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Harnessing Thermal Stress for Sustainable Zero-Energy Building Design in Iraq

Mazin Ismael Raheem [1]*, Xiaofeng Zheng [1] and Christopher Wood [1]

[1] *University of Nottingham, Department of Architecture and Built Environment, Nottingham, United Kingdom.*

ABSTRACT

The built environment in Iraq has been negatively affected by climate change, with high external temperatures and increased heat transfer into buildings creating greater dependence on mechanical and electrical systems for heating and cooling. While these systems are vital for ensuring thermal comfort and healthy indoor conditions, they also drive-up overall energy consumption—an issue of global concern that increases operational costs and places financial pressure on building occupants. This situation highlights a research gap: the widespread reliance on purely mechanical solutions in Iraq overlooks the potential of climate-responsive design strategies to reduce energy demand. By integrating such approaches and applying modern technologies to cover the remaining energy needs, it is possible to significantly cut energy consumption and ultimately achieve zero-energy buildings. In order to control indoor temperature in hot, dry conditions, this study suggests an integrated passive design approach that incorporates courtyard microclimate, thermal stress-driven airflow, and an earth-air heat exchanger system. The suggested method makes use of natural temperature gradients to produce indoor thermal comfort between 21 and 25°C, in contrast to traditional methods that mostly rely on mechanical devices. The paper addresses the limited application of climate-responsive design solutions in such contexts by presenting a low-energy, context-specific design strategy appropriate for areas like Iraq.

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1. INTRODUCTION

The built environment has been increasingly impacted by climate change, particularly due to elevated external temperatures and high rates of heat transfer into buildings. As a result, reliance on mechanical and electrical service systems—such as heating, ventilation, and air-conditioning—has become essential to ensure thermal comfort and maintain a healthy indoor environment. However, these systems directly contribute to overall energy consumption, a global challenge that has substantially increased the operational costs of buildings and imposed financial burdens on occupants.

The necessity for sustainable and energy-efficient building techniques has increased due to the growing effects of climate change on the built environment. Buildings contribute significantly to both global energy consumption and carbon emissions, according to recent studies, underscoring the need for zero-energy building

* Corresponding author. Email address: alymr1@nottingham.ac.uk (Mazin Ismael Raheem)

designs and climate-responsive design strategies (Cherian et al. 2025).

The integrated use of thermal stress mechanisms in conjunction with courtyard microclimate and under/above-ground heat exchange systems has received little attention despite the expanding body of research on zero-energy buildings and passive cooling techniques, especially in hot, arid regions like Iraq.

This work presents a revolutionary method that does not rely on traditional mechanical systems and uses thermal stress as a driving factor for air movement and temperature adjustment. In order to attain indoor thermal comfort within the range of 21–25°C under adverse weather conditions, the suggested system innovatively combines earth-air heat exchanger technology with courtyard-based airflow dynamics.

Although earth-air heat exchangers and passive cooling systems have been thoroughly studied in the past, this study provides a conceptual re-evaluation by combining thermal stress processes with courtyard microclimate dynamics in the particular setting of Iraq. The study offers a fresh framework that reinterprets current environmental techniques to better suit hot-arid climatic conditions, as opposed to proposing completely new technology.

Based on a review of previous studies, the following research gap emerges:

1.1. RESEARCH GAP

Despite the growing body of research on passive cooling and zero-energy buildings, limited studies have explored the integration of thermal stress mechanisms with courtyard-based airflow and earth-air heat exchanger systems in hot-arid climates. Existing research often focuses on isolated strategies rather than combined systems tailored to specific climatic conditions, such as those found in Iraq.

Prior research has mostly concentrated on individual passive cooling methods, such as ground heat exchangers, thermal mass, or ventilation, with little attention paid to their combined use in a single system (Al-Ajmi et al. 2006) & (Lee & Strand 2008).

This study suggests a context-driven combination of several solutions, providing a more comprehensive answer to Iraq's climate concerns than earlier research that concentrated on single passive techniques.

1.2. RESEARCH OBJECTIVES

The primary goals of this research are to:

- Examine thermal stress's potential as a passive method of controlling interior temperature.
- Develop and refine an integrated design approach that integrates earth-air heat exchanger systems with the courtyard microclimate.
- Consider Baghdad's climate when assessing the suggested system's efficacy.
- Help create climate-responsive building design strategies appropriate for hot, dry climates.

