

Article

An Instrumented Earth–Air Heat Exchanger with Embedded Electronic Monitoring for Real-Time Passive Cooling Applications

Abdelaaziz Yagour ¹, Brahim Ydir ^{1,2}, Iulia Antohe ^{3,*}, Ahmed Wifaya ⁴, Ahmed Aharoune ⁵ and Radouane Leghrib ¹

¹ Laboratory of Materials, Signals, Systems and Physical Modeling, Faculty of Sciences of Agadir, Ibn Zohr University, Agadir 80006, Morocco; abdelaaziz.yagour@edu.uiz.ac.ma (A.Y.); brahim.ydir@edu.uiz.ac.ma (B.Y.); r.leghrib@uiz.ac.ma (R.L.)

² Laboratory of Intelligent System Design (ISD), Faculty of Science, Abdelmalek Essaadi University, Tétouan 93000, Morocco; b.ydir@uae.ac.ma (B.Y.)

³ Laboratory of Lasers in Life Sciences, Environment and Manufacturing, National Institute for Lasers, Plasma and Radiation Physics, 077125 Magurele, Ilfov, Romania

⁴ Integrated Crop Production Research Unit, Regional Center of Agricultural Research of Agadir, National Institute of Agricultural Research, Rabat 10090, Morocco; ahmed.wifaya@inra.ma

⁵ Laboratory of Thermodynamics and Energetics, Faculty of Sciences of Agadir, Ibn Zohr University, Agadir 80006, Morocco; a.aharoune@uiz.ac.ma

* Correspondence: iulia Antohe@inflpr.ro

Abstract

The Earth–Air Heat Exchanger (EAHE), also referred to as an air–soil heat exchanger, represents an effective passive cooling technology that exploits the thermal inertia of the ground. This study presents a combined experimental and analytical investigation of an EAHE system installed at the Faculty of Sciences of Agadir (Morocco). A steady-state analytical model based on convective heat transfer between the airflow within a buried duct and the surrounding soil is developed to describe the axial evolution of air temperature along the exchanger. The model is formulated under a sensible heat transfer framework, where the influence of humidity is accounted for through its effect on the thermophysical properties of moist air, while latent heat transfer and condensation phenomena are neglected. An instrumented experimental setup was implemented to perform continuous measurements of air temperature and relative humidity over a seven-month monitoring period. The experimental results indicate that the outlet air temperature remains stabilized within the range of 23.5–23.8 °C, despite significant variations in ambient temperature (13–38 °C). A parametric analysis is conducted to assess the influence of duct diameter, airflow velocity, and humidity through its effect on moist air properties on the thermal performance of the system. The close agreement between experimental observations and analytical predictions demonstrates the validity and predictive capability of the proposed model. These findings highlight the potential of EAHE systems as an effective passive cooling solution for greenhouse applications in semi-arid climatic conditions.



Academic Editor: Huanyu Cheng

Received: 19 March 2026

Revised: 21 April 2026

Accepted: 23 April 2026

Published: 28 April 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

Keywords: Earth–Air Heat Exchanger; electronic instrumentation; real-time data acquisition; temperature sensors; humidity sensors; airflow measurement; automated monitoring system

1. Introduction

In the past decades, enhancing the energy efficiency in buildings has emerged as an important issue due to the growth of global energy demand and its relation with mitigating

climate change [1]. The building industry contributes significantly to primary energy use, which is mainly driven by heating and cooling facilities. This is especially the case in warm and semi-arid climates where the summer loads of cooling are higher. Passive solutions for air conditioning of the indoor thermal comfort become a promising manner to save energy [2–4].

One of the major solutions, the Earth–Air Heat Exchanger (EAHE, also sometimes called the earth–air tunnel or air–soil heat exchanger) has received significant consideration because it is simple to construct, has a low operating cost which acts as an energy independent system, and has reliable long-term performance [5,6]. The operation of the EAHE is based on using such relatively constant temperature of soil (at about 1.5–3 m depth) as a heat source in order to achieve pre-cooling while cooling down air in summer and to get pre-heating when heating air in winter, and further transporting it from earth tubes to buildings [7–10].

Research into the thermal performance and heat transfer mechanisms of EAHE systems has been widely focused on by many researchers, and these studies are represented in the scientific literature as a large number of different types of experimental studies [11,12]. Researchers have documented through the experimental studies published the influence of major design parameters such as burial depth, soil properties, duct size and shape (length and diameter), air flow velocity, and tube materials [13–15]. Many researchers have indicated that the optimization of geometric characteristics, i.e., duct size and shape, and internal surface properties of EAHE systems has increased the heat transfer coefficient of such systems significantly, which in turn has increased the efficiency and overall performance of EAHE systems [16,17]. Conversely, numerical modeling techniques, based on the development of three-dimensional thermal models (i.e., internal energy models), and heat conduction/convection equations using Computational Fluid Dynamics (CFD) techniques have provided researchers with a greater understanding of the coupled thermal and hydrodynamic processes which determine the performance of EAHE systems [18–20]. EAHE systems have been shown to provide a significant reduction in Annual Thermal Loads (approximately 20–40% reduction in Annual Thermal Loads) under different climatic conditions depending upon the local climatic conditions and EAHE system configurations [21].

Despite the extensive body of research on Earth–Air Heat Exchangers (EAHE), several limitations remain in the existing literature, particularly concerning the representativeness of climatic conditions, the duration of experimental investigations, and the integration of validated analytical models. As summarized in the table in Section 3.6, many previous studies are either limited to short-term monitoring campaigns or rely primarily on numerical simulations without long-term experimental validation. Moreover, investigations conducted under semi-arid climatic conditions remain relatively scarce, despite their high relevance for passive cooling applications. In this context, the present work provides a novel contribution by combining a long-term experimental analysis (seven months) with a validated steady-state analytical model under real operating conditions. In addition, a comprehensive parametric study is carried out to evaluate the combined effects of duct diameter, airflow velocity, and humidity on the thermal performance of the system. This integrated experimental–analytical approach, applied under semi-arid conditions, offers new insights into the design and optimization of EAHE systems and contributes to bridging the gap between theoretical modeling and real-world performance.

2. Methodology

2.1. System Description of the Earth–Air Heat Exchanger (EAHE)

The experimental research took place on a full-scale EAHE at the Faculty of Sciences, located in Agadir, Morocco, where the climate is defined as semi-arid. The system made

use of a series of buried PVC pipes that take advantage of the thermal inertia and heat capacity of the soil, and it was utilized for passive air conditioning.

The EAHE is composed of seven PVC pipe sections connected in series, resulting in a total length of 22 m (Figure 1). The pipes have an inner diameter of 7.5 cm and are buried at a depth of 2 m, where soil temperature remains quasi-stable throughout the year. This configuration was selected based on recommendations reported in previous experimental and analytical studies, which indicate that burial depths between 1.5 and 3 m offer optimal thermal performance while remaining economically viable.

Outdoor air is forced through the buried pipes using axial fans, allowing heat exchange between the airflow and the surrounding soil. The system operates continuously, enabling both pre-cooling during summer and pre-heating during winter periods.

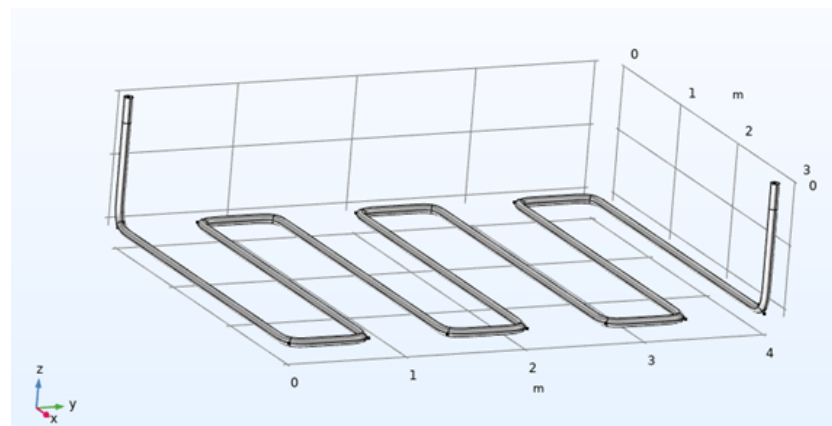


Figure 1. Schematic of a U-shaped Earth–Air Heat Exchanger (EAHE) layout.

2.2. Analytical Thermal Modeling

A steady-state analytical model was developed to describe the thermal behavior of the EAHE, based on the one-dimensional heat transfer between the airflow and the surrounding soil, as illustrated in Figure 2. The soil was modeled as a semi-infinite medium with constant temperature, an assumption widely adopted in the literature for short- and medium-term EAHE operation. Heat transfer between the air and the soil was assumed to occur through forced convection inside the pipe, while the thermal inertia of the pipe material was neglected [18,22,23].

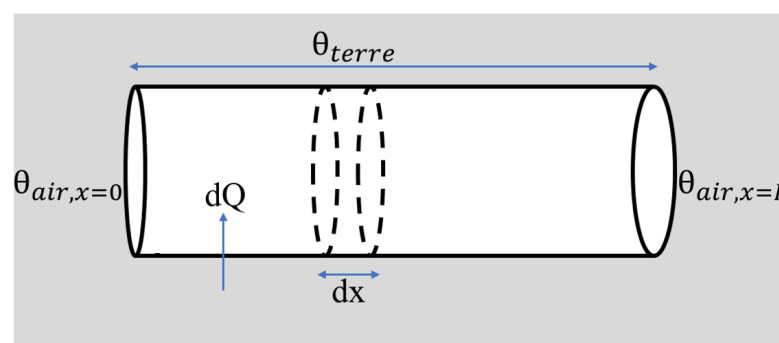


Figure 2. Thermal model of air flow in an EAHE pipe.

