat Exchanger (ETHE) integrated with a solar chimney for natural ventilation in the hot climate of Basrah City, Iraq. The results indicated that the solar chimney substantially increased buoyancy-driven airflow and pressure differentials, thereby enhancing air circulation and indoor comfort compared to the ETHE operating alone. Chiesa (2021) further contextualized such systems within broader frameworks of ventilative cooling, emphasizing that EAHEs can serve as modular components that might be effectively combined with solar chimneys, wind catchers, and cross-ventilation systems to maximize passive cooling potential.

Apart from airflow enhancement, Bourouis et al. (2019) developed a bio-integrated system that combined an EAHE with a green wall, merging ground cooling with the evaporative and shading effects of vegetation. This approach demonstrated the synergistic potential between biological and thermal systems, where evapotranspiration contributed to pre-cooling of air before indoor delivery. Similarly, Pierrès et al. (2021) introduced an eco-efficient cooling concept that coupled underground heat exchange with terracotta evaporative walls, leveraging porous ceramic materials for evaporative cooling while maintaining the thermal buffering benefits of the soil. Ahmadi et al. (2021) also integrated EAHE system with another moisture-driven cooling, which is water spray channel, resulting in greater latent and sensible heat exchange, particularly effective in hot and dry climates where evaporative processes can be maximized.

Beyond these EAHE-centered hybrid approaches, Gupta et al. (2023) introduced a notable scenario by integrating direct and indirect earth-coupled cooling within thermally active retaining walls. In this configuration, the retaining wall itself functions as a direct thermal conductor that exchanges heat with the surrounding soil, while embedded heat exchanger pipes within the wall act as an indirect cooling mechanism similar to an EAHE. This dual-mode system effectively merges the conductive properties of soil–structure interaction with convective heat exchange of buried ducts, resulting in improved heat dissipation and structural efficiency.

These integrations can overcome climatic limitations and extend system performance where direct or indirect earth coupled cooling alone might underperform. This reinforces that performance optimization should not be seen as a matter of a single parameter (pipe, soil, or geometry), but as a systemic design strategy involving climatic adaptation, system coupling, and long-term experimental validation.

4. DISCUSSIONS

Adoption and adaptation of earth-cooling techniques to hot and humid tropical contexts require dedicated and context-specific studies. While it may be tempting to assume that certain techniques, such as those relying heavily on evaporation, thermal mass, or conductivity, are less relevant or unsuitable for tropical climates like Indonesia, such assumptions should be approached with caution. Revisiting ideas or findings that have long been accepted as general truths can sometimes lead to new or unexpected insights. Striking the right balance between building on knowledge acquired from earlier studies and re-examining that knowledge to confirm, refine, or challenge it is essential for advancing understanding and uncovering new perspectives.

5. CONCLUSIONS

This review explores diverse studies concerning earth-coupled cooling across multiple regions and climates, concluding that fundamental aspect of the technique is the usage of ground stable temperature at certain depth, thanks to the earth thermal inertia, to dissipate heat from the interior air into the soil, resulting in lowered indoor temperature. Through systematic review on 30 selected key articles, this research comes up with sequential classifications that facilitate comprehensive understanding towards earth-coupled cooling.

Referring to the heat exchange mechanisms involved, the cooling systems can be categorized into (1) direct earth-coupled cooling, which exploits conductive cooling through direct contact between building's structure and the surrounding soil, and (2) indirect earth coupled cooling, which utilizes convective and radiant cooling using air or water circulated though pipes buried underground, being cooled down before entering the building, thus can be further classified as (1) earth-air thermal exchanger (EAHE) and (2) earth-water heat exchanger (EWHE). EAHE is simpler compared to EWHE, making it more popular in terms of applications and studies.

In general, better cooling performance of EAHE can be achieved through using smaller diameter and longer pipes, multiple parallel arrangement, deeper burial, and slower air velocity inside the tubes. Besides, shaded, covered and more saturated soil with higher thermal conductivity also results in better cooling. In addition, EAHE can be integrated either with (1) other passive cooling systems, e.g., green wall, green roof, water spray channel, and solar chimney, to make use of evaporative cooling and stack-effect driven ventilation, or (2) mechanically assisted cooling systems.

The 30 reviewed studies exhibiting variations of promising concepts and applications of earth-coupled cooling, shaped by climate, available materials, and intended application. Some of the documented systems originate in arid and temperate regions, featuring complex and integrated hybrid cooling systems, offering a transferable lens for understanding, adopting, and adapting the designs in any context, including the hot and humid tropical climate, whose representations in this review only cover the EAHE-alike systems.

When it comes to adopting and adapting an earth-coupled cooling system for the hot and humid tropical environments, this study underlines the importance of not dismissing certain system types, such as those relying on thermal mass or evaporative effects, without careful re-evaluation. In addition, the precise definition and consistent classification derived from this study is expected to serve as an anchor for future researches that expand the role of earth-coupled cooling as a viable pathway toward sustainable thermal comfort.

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