1.3. INNOVATION AND STUDY CONTRIBUTION

This study makes several significant contributions to the field:

- It presents a novel use of thermal stress as a passive temperature and ventilation driver.
- It suggests an integrated system that combines earth-air heat exchangers, vertical air movement, and a courtyard microclimate.
- It offers a context-specific solution adapted to Baghdad, Iraq's climate.
- Without significantly depending on mechanical or electrical systems, it shows the possibility of achieving near zero-energy performance.

2. DEFINITIONS AND GENERAL CONCEPTS

The following section outlines the definition and fundamental concepts of zero-energy buildings, providing the conceptual framework necessary for understanding their role in sustainable architecture and energy-efficient design.

2.1. ZERO ENERGY BUILDINGS

Zero-energy buildings are highly insulated, airtight, and energy-efficient structures that generate as much renewable energy as they consume on an annual basis, resulting in no net carbon emissions for their occupants. These buildings integrate advanced architectural design, innovative building technologies, and energy efficiency measures (Min et al. 2018).

The concept also aligns closely with environmentally responsive design, which seeks to minimise the use of energy, materials, and natural resources while reducing the environmental impact of construction and operation. Green design approaches aim to preserve ecological balance by improving material efficiency and optimising energy use (Liang & Edward 2012) & (Mohammed et al. 2023).

The performance of a zero-energy building is strongly influenced by climate conditions, particularly through the building envelope and HVAC systems. Strategies such as enhancing airtightness, improving thermal insulation, applying heat recovery ventilation, and harnessing internal and solar heat gains reduce heating and cooling demand. Additional techniques, including solar shading, optimal building orientation, high thermal mass with night ventilation, and other passive design measures, further decrease reliance on active systems. In this context, environmental performance, indoor thermal comfort, and air quality must all be carefully considered (Liang & Edward 2012).

Renewable energy plays a central role in achieving zero-energy status. Sources such as wind, geothermal, hydrological, and biomass are abundant worldwide, though their deployment may be limited by cost-effectiveness and technical challenges. Iraq, however, possesses significant potential for utilising renewable and alternative energy sources, particularly wind and solar power. Harnessing these resources can substantially reduce carbon dioxide emissions and contribute to national energy security by offsetting large amounts of oil equivalent (Min et al. 2018).

However, new studies show that preserving thermal comfort in zero-energy buildings is still a significant challenge, especially in harsh climates where the risk of overheating could lower total performance (Aydin et al. 2015).

2.2. NEGATIVE SOLAR DESIGN

To achieve optimal levels of environmental control, several passive (negative) systems can be applied:

- Selecting the best building orientation, shading devices, insulation, and ceiling apertures to minimise the effects of solar radiation (Youssef et al. 2010).
- Using intelligent materials that not only serve structural functions but also provide additional benefits such as insulation, air purification, and emission reduction.
- Regulating indoor temperatures by optimising the building envelope and controlling convective heat transfer through careful material and component selection.
- Ensuring year-round natural ventilation and daylighting, thereby reducing dependence on mechanical and electrical systems.

In addition, the following natural strategies can further reduce building energy consumption:

2.3. THE THERMAL STRESS-INDUCED AIR MOVEMENT INSIDE THE BUILDING

In order to improve building energy performance, advanced thermal storage and passive cooling techniques have been extensively studied, especially in hot areas where thermal mass and heat exchange systems are essential.

Examining the vertical placement of apertures is essential for optimising indoor air quality. When the indoor air is warmer—and therefore less dense—than the outdoor air, airflow occurs from the low-density interior to the higher-density exterior (Maldonado & Oliviera 1993). A single window does not ensure adequate ventilation because of pressure gradients: High pressure forms above the window plane and low pressure below it, restricting effective air circulation. However, when two windows are positioned at different heights, air exits through the upper window due to high pressure near the ceiling, while lower pressure near the bottom window allows cooler outside air to enter. Conversely, when indoor air is cooler than outdoor air, airflow follows a different pattern (Roaf 2005) & (Cherian et al. 2025).