Applying the first law of thermodynamics to an elementary air volume flowing inside the duct leads to an exponential expression describing air temperature variation along the pipe length [6]:

$$Q = m C \Delta \theta \quad (1)$$

Consider an elementary cylindrical air volume of mass dm , thickness dx , and axial position x , receiving a heat amount dQ from the surrounding soil at temperature θ_{soil} . The differential heat balance is given by

$$dQ = dm C d\theta \quad (2)$$

The mass flow rate of air is expressed as

$$\frac{dm}{dt} = \rho q_v \quad (3)$$

which leads to the rate form of the heat transfer:

$$\frac{dQ}{dt} = \rho q_v C d\theta \quad (4)$$

On the other hand, the convective heat transfer between the air and the pipe wall is described by

$$\Phi = h S (\theta_{\text{air}}(0) - \theta_{\text{air}}(x)) \quad (5)$$

As $\Phi = \frac{dQ}{dt}$, the convective heat transfer rate becomes

$$\frac{dQ}{dt} = h (\theta_{\text{terre}} - \theta) 2\pi R dx \quad (6)$$

By equating expressions (4) and (6), the following differential equation is obtained:

$$\rho q_v C d\theta = h (\theta_{\text{terre}} - \theta) 2\pi R dx \quad (7)$$

which can be rearranged as

$$\frac{d\theta}{\theta - \theta_{\text{terre}}} = -\frac{h 2\pi R}{\rho q_v C} dx \quad (8)$$

Equation (8) is integrated from the air inlet temperature $\theta_{\text{air}}(x = 0)$ to the air temperature at position x , and from 0 to x along the pipe length:

$$\int_{\theta_{\text{air}}(0)}^{\theta(x)} \frac{d\theta}{\theta - \theta_{\text{terre}}} = \int_0^x -\frac{h 2\pi R}{\rho q_v C} dx \quad (9)$$

which yields

$$\ln\left(\frac{\theta_{\text{air}}(x) - \theta_{\text{terre}}}{\theta_{\text{air}}(0) - \theta_{\text{terre}}}\right) = -\frac{h 2\pi R}{\rho q_v C} x \quad (10)$$

Thus,

$$\frac{\theta_{\text{air}}(x) - \theta_{\text{terre}}}{\theta_{\text{air}}(0) - \theta_{\text{terre}}} = \exp\left(-\frac{h 2\pi R}{\rho q_v C} x\right) \quad (11)$$

Finally,

$$\theta_{\text{air}}(x) - \theta_{\text{terre}} = (\theta_{\text{air}}(0) - \theta_{\text{terre}}) \exp\left(-\frac{h 2\pi R}{\rho q_v C} x\right) \quad (12)$$

Hence, the air temperature distribution along the exchanger is expressed as

$$\theta_{\text{air}}(x) = (\theta_{\text{air}}(0) - \theta_{\text{terre}}) \exp\left(-\frac{h 2\pi R}{\rho q_v C} x\right) + \theta_{\text{terre}} \quad (13)$$

To perform numerical calculations, the convective heat transfer coefficient h must be evaluated. The Nusselt number is determined using the Colburn correlation for turbulent

forced convection in circular ducts. The thermophysical properties used in the calculations are listed in Table 1:

$$Nu = 0.023 Pr^{1/3} Re^{4/5} \quad (14)$$

where the Reynolds and Prandtl numbers are given by

$$Re = \frac{\rho v D}{\mu} \quad Pr = \frac{\mu C_p}{\lambda} \quad (15)$$

The relationship between the Nusselt number and the convective heat transfer coefficient is

$$Nu = \frac{h D}{\lambda} \quad (16)$$

which leads to

$$h = \frac{Nu \lambda}{D} \quad (17)$$

Table 1. Thermophysical properties.

Property	Value
Air density	$\rho = 1.23 \text{ kg} \cdot \text{m}^{-3}$
Specific heat capacity of air	$C_p = 1008 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$
Thermal conductivity of air	$\lambda = 0.025 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$
Dynamic viscosity of air	$\mu = 1.8 \times 10^{-5} \text{ kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$
Kinematic viscosity of air	$\nu = \frac{\mu}{\rho} = 1.5 \times 10^{-4} \text{ m}^2 \cdot \text{s}^{-1}$

2.3. Experimental Procedure and Operating Conditions

Over a seven-month period (January–July 2024), continuous measurements were executed on a five-minute basis for: inlet temperature at the inlet and outlet; humidity levels at the inlets and outlets of the soil profile; and soil temperature. Ensuring an appropriate balance between temporal resolution and data storage requirements, while maintaining manageable long-term data acquisition and processing, was important. The time frame allows for long-term assessment of seasonal changes and to test the validity of a numerical model during real-life operation. Researchers used experimental data to evaluate features such as pipe diameters, rates of air flow, and relative humidities, and they worked to determine the effects of these elements on the thermal operation of EAHEs and compare the results gathered from their experimentation with the theoretical modeling outcomes. The adopted measurement strategy is consistent with standard experimental practices in EAHE monitoring studies, where short-interval data acquisition is commonly used for system characterization and model validation, as reported in similar experimental studies employing high-resolution temporal monitoring of EAHE systems. Providing a reliable dataset for comparison between experimental measurements and theoretical predictions [24]. The data acquisition interface was developed using LabVIEW 2017, which was also employed for system control, signal processing, and data logging. All equipment used in this work was manufactured by Aosong Electronics Co., Ltd., Guangzhou, China, and sourced from Mossasoft, Agadir, Morocco.

2.3.1. Measurement Instrumentation and Data Acquisition

We developed an electronic monitoring system specifically designed to monitor both the thermal and hygrometric behavior of the EAHE. The temperatures and relative humidities at the points of entry and exit into/from the unit were obtained using DHT22 sensors due to their significant accuracy capabilities and long-term reliability when monitoring environmental conditions. As well, the temperatures of the soil profile were monitored at a

depth of 2 m with the DS18B20 digital sensors that are widely used in studies similar to this due to their accuracy and ease of implementation into other research studies. For this project, all sensors will report through an Arduino-based data acquisition system to synchronize the time of measurement and process data in real time. Measurements will be taken every 5 min, therefore giving a high temporal resolution during the long-term operation of the system. The data collected from the operation of the system will be displayed on a local 20×4 LCD screen and saved onto a microSD memory card for analysis after the end of the experimental investigation. The data will also be transmitted remotely to allow for real-time monitoring of the system using a Google Sheets database, which will be powered by a SIM800L GSM module attached to the data acquisition unit. Prior to installation, all sensors were recalibrated and re-validated under controlled laboratory conditions to ensure measurement reliability and consistency. This calibration procedure follows the experimental methodology reported by Bouchane et al. [25].

The measurement uncertainty was evaluated based on both statistical and instrumental contributions using the DHT22 sensor. For temperature, the random uncertainty was estimated at $0.052\text{ }^{\circ}\text{C}$, while the sensor accuracy ($\pm 0.5\text{ }^{\circ}\text{C}$) led to a combined uncertainty of $0.294\text{ }^{\circ}\text{C}$ and an expanded uncertainty of $\pm 0.59\text{ }^{\circ}\text{C}$. For relative humidity, considering the sensor accuracy of $\pm 2\%$ RH, the expanded uncertainty was estimated at $\pm 2.3\%$ RH. These results confirm that the experimental measurements are subject to moderate uncertainty levels inherent to low-cost sensing devices.

This electronic monitoring architecture, shown in Figure 3, creates a system that continuously collects data, provides redundancy for data storage, and enables access to the data remotely. Having the above characteristics is very important for the successful outcome of future longer-term experimental investigations, as evidenced by the recent EAHE studies.

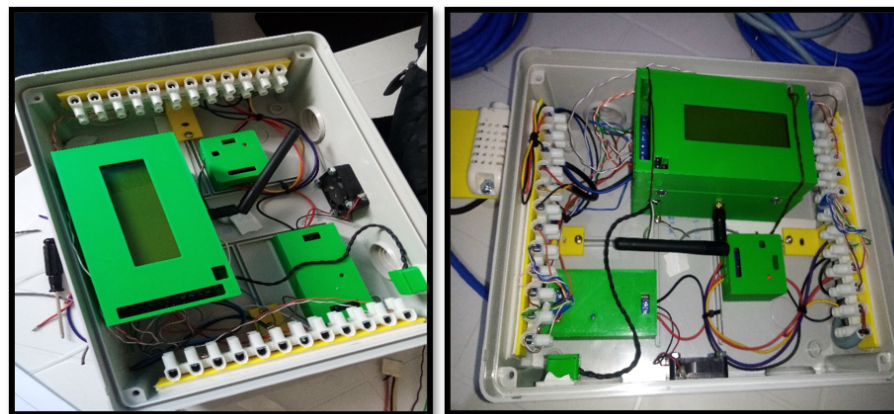


Figure 3. Instrumentation and data acquisition system architecture for the EAHE.

2.3.2. Power Supply and Energy Management Strategy

To prevent the loss of monitoring and ventilation systems due to unexpected power interruptions, a dual-source power supply was designed. Under normal operating conditions, the power will be supplied to the system using a 12 V–5 A CCTV power supply.

In the event of a power interruption, an automatic switching system employing an electromechanical relay to seamlessly transfer power will occur and power will be supplied from a 12 V–7 Ah battery (Figure 4). The battery will be charged by a 12 V–20 W photovoltaic panel using a PWM charging controller (Figure 5).

The total power required for the system equals about 25.5 Watts and therefore will supply approximately 2.5 h of backup power supply when in battery backup mode.

$$E_p = \frac{C \times D \times U}{N} \quad (18)$$

Thus,

$$E_p = \frac{7 \times 0.8 \times 12}{1} = 67.2 \text{ W} \quad (19)$$

The operating time of the system is therefore given by

$$\Delta t = \frac{E_p}{P_{\text{tot}}} = \frac{67.2}{25.5} \approx 2.5 \text{ h} \quad (20)$$

The system is capable of operating for 2.5 h due to this amount of battery capacity. This amount of time is ample for the service provider to respond in a timely manner to assist with the power failure and troubleshoot as necessary.