Heat transfer between a courtyard, its adjacent service areas, and the external environment can be regulated through airflow, thermal mass, and passive solar gains. As Hyde (2005) highlights, ventilation is vital for the courtyard's thermal environment, contributing to structural cooling, user comfort, prevention of overheating, and removal of solar heat from interior spaces. Airflow within buildings is primarily driven by wind pressure or the stack effect, while the building's form and enclosure regulate wind permeability. A semi-enclosed courtyard enhances ventilation both within its space and in adjoining service areas.

In hot and arid climates, the courtyard provides natural cooling to nearby spaces during summer through convection and radiation (Figure 1). At night, it fills with cool air that lowers surrounding temperatures, while radiative heat loss to the night sky helps the courtyard remain cool until late afternoon. Around midday, direct solar radiation heats the courtyard floor, initiating upward air movement. By afternoon, as surrounding spaces warm, stronger convection currents develop. In the evening, accumulated warm air rises to the top of the courtyard and is gradually replaced by cooler night air, restoring thermal balance (Maldonado & Oliviera 1993).

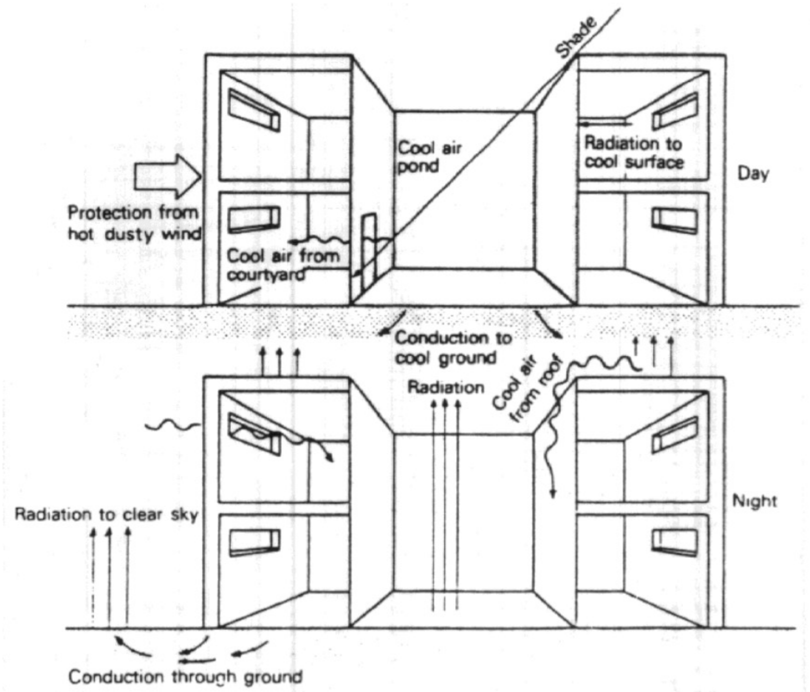

Figure 1. Overview of the thermal behaviour of the courtyard (Roaf 2005).

2.4. MAKING USE OF THE HEAT CAPACITY OF THE EARTH

This system harnesses the earth's thermal energy, taking advantage of the temperature gradient between the air in contact with the ground surface and the cooler subsurface layers, which increases with depth. Key design considerations for the heat exchanger include:

- Soil moisture: Heat exchangers installed in moist soil demonstrate superior thermal performance and achieve greater reductions in air temperature compared to those in dry soil (Agrawal et al. 2020) & (Cuny et al. 2020) & (Raheem et al. 2026).
- Air velocity: Airspeeds between 1–5 m/s ensure sufficient airflow at the outlet; however, higher velocities shorten the air–soil contact time, thereby reducing the temperature difference between inlet and outlet (Lin et al. 2022).
- Pipe materials: PVC pipes are suitable for connectors due to their insulating properties, while aluminium is preferred for heat exchanger pipes located beneath or above the courtyard, as it offers excellent thermal conductivity (Sakhri et al. 2020) & (Uyar & Hayber 2025).
- Pipe diameter: When inlet and outlet diameters are fixed, an increase in pipe diameter leads to a drop in internal pressure (Agrawal et al. 2018) & (Suman et al. 2025).
- Temperature variation: The system can induce air temperature changes ranging from 2–22 °C, depending on soil type, building design, and climatic conditions (Diaz-Hernandez et al. 2020). Such systems may provide substantial cooling or heating, or deliver a significant temperature differential

between inlet and outlet air. However, without adequate ventilation, improvements in supply air temperature alone cannot enhance indoor air quality.

The remaining energy required to achieve zero-energy buildings can be supplied through the integration of additional technologies.

2.5. MICRO WIND TURBINES

In order to improve building efficiency and lower carbon emissions, recent research have highlighted the significance of integrating passive and hybrid energy systems (Cherian et al. 2025) & (Mohammed et al. 2023).

Wind turbines generate electricity by converting the kinetic energy of moving air into rotational motion through their blades. This rotation drives the main shaft, which is connected to a gearbox that increases rotational speed and, in turn, powers the generator located in the nacelle at the top of the mast (RUC 2013). The generator transforms the mechanical energy into electrical energy using magnetic fields induced by rotation (Hall 2008). The electrical output is then adjusted to the required voltage level by a transformer. This process is commonly referred to as wind power. A collection of turbines operating together is termed a wind farm, and these turbines may be mounted on rooftops or installed as freestanding structures (Raheem & Raheem 2026).

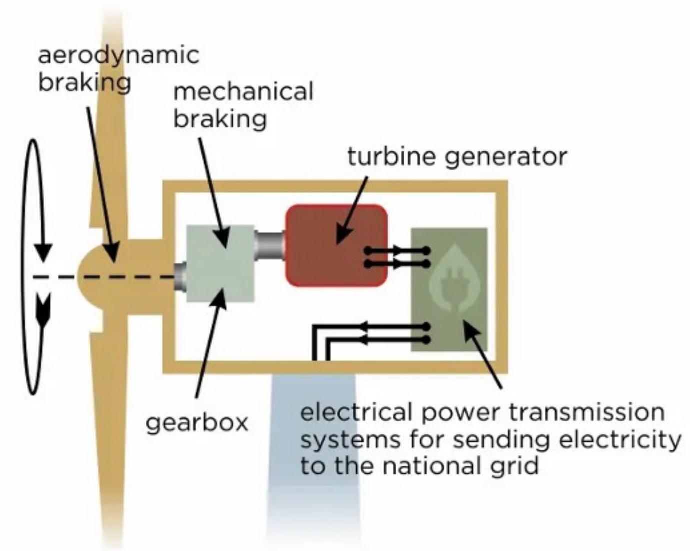

Figure 2. An internal look at a conventional wind turbine (Hall 2008 & RUC 2013).

The following section presents the methodology used to evaluate the proposed system.

3. METHODOLOGY

This study's methodology is based on well-established concepts of heat transfer as well as other studies on earth-air heat exchanger systems and passive cooling techniques. Numerous studies have shown how beneficial these systems are in hot and dry conditions, especially when it comes to improving thermal comfort and lowering building energy use. The modelling strategy employed in this work expands upon experimental and analytical frameworks that have been verified and published in the literature.

This study proposes a novel approach to optimise under- and above-courtyard-to-air heat exchange systems by harnessing thermal stress and leveraging the courtyard microclimate to assist in heating and cooling. The research focuses on local soil and climatic conditions in Baghdad, Iraq. Key variables—including soil properties, air velocity, and heat exchanger pipe parameters (length, diameter, and depth)—will undergo parametric analysis within the heat exchanger system. By burying the heat exchanger three meters below ground and utilising building rooftops as the above-courtyard level, the system is designed to maintain indoor temperatures between 21–25 °C.

For any given set of influencing variables, the system can reduce indoor temperatures during summer to meet cooling demands and increase temperatures in winter to satisfy heating requirements. Critical specifications such as air velocity, pipe length, depth, and diameter—assuming fixed soil properties in the building zone—can be calculated using mathematical models. Furthermore, because both heating and cooling operations exploit thermal stress, the system functions without requiring electrical energy input.

The proposed system does not introduce entirely new physical equations but rather integrates existing validated models into a novel configuration tailored for courtyard-based buildings in hot-arid climates.