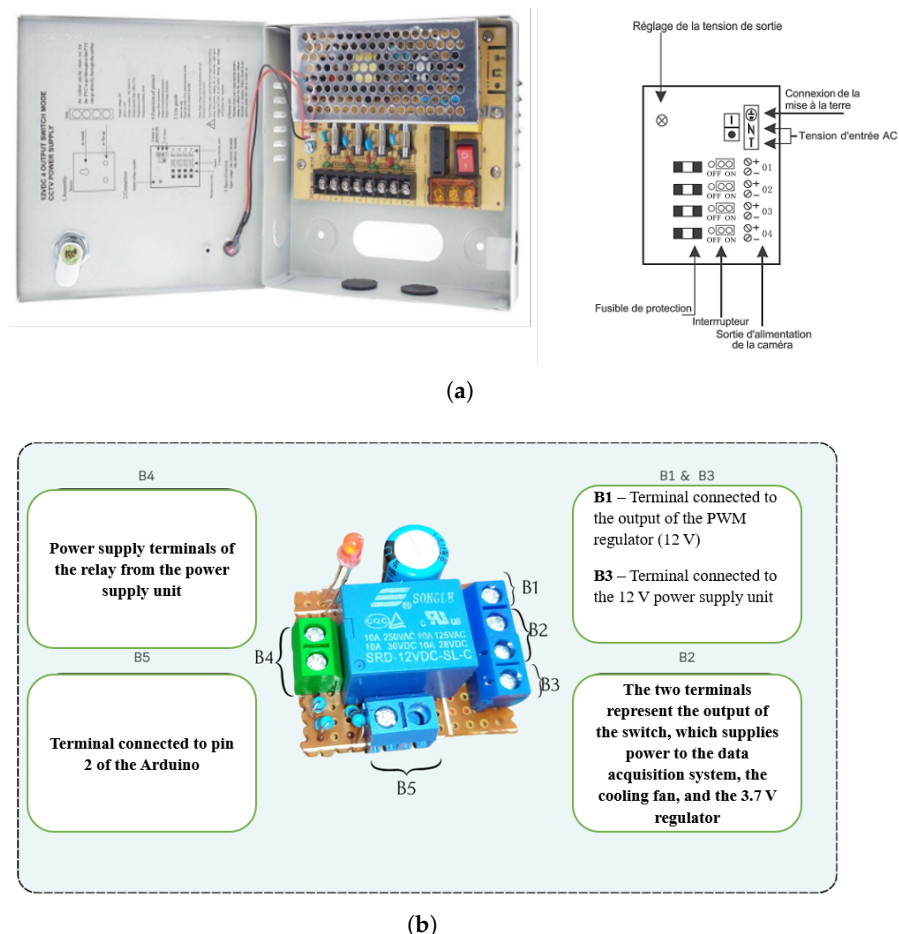


Figure 4. Switched-mode power supply enclosure showing (a) internal layout and (b) electrical connections.

The relay used for switching the power supply sources is set up to select between the primary source and the secondary source. When power is present and the system is functioning normally, the relay is powered from the 12 V supply. The circuit has a voltage divider to present a reduced voltage (5 V) to Digital Pin 2 on the Arduino. In the event of a power outage, the relay becomes unpowered and the load must be switched to use the battery. The voltage at the divider drops to zero volts, which is detected on Digital Pin 2 of the Arduino, causing the Arduino to initiate a notification of the event.

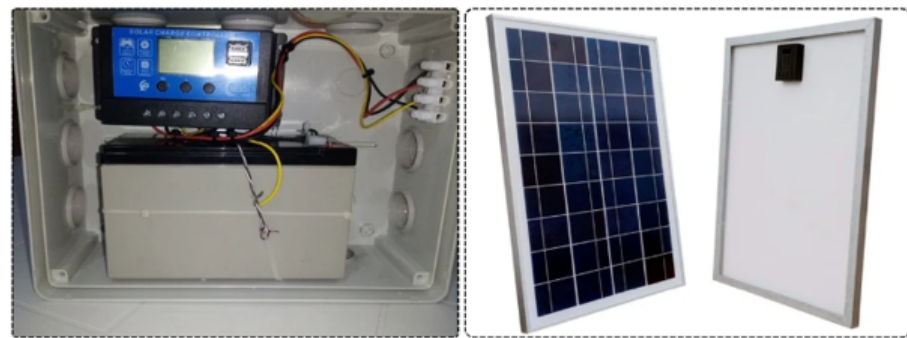


Figure 5. Photovoltaic-based power supply and energy management system.

2.3.3. Airflow Regulation and Measurement Techniques

Two 12 V axial fans, mounted in series, were installed to provide air circulation within the EAHE. By mounting the fans in series, the airflow rate is increased and improves the overall robustness of the system (Figure 6). Each fan has an integrated rotational speed sensor (RPM TRANSMITTER) and the Arduino continuously monitors fan operating conditions. The Arduino can control the rotational speed of each fan to maintain a constant flow of air regardless of the power source available.

The used digital anemometer (GM816) to determine or measure the air velocity through the EAHE's outlet averages for air velocity was about $2.5 \text{ m} \cdot \text{s}^{-1}$. The type of airflow at the EAHE outlet is of turbulent forced convection, as described in other analytical and experimental studies examining EAHE systems.



Figure 6. Experimental setup for the installation of airflow regulation and measurement techniques.

2.4. Implementation of the Monitoring System and Data Acquisition Protocol

The initial setup and installation of the monitoring system were done so that it would provide the most accurate and effective means of operating the EAHE System, as shown in Figure 7. Moreover, the monitoring system automatically records and sends information, including timestamps of when the data were taken, the air temperature of the duct (inlet and outlet), the temperature of the soil (at the depth of 2 m), and the concentration of moisture (humidity) in the duct (inlet and outlet), these parameters are all checked every 5 min. Therefore, the monitoring system has been continually monitoring the temperature and environmental conditions inside the EAHE system, thus providing an excellent source of data for evaluating the performance of the EAHE system.

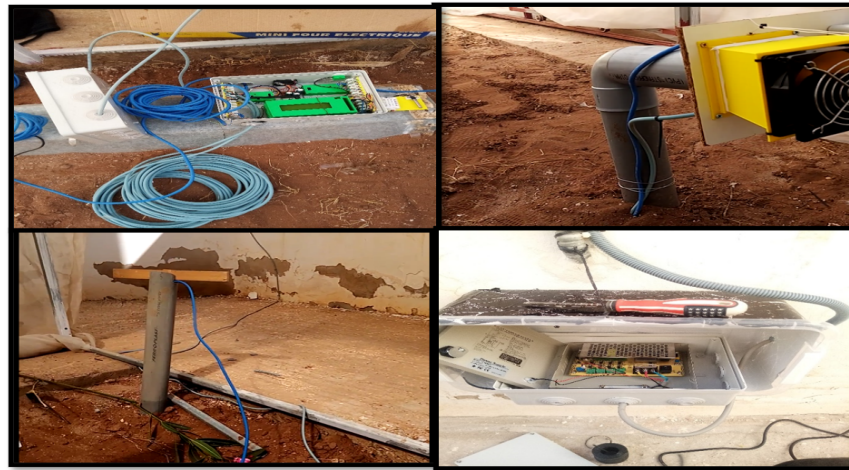


Figure 7. Different stages of the monitoring system implementation with data acquisition.

3. Results and Discussion

3.1. Long-Term Soil Temperature Behavior

Soil temperature at 2 m depth was recorded by the monitoring system every month (January–July), and the soil temperature was stable (i.e., did not experience significant changes) (23.7–25.8 °C) on average, as summarized in Table 2. The Soil temperature changes very little during this time, although there were fluctuations in the air temperature outside (Figures 8 and 9). The soil at this depth has a great deal of stable heat capability, which is essential for the successful operation of EAHE.

Semi-arid climatic temperature values are significantly greater than the ranges of temperate region soil temperatures (soil temperatures at 2 m depth in temperate regions typically being 10 °C to 15 °C) and cold climates (where winter soil temperatures can fall below 10 °C and summer soil temperatures rarely exceed 15 °C) [26,27]. At the Agadir location, the high and relatively stable soil temperature also suggests a potential to use geothermal energy from a low soil depth for passive greenhouse cooling and other agricultural usages.

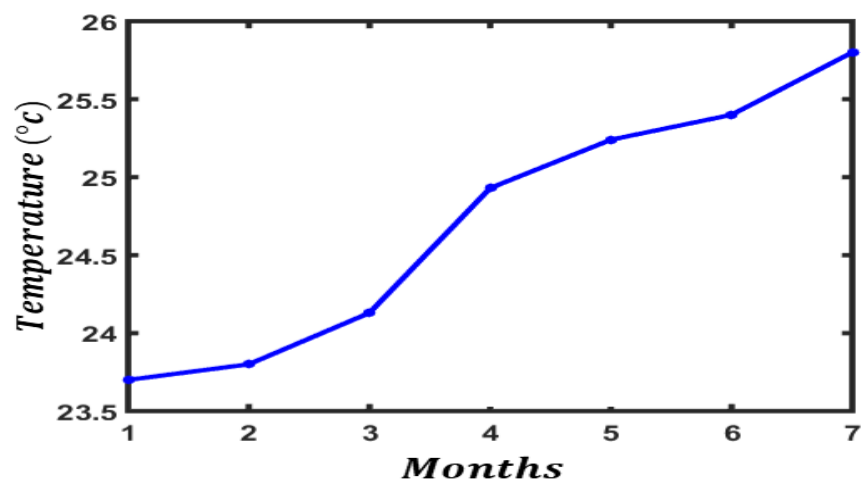
Air drawn from the outside environment into the EAHE system via airflow through fan-assist systems passes through underground ducting located about 2 m below ground level and roughly 22 m in length. As air moves through an EAHE, thermal energy is transferred from the air to the cooler soils, resulting in the air temperature near that of the underground air temperature range (23.7 °C to 25.8 °C). Due to environmental variables (thermal loss through the ducting, air flow rate and moisture content), the resulting air temperature at the outlet should closely approximate but never exceed the estimated underground soil temperature. The limitations of practical heat exchange capabilities in real EAHE systems indicate that the use of EAHE systems effectively mitigates extreme fluctuations in ambient air temperature, ultimately allowing an environment stable enough to be used for the purposes of ventilation.

The EAHE stabilizes the temperatures of the inlet and outlet air, as shown in the temporal progression of the inlet and outlet air temperatures. The inlet air went through a broad range of temperatures (13–38 °C), while there was only a small range of temperatures in the outlet air (23.5–23.8 °C) during the entire monitoring period. The slight difference between the outlet air temperature and the soil temperature may be due to loss of heat, airflow rate, soil moisture differences, and finite new-pipe lengths. Therefore, these results show that the EAHE can significantly reduce any fluctuation in air temperature, and also provide air with a temperature very close to the Earth's temperature.

Table 2. Monthly monitoring system data including environmental and system parameters (January–July 2024).

Number of Samples	Time	h_1	t_1	h_2	t_2	T_1	T_2	Soil T	Fan Speed
1	18:06:35	30.8	23.8	32.8	22.7	23.88	23.00	23.69	3645.6
2	18:11:34	31.2	23.7	34.2	22.7	23.75	22.94	23.69	3498.6
3	18:16:35	31.6	23.6	33.9	22.8	23.63	22.88	23.69	3449.6
4	18:21:35	31.3	23.4	34.3	22.8	23.44	22.94	23.75	3518.2
5	18:26:35	31.5	23.2	34.0	22.7	23.25	22.94	23.75	3420.2
6	18:31:36	32.1	23.1	34.4	22.7	23.19	22.94	23.75	3420.2
7	18:36:35	32.1	23.0	35.1	22.8	23.06	22.94	23.69	3528.0
8	18:41:36	32.5	22.9	34.5	22.8	23.00	22.94	23.69	3420.2
9	18:46:35	32.3	22.7	34.7	22.8	22.69	22.94	23.69	3498.6
10	18:51:35	33.6	22.6	35.5	22.7	22.63	22.94	23.69	3498.6
11	18:56:36	34.1	22.5	35.8	22.8	22.50	22.94	23.63	3498.6
12	19:01:35	34.3	22.3	36.3	22.7	22.44	22.94	23.64	3420.2
13	19:06:35	34.9	22.2	36.3	22.7	22.13	23.00	23.75	3459.4
14	19:11:36	35.5	22.0	36.5	22.7	21.75	22.94	23.75	3577.0
15	19:16:36	35.4	21.7	36.8	22.7	21.56	22.94	23.69	3518.2
16	19:21:35	36.2	21.5	36.8	22.8	21.38	22.88	23.69	3498.6
17	19:26:35	36.7	21.3	37.6	22.7	21.19	22.94	23.69	3420.2
18	19:31:35	37.0	21.2	37.2	22.7	21.13	22.94	23.75	3459.4
19	19:36:35	37.7	21.0	37.4	22.8	21.00	22.94	23.63	3420.2
20	19:41:35	38.1	20.9	37.6	22.7	20.88	22.94	23.75	3415.3
21	19:46:35	38.6	20.9	38.0	22.8	20.88	22.94	23.69	3420.2
22	19:51:35	39.1	20.8	38.4	22.7	20.94	22.88	23.69	3420.2
23	19:56:35	39.7	20.8	38.9	22.7	20.75	22.88	23.69	3454.5
24	20:01:35	40.1	20.7	39.5	22.7	20.69	22.94	23.69	3547.6
25	20:06:35	41.0	20.6	39.8	22.7	20.50	22.94	23.69	3459.4
26	20:11:35	41.2	20.5	40.1	22.8	20.50	22.88	23.75	3488.8

h_1 —outdoor humidity (%); t_1 —outdoor temperature (°C); h_2 —humidity at earth tube outlet (%); t_2 —outlet temperature (°C); T_1 —outdoor temperature (°C); and T_2 —earth tube outlet temperature (°C).

**Figure 8.** Temporal evolution of soil temperature at 2 m depth over seven months.

To further quantify the thermal performance of the EAHE, the temperature difference ($\Delta t = t_1 - t_2$) was analyzed as a function of the sample number (Figure 10). The results show a consistent positive temperature difference, confirming that the outlet air temperature remains systematically lower than the outdoor air temperature. Moreover, the progressive evolution of ΔT highlights the enhancement of heat exchange between the air and the surrounding soil, reflecting the system's ability to effectively dissipate heat.

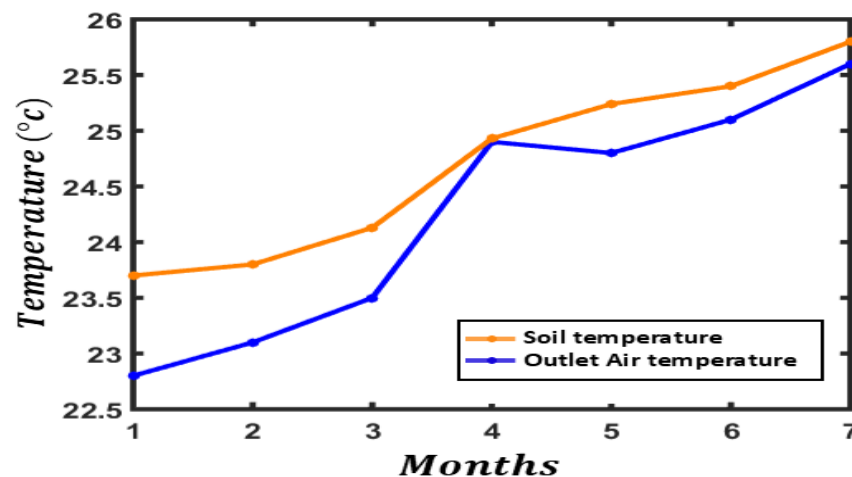


Figure 9. Comparison of inlet and outlet air temperatures along the EAHE.

In addition to the thermal analysis, the relative humidity evolution reveals a dynamic hygrometric behavior. An initial phase of slight humidification ($h_2 > h_1$) is observed, followed by a transition toward equilibrium and, subsequently, a significant dehumidification phase ($h_2 < h_1$). This shift indicates that moisture transfer mechanisms are strongly influenced by the temperature decrease along the pipe, leading to condensation effects under favorable conditions.

These combined thermal and hygrometric results reinforce the capability of the EAHE system to simultaneously stabilize air temperature and regulate humidity, thereby improving indoor environmental conditions and confirming its effectiveness as a passive and energy-efficient solution.

3.2. Validation of the Analytical Model

The purpose of the analytical model was to assess its accuracy and suitability through the comparison of experimental data with predicted values of air outlet temperatures over identical testing conditions, as represented in Figure 11. In so doing, the analytical model estimated outlet air temperatures within 23.19 to 23.21 degrees Celsius (°C), while the experimental results revealed variations between 23.5 and 23.8 °C. Further, although the ambient outdoor air temperatures were quite variable (13 to 36 °C), the predicted and experimentally measured outlet air temperatures were similar. This agreement, despite a small systematic offset, confirms that the model correctly captures the dominant heat transfer behavior governing the EAHE system.

To quantitatively evaluate this agreement, statistical error indicators were computed. The results show a Root Mean Square Error (RMSE) of 0.449 °C and a Mean Absolute Error (MAE) of 0.446 °C, indicating a low overall deviation between predicted and measured temperatures. In addition, the Mean Bias Error (MBE) of +0.446 °C indicates a slight but consistent overestimation of the outlet air temperature by the analytical model.

The differences observed between the two sets of values are primarily attributable to the assumptions and simplifications that were made in the analytical model, which include the complete disregard of the thermal inertia of pipes, the non-uniform thermal characteristics of the soil, and transient thermal characteristics within the design of the EAHE systems. However, the experimental results confirm that the analytical model trends and estimates the temperature changes along the EAHE systems, thus validating the model's assumptions and supporting its use as a tool to assist with preliminary design, optimize design, and determine the anticipated performance of EAHE systems. The magnitude of the error remains small and within acceptable limits, confirming the reliability and practical applicability of the proposed analytical model for EAHE performance prediction.