4. THE PRACTICAL STUDY

This study presents a practical investigation into methods for utilising thermal stress to develop zero-energy buildings in Iraq, focusing on a case study in Baghdad. A heat exchanger system will be implemented to exploit the courtyard microclimate. During summer, aluminium pipes with diameters and lengths calculated using mathematical formulas will be placed beneath the courtyard. The hollow, serrated interior of the pipes allows them to be folded and twisted multiple times, facilitates secure installation of fittings, strengthens the pipe, and slows air movement to maximise heat exchange with the under-courtyard, which maintains a year-round temperature of 22–25 °C. PVC, being an effective and economical insulator, is installed on the southern wall of the courtyard, connecting to the aluminium pipe buried at a depth of three meters. This orientation minimises solar heat gain, while the courtyard provides shading.

A fan at the inlet uses wind movement to draw air into the system without altering the total airflow when velocities inside the aluminium pipe decrease. Inlet and outlet valves regulate ventilation, and each aluminium pipe buried beneath the courtyard serves a single floor to ensure consistent airflow for multi-storey buildings. The pipe layout is repeated for each floor, and the energy generated by an adjacent wind turbine can power internal building technologies and lighting, either independently or in conjunction with the fan.

In winter, the system is reversed: Serrated aluminium pipes are installed on rooftops surrounding the courtyard to capture solar heat for warming, while PVC pipes are positioned on the northern wall to allow adequate solar gain, maintaining indoor air temperature. During summer, the winter pipe can provide natural ventilation, and in winter, the summer pipe can support ventilation. The system relies on thermal stress to drive airflow, and valves control ventilation, heating, and cooling as needed.

The proposed building incorporates multiple strategies to achieve a high-quality and comfortable living environment. It features superior airtightness and insulation, with an integrated sunspace providing passive solar heating and abundant natural light in winter, while reducing interior temperatures in summer. The design prioritises spacious, flexible living areas that remain comfortable year-round, informed by wind patterns and shading from surrounding trees and structures. Service spaces are grouped on the north side, while main living areas are optimally oriented to maximise solar energy use.

The potential of earth-air heat exchanger systems for passive cooling and heating applications in buildings has been extensively researched (Al-Ajmi et al. 2006) & (Lee & Strand 2008).

4.1. THE SOIL AND HEAT EXCHANGER SYSTEM MATHEMATICAL MODELS

Heat conduction theory in semi-infinite media, which has been widely used in earlier research, is the foundation of the soil temperature modelling approach (Gurtug et al. 2018) & (ASHRAE 2012).

The mathematical models were developed using heat transfer equations from the literary contributions of various experts on this topic (Lee & Strand 2008) & (Al-Ajmi et al. 2006). Heat transfer and outlet temperature are the thermal performance indicators used in this study, and they were estimated using the soil model and the heat exchanger model.

Utilizing the heat conduction principle, a soil model was created to predict the temperature of the soil at system depths. The heat conduction principle predicts the soil temperature $T_{(d,D)}$ at a different date of the year (d) and different depths (D) when applied to a semi-infinite solid. According to Gurtug, Sridharan & Kizler (Gurtug et al. 2018), While the temperature varies depending on the depth beneath the court, the norm for ground temperature is usually thought to be the same as the surface temperature at that same moment.

The study's heat transfer equations are based on heat exchange and classical thermodynamic models that are frequently used in building energy analysis (ASHRAE 2012) & (Engineering Toolbox 2003).

Equation (1): Temperature $T_{(d,D)}$ at a given date d & depth D

$$T_{(d,D)} = T_{mean} + T_{amp} \times e^{-D\sqrt{\frac{\pi}{365 \times \alpha}}} . \cos\left(\frac{2\pi}{365}\left(d - do - \frac{D}{2}\sqrt{\frac{365}{\alpha \times \pi}}\right)\right) \quad (1)$$

It is important to determine which are variables and constants to calculate the previous equation where:
$T_{(d,D)}$: It is the temperature (°C) of indoor (date, depth).
D: It is the depth of the pipe of the system (m). [Variable]
d: It is the date, usually in days. [Variable]
T_{mean}: It is an annual average temperature °C. [Constant]
T_{amp}: It is an annual temperature variation (amplitude). [Constant]
do: It is the day of the year when the average temperature is measured, serving as a benchmark for the temperature cycle phase. [Constant]
e: It represents the number of Euler. [Constant]

The thermal diffusivity (α) is estimated by the next equation (ASHRAE 2012):
Equation (2): Thermal diffusivity (α) (m²/s)

$$\alpha = \frac{86.4 \times k_s}{ps\left[Cs + 4.18\left(\frac{m}{100}\right)\right]} \quad (2)$$

Where:
k_s: It is the thermal conductivity of soil (W/m °C), given by ASHRAE Charts (ASHRAE 2012).
ps: It is the density of soil (kg/m³).
Cs: It is the specific heat of soil (J/kg K).
m: It is the moisture content of the soil (%).