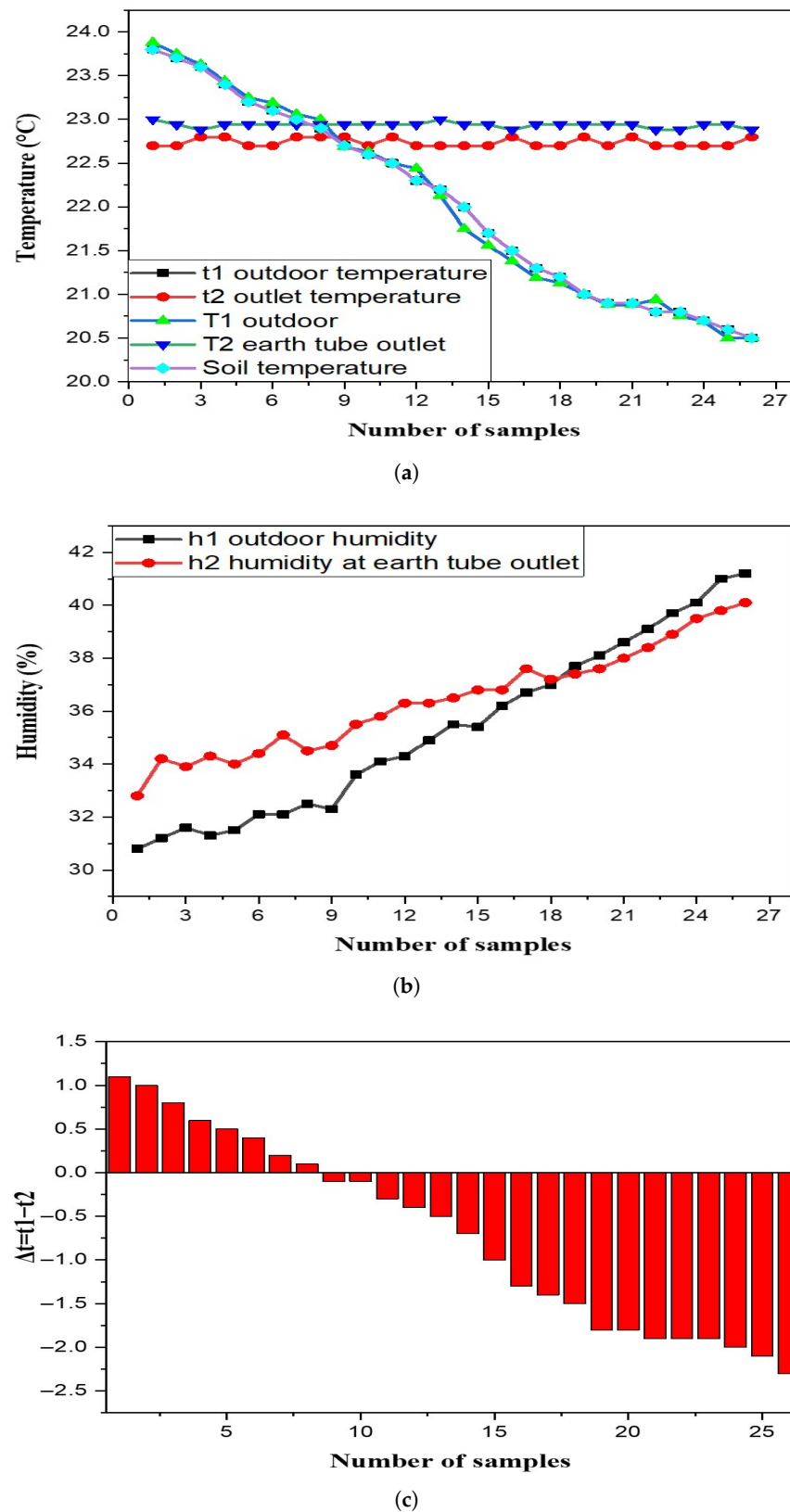
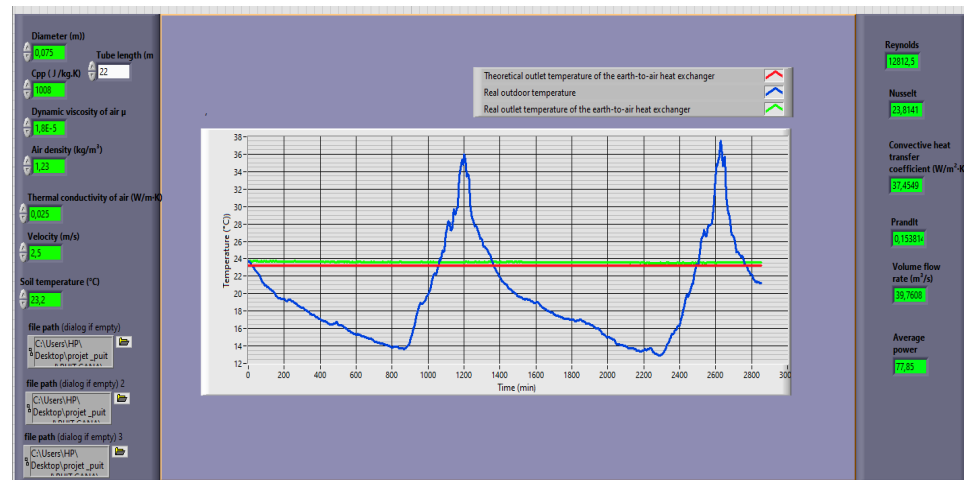
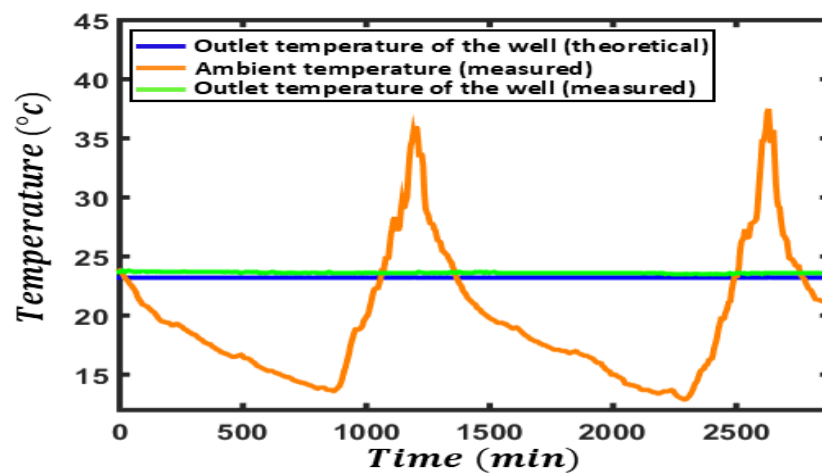


Figure 10. Variation of thermo-hygrometric variables over sample number: (a) air and soil temperature profiles; (b) inlet and outlet relative humidity evolution; and (c) corresponding temperature gradient.



(a)



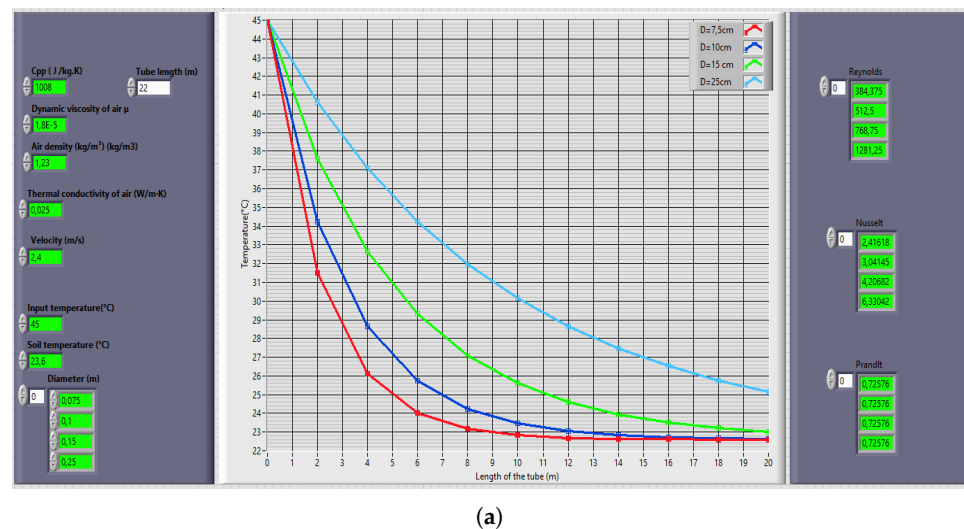
(b)

Figure 11. Validation of analytical model: measured and predicted outlet air temperature (a) obtained from the interface and (b) plotted.

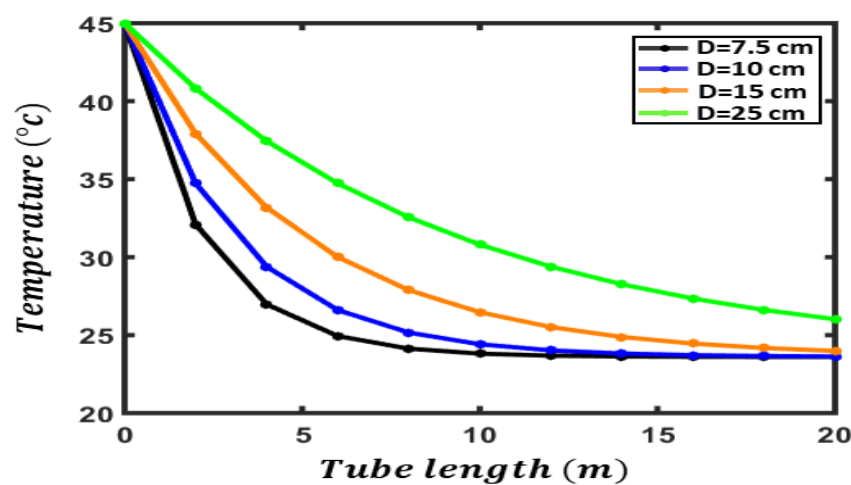
3.3. Effect of Pipe Diameter on Air Temperature Profile

Research on the effect of pipe size (diameter) on the temperature evolution of air in an EAHE, with an outdoor air temperature of 45 °C and a 23.6 °C soil temperature, as illustrated in Figure 12, suggests that as the pipe diameter increases, the distance required for the air to attain the soil temperature will also increase. This behavior can be attributed to the reduction in the surface area-to-volume ratio of the pipe as the diameter increases, resulting in reduced heat transfer efficiency over the length of the pipe. This leads to a delay in thermal equilibration between the air and soil with the larger pipe, while increased thermal exchange is obtained with the smaller pipe, although the former may suffer from increased frictional losses and resistance to airflow.

The results indicate that there is a need to optimize pipe size when designing an EAHE to obtain the best balance between the thermal performance and airflow efficiency. The proper pipe size should be selected to ensure proper temperature regulation and adequate ventilation in passive cooling systems in greenhouses and buildings located in semi-arid regions.



(a)

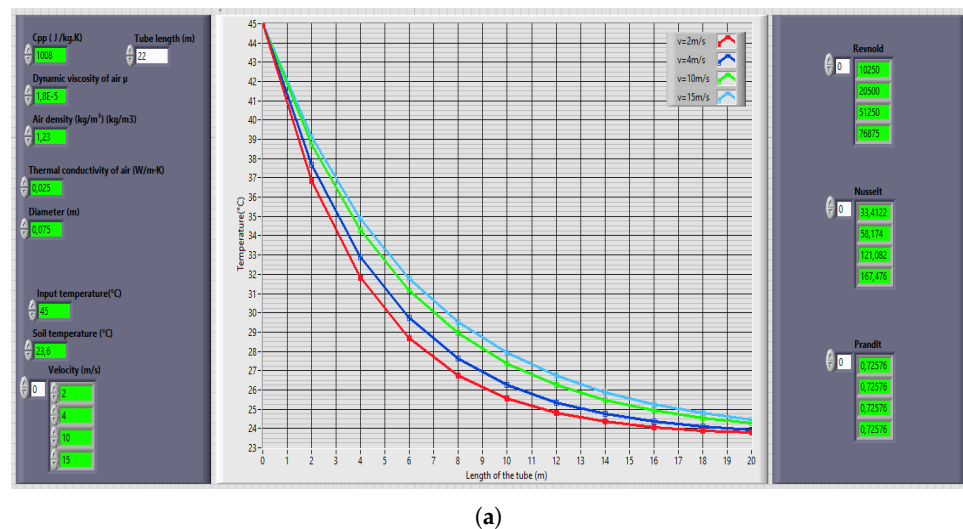


(b)

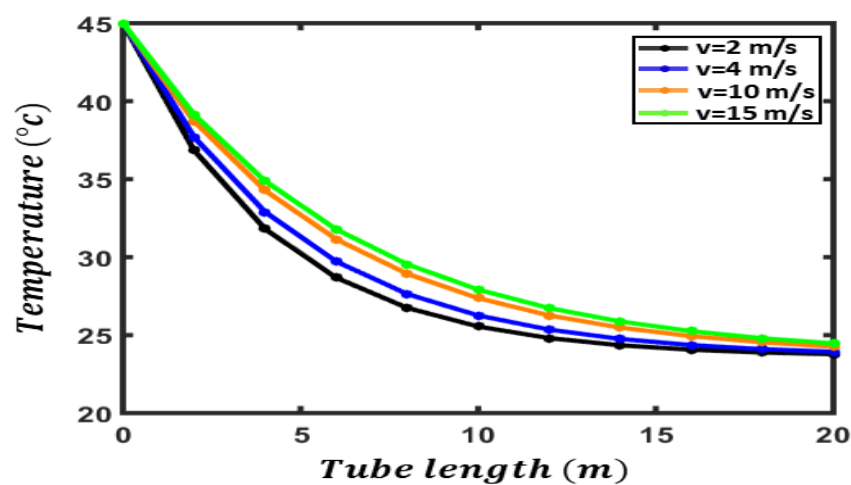
Figure 12. Effect of pipe diameter on air temperature evolution along the EAHE (a) obtained from the interface and (b) plotted.

3.4. Effect of Air Velocity

The velocity of air is a critical factor in determining the thermal response of an Earth-Air Heat Exchanger (EAHE), as greater velocities lead to a reduction in the time that air spends in the EAHE and therefore the distance over which the EAHE can transfer heat to soil. Experimental results, depicted in Figure 13, show little variation in outlet temperatures among the four different airflow velocities tested; therefore, it can be concluded that (for a given length of pipe) by increasing the airflow rate, the ventilation of the EAHE can be improved without greatly compromising the thermal efficiency of the system. Thus, the EAHE system provides sufficient flexibility to adjust the airflow to meet the required level of ventilation while maintaining an adequate level of heat transfer. All of these aspects of the EAHE system are in agreement with the results of the theoretical model and are critical for optimally balancing airflow rates and pipe length for maximum use of both thermal exchange and air delivery within the EAHE applications in practice.



(a)



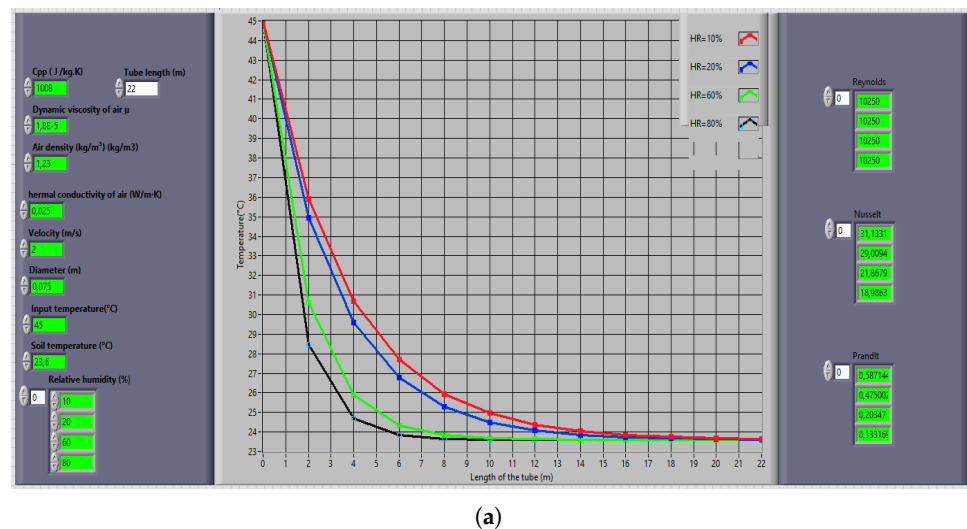
(b)

Figure 13. Impact of airflow velocity on temperature profiles in the buried duct (a) obtained from the interface and (b) plotted.

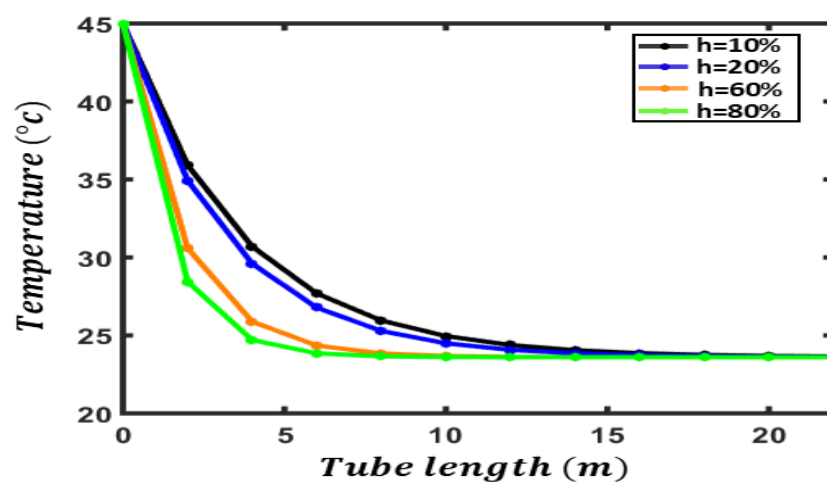
3.5. Influence of Air Humidity

The moisture content in the air plays an integral role in the thermal performance of the Earth–Air Heat Exchanger (EAHE). In contrast, when comparing humid air with dry air, humid air transfers the temperature of the surrounding soil (ambient temperature) to the duct more quickly than dry air, which comprises a higher amount of moisture, which means that less distance is needed for that air to reach thermal equilibrium with the surrounding soil. In addition, moisture-containing air can represent a larger amount of energy transfer than dry air because humid air has a greater specific heat capacity than dry air. Thus, when the air is dry, a longer length of duct will require the duct length to be fully thermally equilibrated with the soil temperature than when the air is humid.

As an example, in humid climates, designers can omit longer duct lengths to optimally design the EAHE. In addition, in dry climates where moisture levels vary significantly, the designers should factor in the potential efficiencies gained from using humid air to optimize the design and performance of EAHE duct systems to achieve the highest levels of thermal performance. Figure 14 depicts the effect of air moisture on the change in air temperature along the length of an EAHE.



(a)



(b)

Figure 14. Influence of air humidity on temperature evolution along the EAHE (a) obtained from the interface and (b) plotted.

The moisture content of air plays a significant role in the thermal performance of the Earth–Air Heat Exchanger (EAHE) and must be interpreted within a rigorous psychrometric and thermodynamic framework [28–31]. In moist air systems, the total specific enthalpy is given by

$$h_{\text{air}} = c_{p,a}T + \omega(h_{fg} + c_{p,v}T) \quad (21)$$

where ω is the humidity ratio, explicitly showing that both sensible heat and latent heat associated with water vapor contribute to the total energy balance. Therefore, the observed differences between dry and humid air cannot be attributed solely to variations in specific heat capacity, but rather to combined sensible–latent heat effects [29].

From a heat transfer perspective, humid air can exhibit a higher total enthalpy content; however, the presence of moisture does not inherently increase the rate of thermal equilibrium with the surrounding soil. Instead, the rate of temperature evolution along the duct is primarily governed by the convective heat transfer coefficient, airflow rate (residence time), and the thermophysical properties of the moist air mixture. The influence of humidity is therefore indirect and manifests through changes in air density, specific heat, and enthalpy gradients, which may slightly modify the heat exchange rate [30].

In addition, the thermal interaction between the air stream and the surrounding soil remains governed by classical convection–conduction coupling, and equilibrium is

achieved when the air temperature approaches the soil temperature asymptotically along the duct length. Consequently, the required duct length for thermal stabilization is not directly reduced by humidity alone, but depends on the coupled effect of psychrometric properties and operating conditions [31].

3.6. Thermal Power Gained by the Airflow

From the data collected from the 'EAHE' project, we generated graphs (Figure 15) that depicted the thermal energy transferred to the airflow via those ducts based on the measured inlet and outlet temperatures of the air within the duct.