The diameter (Di) of the pipe used in the heat exchanger system, its length (L). The surrounding environment provides ambient air to the underground buried pipes. The pipe depth (D). The temperature of the soil is known, and the width of the soil layer is double the radius of the pipe.

The heat flux between the air travelling through the pipe and the surrounding soil layer is represented by the following equation, which is the ratio of the total temperature fluctuation to the heat flow resistance between the hotter and colder areas (ASHRAE 2012):
Equation (3): The heat flux or heat load in (watts)-1

$$Q = Tf - \frac{Ts}{Rt} \quad (3)$$

Where:
Tf: It is the fluid temperature in the pipe (°C).
Ts: It is the soil temperature (°C).
$Rt.$: It is the thermal resistivity (m² °C/W).

The following equation also provides the heat flux or heat load:
Equation (4): The heat flux or heat load in (watts)-2

$$Q = U \times A \times \Delta t \quad (4)$$

Where:
Q: It represents heat load in (watts).
U: It represents the overall thermal conductivity of the pipe (W/m² °C).
A: It represents the surface area of the cylindrical pipe here, which equals (area) = Length (L.) × Diameter (Di.) × π, or the surface area of the served building(floor, walls and roof).
Δt: The temperature difference between indoor and outdoor (C°).
Equation (5): The heat flux or heat load in (watts)-3

$$Q = \dot{m}cp(T\ in\ -\ T\ out) \tag{5}$$

Where:
Q: It is the heat flux or heat load in the pipe.
ṁ: It is the mass flow rate of the air, (kg/s).
Cp: It is the heat capacity of the air, (J/kg K).
T in: It is the temperature of the air inlet.
T out: It is the temperature of the air outlet.
Equation (6): The thermal resistance (m^2 °C/W)

$$Rt = \frac{D}{ks} \tag{6}$$

Equation (7): The overall thermal conductivity of the pipe (W/m^2 °C)

$$U = \frac{1}{Rt} \tag{7}$$

To determine the length of the pipe (L):
Equation (8): The length of the pipe (L)

$$L = \frac{Q}{U \times A \times \Delta T\ lm} \tag{8}$$

Where:
$\Delta T\ lm$: It represents the logarithmic mean temperature difference between the soil and the air.
To determine the diameter of the pipe (Di):
Equation (9): The diameter of the pipe (Di)

$$Di = \sqrt{\frac{4\dot{m}}{\pi \times \rho \times \upsilon}} \tag{9}$$

To determine the velocity of air:
Equation (10): The velocity of air

$$\upsilon = \frac{4\dot{m}}{\pi \times \rho \times Di^2} \tag{10}$$

Where:
ρ: It is the air density.
υ: It is the velocity of the air, (The Engineering ToolBox 2003).

4.2. DATA ANALYSIS TECHNIQUES APPLIED IN THIS STUDY

The governing equations for the heat exchange model—including the soil, pipe, and air—will be solved as if all domains were fluids, with thermophysical properties assigned according to their location within the system. In the solid zones (soil and pipe), velocity components are set to zero, as hydrodynamic effects are negligible; thus, heat transfer occurs solely via conduction. In the fluid zones (inside the pipes), both temperature and velocity fields are determined. The mathematical model, together with its boundary conditions, is solved to evaluate soil temperature, which depends on soil type, the interaction with the heat exchanger pipes, and upper boundary conditions influenced by external factors.

Based on Weather & Climate data (Weather & Climate 2024), the soil samples have an average density of 1915 kg/m³ and a moisture content of 6.15%. These parameters are incorporated into the model to calculate soil thermal diffusivity and conductivity. The resulting thermal properties allow estimation of subsurface temperatures at various depths and throughout different seasons.