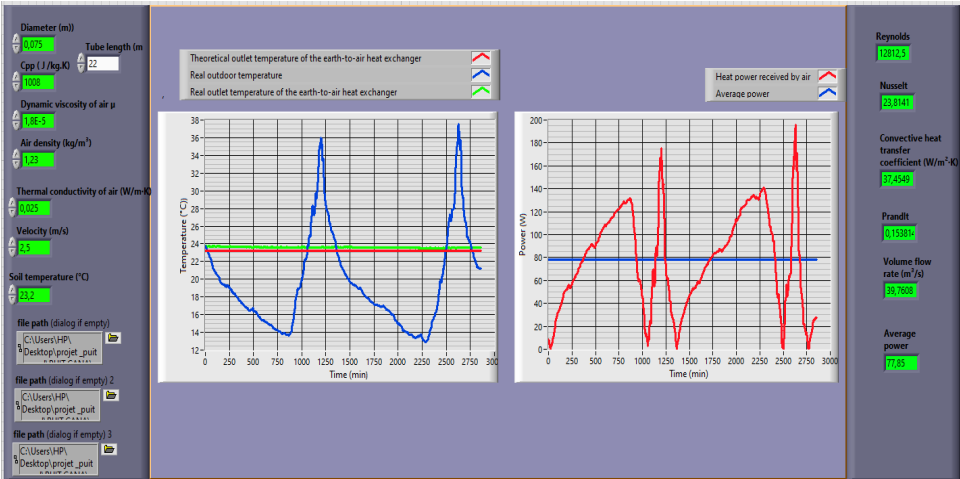
$$P_{th} = \rho q_v C(\theta_{air}(x = L) - \theta_{air}(x = 0)) \quad (22)$$

where ρ is the air density, q_v is the volumetric flow rate of air, C_p is the specific heat capacity of air, and θ_{in} and θ_{out} are the air temperatures at the duct inlet and outlet, respectively. Our analysis assumed that the soil temperature remained constant at 23.6 °C, and the effect of outdoor air temperature on thermal power was tracked for two consecutive days. The instantaneous thermal power of the air was observed to vary from 0 W to 190 W, depending on the variation of the outdoor air temperature from the soil temperature. The average thermal power was 81 W, which indicates that there was a substantial amount of thermal energy transferred to the air over the 22 m duct length.

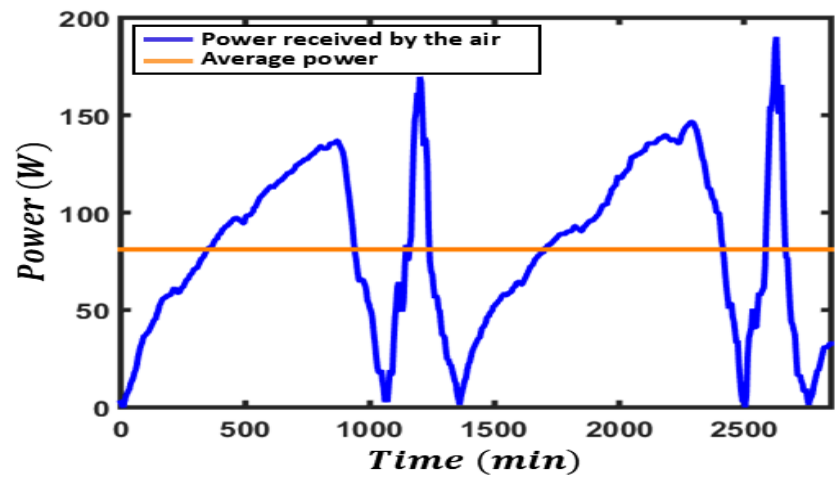
The EAHE system uses a 12 V fan rated at 0.5 A to maintain the necessary airflow through the duct, thereby illustrating that a significant quantity of thermal energy may be recovered by the EAHE system with very low electrical energy input, thus exhibiting the high energy efficiency and suitability for passive cooling applications.

Overall, these results demonstrate that the EAHE system will be able to deliver consistent, thermally conditioned air, even in variable climatic conditions (13–38 °C), and thus are suitable for use as an environmentally friendly, low-energy method of providing ventilation for greenhouse and building applications.

To further evaluate the performance of the proposed Earth–Air Heat Exchanger (EAHE), a quantitative comparison with representative studies reported in the literature has been carried out and presented in Table 3. The present system exhibits a stabilized outlet air temperature in the range of 23.5–23.8 °C, despite ambient temperature variations between 13 °C and 38 °C, corresponding to a maximum temperature attenuation of approximately 14–15 °C. This performance is comparable to, and in some cases exceeds, values reported in previous experimental studies. For instance, Rosa et al. [32] reported temperature reductions of 8–12 °C under Mediterranean climatic conditions with long-term monitoring, while Alkrush et al. [33] observed cooling capacities between 6 and 10 °C in arid environments depending on airflow conditions and system configuration. Similarly, Hatraf et al. [34] reported temperature drops of approximately 7–11 °C in semi-arid regions, although their investigations were limited to shorter monitoring periods. In contrast, numerical studies such as Michalak et al. [35] demonstrated stable outlet temperature predictions without experimental validation. The relatively higher thermal attenuation observed in the present study can be attributed to the combined influence of extended monitoring duration, optimized airflow velocity, and appropriate duct geometry, which enhance the heat exchange process and promote thermal equilibrium with the surrounding soil. These results confirm the effectiveness and robustness of the proposed EAHE system and highlight its strong potential for passive cooling applications under semi-arid climatic conditions.



(a)



(b)

Figure 15. Instantaneous and average thermal power exchanged between air and soil (a) obtained from the interface and (b) plotted.

Table 3. Comparative analysis of representative EAHE studies.

Reference	Location/Climate	Monitoring Duration	Methodology	Key Parameters Studied	Main Findings	Limitations
Rosa et al. (2018) [32]	Portugal/Mediterranean	~1 year	Experimental + Analytical	Pipe length, diameter, airflow velocity	Effective cooling performance and validated model	Site-specific results
Hatraf et al. [34]	Algeria/Semi-arid	~2–3 months	Experimental	Airflow rate, burial depth	Improved cooling with optimized airflow	Limited duration and variables
Michalak (2022) [35]	Poland/Temperate	Simulation	Numerical	Soil properties, airflow conditions	Accurate prediction of EAHE thermal behavior	No experimental validation
Alkrush et al. (2024) [33]	Middle East/Arid	~3 months	Experimental + Analytical	Air velocity, pipe configuration	Good agreement between model and experiment	Short-term monitoring
Morshed et al. (2022) [36]	Middle East / Arid	Few weeks	Experimental	Pipe length, diameter, airflow	Enhanced greenhouse thermal performance	Limited monitoring duration
Present Work	Morocco (Agadir)/Semi-arid	7 months	Experimental + Analytical	Duct diameter, airflow velocity, humidity	Stable outlet temperature (23.5–23.8 °C) with strong model validation	Steady-state assumption

4. Conclusions

This study includes both an experimental and analytical evaluation of a data-validated (instrumented) Earth–Air Heat Exchanger (EAHE) operating under semi-arid conditions in Agadir, Morocco, through passive (natural) cooling, based on the thermal inertia of the ground. The study includes long-term monitoring of the system, an analytical model based on the experimental data, and an overall performance evaluation of the system. During seven months of monitoring, the average soil temperature at 2 m from ground level remained constant between 23.7 and 25.8 °C, and the outlet air temperature of the EAHE remained in a similar range at 23.5–23.8 °C during times when the outdoor environmental temperature fluctuated between 13 and 38 °C. The study results confirm that the EAHE significantly mitigated the thermal fluctuation, resulting in a constant outlet air temperature.

The validated steady-state analytical model accurately predicts the outlet air temperature, confirming the relevance of the adopted assumptions and its suitability as a tool for preliminary design and system optimization. The parametric analysis identified pipe diameter, airflow rate, and air humidity (through its effect on air properties) as the primary factors influencing the thermal performance of the EAHE system. These findings highlight the importance of properly selecting design and operating parameters to enhance system efficiency under real climatic conditions.

Thermal energy analysis indicates an average heat exchange rate of approximately 81 W, with peak values reaching 190 W under the investigated conditions, while maintaining low electrical energy consumption. Although this level of cooling capacity confirms the ability of the EAHE system to extract heat from the airflow, it remains limited compared to the high cooling loads typically encountered in greenhouse environments, which are primarily driven by solar radiation and internal heat accumulation. Therefore, the investigated EAHE configuration is not sufficient as a standalone cooling system to meet peak greenhouse cooling demands. Instead, it should be considered as a passive pre-cooling solution that reduces the inlet air temperature and partially offsets the sensible cooling load.

This pre-conditioning effect can contribute to improving the overall efficiency of hybrid ventilation or active cooling systems when integrated into a comprehensive greenhouse thermal management strategy.

Future work will focus on improving the physical completeness and predictive accuracy of the proposed model by incorporating transient heat transfer effects and a comprehensive thermal resistance network, including internal convection, pipe wall conduction, and soil-side resistance. In addition, a coupled heat and mass transfer formulation will be developed to account for latent heat effects and potential condensation within the duct. Further investigations will also address system scaling and optimization, including multi-duct configurations and varying airflow conditions, in order to enhance cooling capacity and assess the integration of EAHE systems within hybrid greenhouse cooling strategies under semi-arid climates.

Author Contributions: A.Y.: conception and design; methodology; investigation; validation; writing—original draft; visualization; software; formal analysis. B.Y.: conception; methodology; investigation; validation; review and editing; visualization; software; formal analysis. I.A.: investigation; methodology; review and editing. A.W.: investigation; review and editing; funding acquisition. A.A.: resources; investigation; review and editing; funding acquisition. R.L.: resources; methodology; writing—review and editing; supervision; project administration; conceptualization. All authors have read and agreed to the published version of the manuscript.

Funding: The authors declare that they received no funding, grants, or other forms of support while writing this article.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data from this study are available upon request from the corresponding authors.

Conflicts of Interest: The authors declare that they have no conflicts of interest.

Nomenclature

Symbol	Description	Unit
Q	Heat energy	J
$\frac{dQ}{dt}$	Heat transfer rate	W
$\dot{m}$	Mass flow rate	kg s ⁻¹
q_v	Volumetric flow rate	m ³ s ⁻¹
ρ	Air density	kg m ⁻³
C	Specific heat capacity of air	J kg ⁻¹ K ⁻¹
$\theta_{\text{air}}(x)$	Air temperature along the duct	°C
$\theta_{\text{air}}(0)$	Inlet air temperature	°C
θ_{terre}	Soil temperature	°C
θ	Local air temperature variable	°C
$\Delta\theta$	Temperature difference	°C
h	Convective heat transfer coefficient	W m ⁻² K ⁻¹
S	Heat transfer surface area	m ²
R	Pipe radius	m
D	Pipe diameter	m
x	Axial coordinate along pipe length	m
dx	Differential pipe length element	m
v	Air velocity	m s ⁻¹
μ	Dynamic viscosity of air	Pa s
λ	Thermal conductivity of air	W m ⁻¹ K ⁻¹
Re	Reynolds number	–
Pr	Prandtl number	–
Nu	Nusselt number	–
$c_{p,a}$	Specific heat capacity of dry air	J kg ⁻¹ K ⁻¹
$c_{p,v}$	Specific heat capacity of water vapor	J kg ⁻¹ K ⁻¹
ω	Humidity ratio	kg _v /kg _{da}
h_{fg}	Latent heat of vaporization	J kg ⁻¹
h_{air}	Specific enthalpy of moist air	J kg ⁻¹
RMSE	Root Mean Square Error	°C
MAE	Mean Absolute Error	°C
MBE	Mean Bias Error	°C
ε	Random uncertainty	°C

References

1. Aste, N.; Del Pero, C.; Leonforte, F. Toward building sector energy transition. In *Handbook of Energy Transitions*; CRC Press: Boca Raton, FL, USA, 2022; pp. 127–150.
2. Marzouk, O.A. Summary of the 2023 report of TCEP by the International Energy Agency and proposed process for computing a single aggregate rating. *E3S Web Conf.* **2025**, *601*, 48. [\[CrossRef\]](#)
3. Hamilton, I.; Kennard, H.; Rapf, O.; Amorcho, J.; Steuwer, S.; Kockat, J.; Toth, Z. *Global Status Report for Buildings and Construction—Beyond Foundations: Mainstreaming Sustainable Solutions to Cut Emissions from the Buildings Sector*; UNEP: Nairobi, Kenya, 2024.
4. Santamouris, M. Recent progress on urban overheating and heat island research: Integrated assessment of energy, environmental, vulnerability and health impacts. *Energy Build.* **2020**, *207*, 109482. [\[CrossRef\]](#)
5. Bisioniya, T.S. Design of earth–air heat exchanger system. *Geotherm. Energy* **2015**, *3*, 18. [\[CrossRef\]](#)

6. Koshlak, H. A review of earth-air heat exchangers: From fundamental principles to hybrid systems with renewable energy integration. *Energies* **2025**, *18*, 1017. [\[CrossRef\]](#)
7. Agrawal, K.K.; Misra, R.; Agrawal, G.D.; Bhardwaj, M.; Jamuwa, D.K. State of the art on applications and research trends of earth-air heat exchanger systems. *Geothermics* **2019**, *82*, 34–50. [\[CrossRef\]](#)
8. Kundu, A.; Kumar, A.; Awasthi, M.K.; Dwivedi, G.; Shukla, A.K. Explorative study of an earth-air heat exchanger for sustainable building applications. *Int. J. Energy Clean Environ.* **2025**, *26*, 1–22. [\[CrossRef\]](#)
9. D'Agostino, D.; Kouki, N.; Minelli, F.; Minichiello, F. Application of earth-to-air heat exchangers for sustainable energy management in school buildings. *J. Phys. Conf. Ser.* **2025**, *3143*, 12050. [\[CrossRef\]](#)
10. Zhang, C.; Wang, J.; Li, L.; Wang, F.; Gang, W. Utilization of earth-to-air heat exchanger to pre-cool/heat ventilation air and its annual energy performance evaluation. *Sustainability* **2020**, *12*, 8330. [\[CrossRef\]](#)
11. Thamer, H.L. Experimental testing of earth-to-air heat exchanger for greenhouse air conditioning in hot climates. *Int. J. Comput. Methods Exp. Meas.* **2025**, *13*, 908–927. [\[CrossRef\]](#)
12. Lattieff, F.A.; Atiya, M.A.; Lateef, R.A.; Dulaimi, A.; Jweeg, M.J.; Abed, A.M.; Mahdi, J.M.; Talebizadehsardari, P. Thermal analysis of horizontal earth-air heat exchangers in a subtropical climate. *Front. Built Environ.* **2022**, *8*, 981946. [\[CrossRef\]](#)
13. Zheng, X.; Song, Z.; Ding, Y. Heat exchange characteristics of underground buried pipes for bridge deck heating. *PLoS ONE* **2024**, *19*, e0298077. [\[CrossRef\]](#)
14. Ahmed, S.F.; Amanullah, M.T.O.; Khan, M.M.K.; Rasul, M.G.; Hassan, N.M.S. Parametric study on thermal performance of horizontal earth pipe cooling systems. *Energy Convers. Manag.* **2016**, *114*, 324–337. [\[CrossRef\]](#)
15. Sedighi, A.A.; Bazargan, M. Effects of buried pipe configuration on underground passive cooling system performance. *J. Build. Eng.* **2021**, *43*, 103212. [\[CrossRef\]](#)
16. Bansal, V.; Misra, R.; Agrawal, G.D.; Mathur, J. Performance and economic analysis of integrated earth–air heat exchanger systems. *Energy Build.* **2012**, *55*, 102–108. [\[CrossRef\]](#)
17. Huang, K.; Sun, Q.; Feng, G.; Zhang, L.; Li, A.; Wei, J.; Zhang, X.; Meng, X. Experimental and numerical study of vertical earth-to-air heat exchanger systems. *Geothermics* **2025**, *125*, 103182. [\[CrossRef\]](#)
18. Asadi, S.; Mohammadagha, M.; Naeini, H.K. Review of analytical and numerical approaches in earth-to-air heat exchangers. *arXiv* **2025**, arXiv:2502.08553.
19. Altwieb, M.; Kubiak, K.J.; Aliyu, A.M.; Mishra, R. Three-dimensional CFD model for efficiency optimization of heat exchangers. *Therm. Sci. Eng. Prog.* **2020**, *19*, 100658. [\[CrossRef\]](#)
20. Łach, Ł.; Svyetlichnyy, D. Advances in numerical modeling for heat transfer and thermal management. *Energies* **2025**, *18*, 1302. [\[CrossRef\]](#)
21. Mostafaeipour, A.; Goudarzi, H.; Khanmohammadi, M.; Jahangiri, M.; Sedaghat, A.; Norouzianpour, H.; Chowdhury, S.; Techato, K.; Issakhov, A.; Almutairi, K. Techno-economic analysis of earth-to-air heat exchanger systems in buildings. *Energy Sci. Eng.* **2021**, *9*, 1807–1825. [\[CrossRef\]](#)
22. Ahmed, S.F.; Liu, G.; Mofijur, M.; Azad, A.K.; Hazrat, M.A.; Chu, Y.-M. Physical and hybrid modelling techniques for earth-air heat exchangers. *Sol. Energy* **2021**, *216*, 274–294. [\[CrossRef\]](#)
23. Simonetti, M. Study of Convective Heat Transfer Phenomena for Turbulent Pulsating Flows in Pipes. Ph.D. Thesis, Université d'Orléans, Orléans, France, 2017.
24. Alidrissi, Y.; Wakil, M.; Najib, M.; Kaitouni, S.I.; Mghazli, M.O.; Bakhouya, M. EAHE-D: A dataset for modeling and performance evaluation of earth-to-air heat exchangers. *Data Brief* **2024**, *57*, 111110. [\[CrossRef\]](#)
25. Bouchane, K.; Ydir, B.; Soumane, M.; Yagour, A.; Haijoub, I.; Leghrib, R.; Lahlou, H. Development and Evaluation of an Automatically Controlled Environmental Chamber System for Stable and Independent Regulation of Ambient Parameters. *Rom. J. Phys.* **2026**, *71*, 904.
26. Jiao, Y.; Chen, C.; Li, G.; Fu, H.; Mi, X. Variation patterns and predictive models of soil temperature in solar greenhouses. *Sol. Energy* **2024**, *270*, 112267. [\[CrossRef\]](#)
27. Yang, Y.; Wu, Z.; He, H.; Du, H.; Wang, L.; Guo, X.; Zhao, W. Changes in soil temperature in cold and mid-temperate zones. *Theor. Appl. Climatol.* **2018**, *134*, 633–643. [\[CrossRef\]](#)
28. ASHRAE. *ASHRAE Handbook—Fundamentals*; American Society of Heating, Refrigerating and Air-Conditioning Engineers: Atlanta, GA, USA, 2021.
29. Çengel, Y.A.; Boles, M.A. *Thermodynamics: An Engineering Approach*, 8th ed.; McGraw-Hill Education: New York, NY, USA, 2015.
30. Incropera, F.P.; DeWitt, D.P.; Bergman, T.L.; Lavine, A.S. *Fundamentals of Heat and Mass Transfer*, 7th ed.; Wiley: Hoboken, NJ, USA, 2011.
31. Bansal, V.; Misra, R.; Agrawal, G.D. Earth–air tunnel heat exchanger system: A review. *Renew. Sustain. Energy Rev.* **2012**, *16*, 9–23.
32. Rosa, N.; Santos, P.; Costa, J.J.; Gervásio, H. Modelling and performance analysis of an earth-to-air heat exchanger in a pilot installation. *J. Build. Phys.* **2018**, *42*, 259–287. [\[CrossRef\]](#)

33. Alkrush, A.A.; Abdelrehim, O.; Hegazi, A.A.; Salem, M.S. Optimizing earth-to-air heat exchanger performance: Thermal analysis and parametric optimization study using laboratory simulation and response surface methodology. *Therm. Sci. Eng. Prog.* **2025**, *67*, 104115. [[CrossRef](#)]
34. D'Agostino, D.; Esposito, F.; Greco, A.; Masselli, C.; Minichiello, F. Parametric analysis on an earth-to-air heat exchanger employed in an air conditioning system. *Energies* **2020**, *13*, 2925. [[CrossRef](#)]
35. Michalak, P. Hourly simulation of an earth-to-air heat exchanger in a low-energy residential building. *Energies* **2022**, *15*, 1898. [[CrossRef](#)]
36. Morshed, W.; Abbas, L.; Nazha, H. Heating performance of the PVC earth-air tubular heat exchanger applied to a greenhouse in the coastal area of west Syria: An experimental study. *Therm. Sci. Eng. Prog.* **2022**, *27*, 101000. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.