Table 1 summarises the input parameters for the soil model, which are derived from soil compaction tests and local climate data. The average annual temperature in Baghdad is 21.88 °C, with an annual variation of 6.11 °C (Weather & Climate 2024).

Table 1. Input parameters for the soil model.

Parameters	**T amp. °C**	**T mean °C**	**Depth (D) Meter (m)**	**Thermal conductivity W/(m.°C)**
Values	6.11	21.88	1 to 5	1.44

Meteorological data for Baghdad from 2020 to 2023 were obtained from the Meteorological Data Centre. For the analysis, the warmest day is assumed to be 4th August, with a maximum temperature of 47 °C, and the coldest day is 4th February, with a minimum temperature of 0 °C. The study is based on the average conditions recorded over the three-year period (Weather & Climate 2024).

Using the proposed heat exchanger system, the influence of various factors on the outlet air temperature and its contribution to the building's cooling load will be evaluated. Four key parameters—air velocity, pipe depth, diameter, and length—will be investigated. Each parameter will initially be set at a baseline value, and its effect will be assessed by systematically varying the other parameters. The baseline and range values for these variables are presented in Table 2.

Table 2. Parameters of the heat exchanger system.

Parameters	**Soil temp. (◦C)**	**Soil depth (m)**	**Pipe length (m)**	**Pipe diameter (m)**
Base value	22-25	1.5-4	25-75	0.1-0.4

5. RESULTS

In order to achieve optimal performance and minimise environmental effect, it is crucial to integrate modern technology with passive systems, according to recent studies on energy-efficient and zero-carbon buildings.

The pipe length is the most influential factor affecting the overall heating or cooling performance of ground air. While increasing the pipe diameter reduces air velocity, a longer pipe length results in a greater pressure drop. The optimal diameter of an earth-air heat exchanger depends on the pipe length, depth, and air velocity. Selecting a pipe that balances thermal performance with cost considerations ensures the best efficiency at the lowest possible expense.

For the proposed system, the heat exchanger should be installed 3 meters underground, with a pipe diameter of 0.19–0.24 m, air velocity of 1–4 m/s, and a length of 40–50 m for a building volume of 401 m³, as illustrated in Figures 3 and 4. These specifications were determined to achieve an outlet temperature range of 21–25 °C. The results indicate that, when other variables are held constant, burial depths below 4 meters have a negligible effect on performance. For under- and above-courtyard-to-air heat exchange systems, temperature extraction efficiency increases with longer pipe lengths but decreases with higher air velocities. Moreover, based on average heat transfer rates, coefficient of performance, and soil thermal conductivity, wet under/above-courtyard-to-air heat exchanger systems are more efficient than dry systems.

Recent research on passive cooling systems, where airflow, soil characteristics, and system geometry interact to significantly affect system performance, has shown similar tendencies. These findings are consistent with previous studies that highlighted the significant influence of pipe length and air velocity on the thermal performance of earth-air heat exchanger systems (Al-Ajmi et al. 2006) & (Lee & Strand 2008). The enhanced performance seen in moist soil conditions is consistent with previous studies showing that increased soil moisture improves heat exchange efficiency and thermal conductivity (Agrawal et al. 2020).

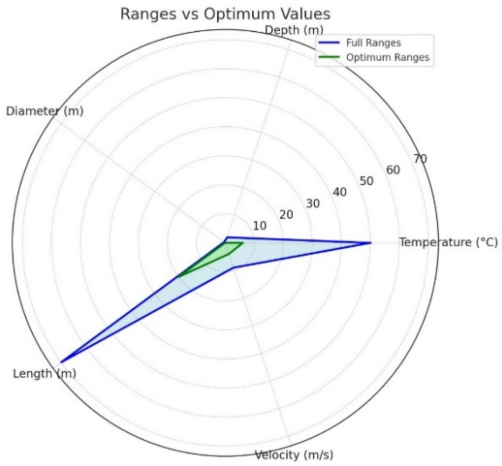

Figure 3. The radar chart that shows the varying ranges and optimum values.

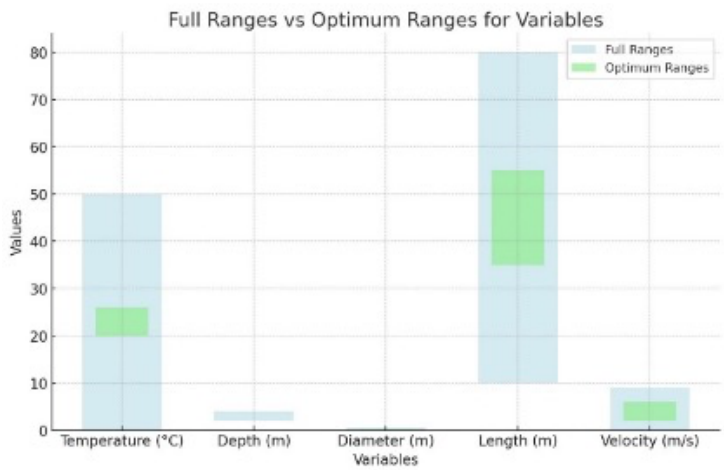

Figure 4. The bar chart displays the entire range and optimal values for the specified variables.

6. DISCUSSION

This paper describes a hybrid passive system that uses thermal stress as the main driving force for temperature control and indoor air flow. The suggested solution incorporates earth-air heat exchanger technology, vertical airflow dynamics, and courtyard microclimate into a single design framework, in contrast to traditional methods that mostly rely on mechanical HVAC systems or isolated passive tactics.

The findings show that important factors including pipe length, air velocity, and soil conditions have a significant impact on system performance. Specifically, longer pipes improve heat exchange efficiency, while increased air velocity limits thermal interaction by shortening the air's residence time in the system. These results are in line with earlier research on earth-air heat exchanger systems, which emphasise the significance of airflow parameters and system design in determining thermal performance (Al-Ajmi et al. 2006) & (Lee & Strand 2008).

In line with previous research findings, the results also show that moist soil conditions greatly increase system effectiveness due to increased heat conductivity (Agrawal et al. 2020). Under extreme weather circumstances, the ideal configuration found in this study—which includes a burial depth of roughly 3 m, pipe diameter of 0.19–0.24 m, air velocity of 1–4 m/s, and pipe length of 40–50 m, maintained indoor air temperatures within the comfortable range of 21–25°C.

This study emphasises the efficacy of combining several tactics into a single system designed for hot-arid conditions, in contrast to earlier research that concentrated on individual passive cooling systems. By improving thermal performance and lowering reliance on mechanical systems, this integrated approach promotes sustainability and energy efficiency in building design.

This study's conceptual approach, which reinterprets current passive techniques through the lens of thermal stress and climatic adaptation unique to Iraq, is just as important as the system layout.

These results bolster the potential of passive and climate-responsive design approaches as workable substitutes for traditional energy-intensive building systems in places like Iraq.

7. CONCLUSIONS

The findings show that, even in severe weather, the suggested under- and above-courtyard-to-air heat exchange system can successfully control indoor air temperature within a comfortable range of 21–25°C. At a burial depth of roughly 3 m, pipe diameter of 0.19–0.24 m, air velocity of 1–4 m/s, and pipe length of 40–50 m, the system performed at its best.

The results show that while faster air velocity shortens thermal interaction time, pipe length increases heat exchange efficiency. Furthermore, it was shown that moist soil conditions greatly enhance system performance because of increased thermal conductivity.

Overall, the study shows that incorporating earth-air heat exchanger systems and courtyard microclimate with thermal stress-driven airflow can significantly lessen reliance on mechanical heating and cooling systems, helping to develop low-energy and sustainable buildings in hot, dry areas.

This strategy has the potential to drastically lower the energy consumption of buildings, especially in areas with similar climates to Baghdad.

AUTHOR CONTRIBUTIONS

Mazin Ismael Raheem, Xiaofeng Zheng, and Christopher Wood: Contributed equally to all aspects of the study, including conceptualisation, methodology, analysis, and manuscript preparation. All authors have read and approved the final version of the manuscript.

COMPETING INTERESTS

The authors have no competing interests to declare

DATA ACCESSIBILITY

The data supporting the findings of this study are available within the article. Additional simulation data can be provided by the corresponding author upon reasonable request.

ETHICAL APPROVAL

This study does not involve human participants or animals, and therefore, ethical approval was not required.

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